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Effect of Regeneration Method on Growth, Wood Density and Fibre Properties of Downy Birch (*Betula pubescens* Ehrh.)

Katri Luostarinen, Noora Huotari and Eila Tillman-Sutela

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Short rotation tree stands, established by coppicing, are nowadays used mainly for energy purposes in Fennoscandia, but their usage for pulp raw material may increase in the future. Downy birch (*Betula pubescens*), which is commonly used for pulp production in boreal zone, has good sprouting capacity. However, it is not known if the fibre properties of sprout-originated downy birches differ from those of seed-originated ones. Therefore, fibre length and width of sprout- and seed-originated downy birches grown on fertile soil were measured at a stand age of 25 years. Additionally annual ring width, stem height and diameter, and wood density were studied to compare the growth and wood properties of sprout- and seed-originated birches. Annual rings were slightly wider in sprout- than in seed-originated birches, whereas no differences were observed in wood density. Fibres, too, were slightly longer and wider in sprout- than in seed-originated trees. Still these minor differences observed here are hardly significant for the industries using birch wood. Consequently downy birch wood from coppiced stands is well suited for pulp. The advantages of coppice, i.e. rapidity and low costs of establishment, productivity, and the ability of downy birch to grow on untypical forest sites, may even increase the importance of the wood coming from coppiced birch stands in the future.

Keywords coppice, fibre length, fibre width, regeneration methods, wood properties
Addresses *Luostarinen*, Faculty of Forest Sciences, University of Joensuu, P.O. Box 111, FI-80101, Joensuu, Finland; *Huotari* and *Tillman-Sutela*, Finnish Forest Research Institute, Muhos Research Unit, Kirkkosaarentie, FI-91500 Muhos, Finland
E-mail katri.luostarinen@joensuu.fi
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1 Introduction

Coppicing is frequently used as a regeneration method in short-rotation cultures to produce wood biomass for energy production or pulp production. Recently an important aim of forest regeneration has also been to sequester atmospheric carbon efficiently into the ecosystem (Kirkinen et al. 2007). In North America (DeBell et al. 1998) and in Central Europe (Klasnja et al. 2003), especially *Populus* species are cultured in short rotations for the pulp and paper industry, whereas in warmer regions the species cultivated are frequently *Eucalyptus, Gmelina* and *Acacia* species (Zobel and Sprague 1998). In Finland, the studies of short-rotation cultivation have mainly concentrated on exotic willow species (*Salix* spp.), grey alder (*Alnus incana* (L.) Moench), silver birch (*Betula pendula* Roth), and downy birch (*B. pubescens* Ehrh.) (Hytönen et al. 1995, Hytönen and Kaunisto 1999, Tahvanainen and Rytkönen 1999, Hytönen and Issakainen 2001). The short-rotation cultivations of these species are typically established on abandoned areas, other than forests, such as cut-away peatlands or former agricultural fields.

Downy birch, which thrives on moist peat soils, is a common deciduous tree species in Finland with the main yield of its wood being used for pulping because its stem form does not attain as often as that of silver birch the quality required for saw logs or veneer (Verkasalo 1997, Niemistö and Korhonen 2008). The estimated amount of downy birch timber used for pulp production is more than 4 million cubic meters per year in Finland (Niemistö 2000). It is also a potential tree species for reasonable short-rotation forestry due to its good sprouting capacity and relatively fast growth (Ferm et al. 1985, Ferm 1993). Although the first generation is usually allowed to grow through natural seeding (Huotari et al. 2008), the second one is commonly established through coppicing.

The regenerating cycle of short-rotation plantations may vary significantly, from 2 years to up to 50 years, depending on climate, site conditions, cultivated tree species and end-use requirements of the wood biomass. In Finland the minimum rotation for downy birch stands should be at least 20 years in order to maximize the biomass production (Hytönen and Issakainen 2001, Hytönen and Aro 2004) and the maximum rotation for pulp wood is around 50 years because at this age the poorer trunks, still suitable for pulp, start to decay markedly (Niemistö 1998). However, the fact that the trunks originate from sprouts is not necessarily the main reason for decay (Ferm 1990). Thus, the cultivation of dense downy birch stands through coppicing, with a rotation of 20–40 years, could be a good alternative as the demand of the domestic bioenergy has recently increased in Finland as a consequence of the goal of the European Union to reduce its CO_2 emissions. The wood from coppiced birch stands could replace, to a certain extent, *Eucalyptus* and other pulp wood often imported from far away (Peltola 2008), and the Russian birch pulp wood, the imports of which presumably ceases in the near future (Venäläisen puun … 2008). In addition, the warming climate, which is predicted to increase the growth of deciduous trees in the boreal zone (Kuusisto et al. 1996), as well as the additional carbon in the atmosphere bound mainly in the aboveground growth (Overdieck et al. 2007), may further enhance the future possibilities to grow downy birch in short rotations. Short-rotation cultivation, when based on coppicing, would also diminish the costs of regeneration and later management, also because early growth of birch coppices is faster than that of seedlings (Kauppi et al. 1988, Hytönen and Kaunisto 1999).

Tree age affects the fibre properties of wood, and, thus, its suitability as a raw material for the pulp and paper industry. For example, some fast growing tropical short rotation tree species consist only of juvenile wood when they are harvested at only a few years of age (Zobel and Sprague 1998). Fibres are shorter and narrower and the wood is commonly less dense in the juvenile zone than in the mature wood although the differences are smaller in deciduous species than in conifers. On the other hand, growth rate is a significant factor affecting wood properties, such as density particularly in conifers (Zobel and van Buijtenen 1989, Kärkkäinen 2007), but it has not been found to affect wood density of mature wood in seed-originated downy birch (Ollinmaa 1960). The small dimensions of fibres are an advantage for certain sectors of the pulp and paper industry, whereas low density of wood is a disadvantage for both pulp and energy purposes.

The effect of regeneration method on fibre properties of downy birch is still unknown, although differences in physiology and growth between young sprouts and seedlings have been reported (Kauppi et al. 1990, Paukkonen and Kauppi 1998, Luostarinen and Kauppi 2005). Consequently coppicing may affect the development of xylem and its properties, and possible changes are probably most distinguishable in the juvenile zone. In the above context, growth, wood density and fibre properties of sprout- and seed-originated downy birches were studied at a stand age of 25 years.

2 Material and Methods

2.1 Sampling

The experimental downy birch (*Betula pubescens*) stand is located in Kempele, central Finland (64°54´N, 25°27´E). The area is a mesotrofic seaside meadow, which resembles a mined peatland. The soil on the experimental plot is peat. The original stand was harvested and the area was ditched in 1981, when coppicing and natural seeding were used as regeneration methods for the area. The stand was thinned to 3000 stems/ha in 1991 leaving only one stem per each coppiced stump cluster.

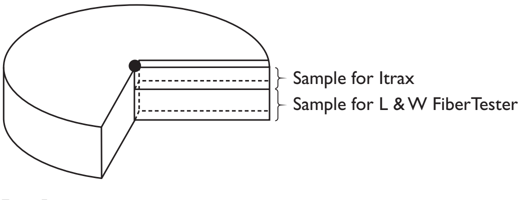

Fig. 1. Sampling from the discs: the upper and lower surfaces of the sawn sample discs were discarded and only 30 mm thick disc was used. The sample strips for analysing annual ring width (radius × 5 × 5 mm^3) using Itrax and for fibre properties (radius × 5 × 20 mm^3) using L & W Fiber Tester were taken at the southern radius.

Five seed-originated and five sprout-originated birch trunks were sampled in October 2006 when the age of the sampled trunks was 25 years, but the root systems of the sprout-originated trees were considerably older. The chosen trunks were sound and free of decay and their height varied from 10 to 14 metres. The coppiced individuals were distinquished visually from seed-originated ones by their form, the surrounding cluster of coppiced trunks, and the remnants of original stumps. Coppicing in 1991 had resulted in about three living stems per stump surrounding the older stem, that was sampled. Sample discs of 5 cm thick were cut at breast height (130 cm), southern direction of the trunk was marked on the sample discs, and the diameters without bark were measured. The number of the annual rings in the discs varied from 17 to 23.

2.2 Fibre Dimension, Annual Ring Width and Wood Density Measurements

Strips of 5 mm thick were sawn at the southern radius of each disc (total of ten strips) and divided for fibre, annual ring width and wood density analyses, after the cross-cut surfaces of the strips (sawn by chain saw) were discarded (Fig. 1). The fibre samples (radius × 5 × 20 mm^3) were divided into eight lots of 3 annual rings from pith to bark. However, the outermost samples from the pith, from the 16th to the 23rd annual rings, consisted of 2–4 annual rings depending on the total number of rings in the sample (Fig. 2). The total number of studied fibre samples was 69. Annual rings were grouped, because single rings were too thin to supply enough fibre mass for accurate Fiber Tester measurements.

The wood samples for fibre measurements were macerated in a solution of acetic acid and peroxide (1:1) for 24 hours at 60 °C. After macerating, the cells were separated with a glass rod in a small volume of water and washed to remove all the macerating solution. The Fiber Tester measurement method (AB Lorenzen & Wettre, Kista, Sweden) is based on image analysis: the device photographs fibres flowing in water in the narrow space between two glass sheets. The fibre dimensions (length, width) are then measured from the photographs. According to the manufacturer, a

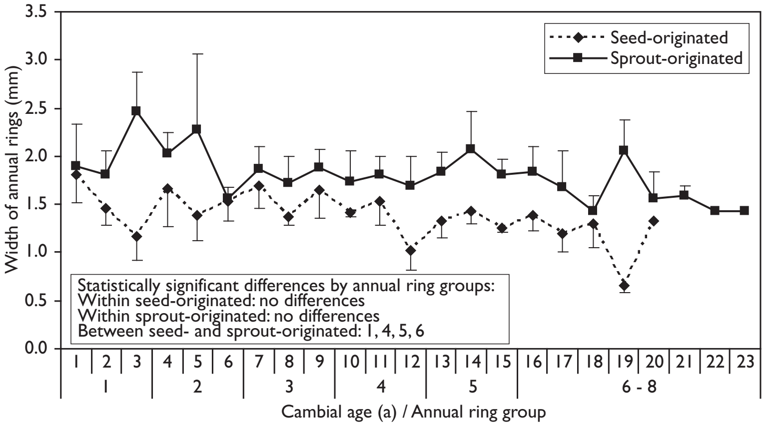

Fig. 2. Widths of annual rings (mm) by regeneration method, cambial age (1–23) and annual ring group (1–8). Annual ring group 1 contained the rings 1–3 from the pith, group 2 the rings 4–6, etc, and ring group 6 contained rings 16–17, 16–18 or rings 16–19, group 7 contained rings 19–20, 19–21 or 19–22, and group 8 rings 22–23, the last three depending on the total number of the rings in the sample. The bars are standard error of the mean in one direction.

minimum of 4000 fibres per sample, which was exceeded, is needed for reliable results.

Profiles of wood strips were scanned for annual rings using air-dried (moisture content, MC, 12% at dry weight basis) wood strips from pith to bark (radius × 5 × 5 mm^3) (Fig. 1). Scanning was performed with an Itrax X-ray microdensitometer (Cox Analytical Systems, Göteborg, Sweden) with automatic collimator alignment at a geometrical resolution of 40 measurements per millimetre. The standard X-ray flux (30 kV, 35 mA) was used, with an exposure time of 20 ms. The Itrax X-ray images were analysed using Density software to determine the width of the annual rings (Bergsten et al. 2001). The same strips were weighed (g) and their volumes (mm^3) were measured to calculate the average wood density at MC of 12%.

2.3 Statistical Analyses

For the statistical analyses, annual ring width measurements were grouped into 8 annual ring groups according to the cambial age, similarly to the grouping of the measurements of fibre dimensions (see Fig. 2). The data were analysed using SPSS (Version 14.0 for Windows, SPSS Inc., 2005) statistical software. Growth (height, diameter, annual ring width), as well as wood density and fibre properties were compared between and within sprout- and seed-originated birches using the General Linear Model (GLM) procedure, t-test or Kruskall-Wallis nonparametric test if parametric test could not be used. The growth

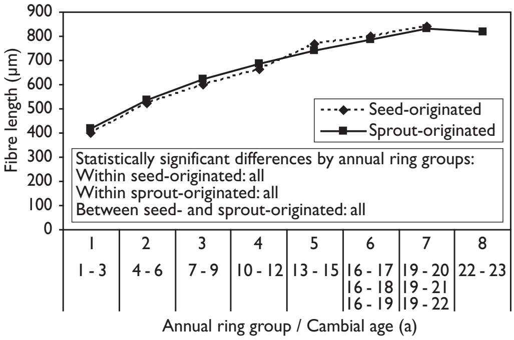

Fig. 3. Average fibre length (mm) by regeneration method, annual ring group (1–8) and cambial age (1–23). Standard errors of the means were not included, because they were very small and therefore indistinguishable from the figure.

Table 1. Comparison of means of analyzed properties between different regeneration methods. At tree level n = 5, at annual ring level n = 100 for seed-originated trunks, n = 110 for sprout-originated trunks, and at fibre level n ≥ 4000 for each annual ring group of an individual. GLM procedure was used when possible (F-value), and Kruskall-Wallis test was used when GLM could not be used (χ^2-value, which is marked with *). The numbers are mean ± standard error of the mean.

Measured property	Seed-originated	Sprout-originated	F/χ^{2*}	*p*
Height, m	10.2 ± 0.19	13.2 ± 1.89	2.517	0.151
Diameter without bark, mm	57.4 ± 3.07	77.7 ± 6.99	4.811*	0.028
Density at 12% MC, kg/m^3	605.0 ± 11.37	582.9 ± 9.23	2.479	0.154
Width of annual rings, mm	1.4 ± 0.05	1.8 ± 0.07	26.451*	< 0.001
Fibre length, mm	0.635 ± 0.001	0.669 ± 0.008	146.06*	< 0.001
Fibre width, μm	19.1 ± 0.01	20.4 ± 0.01	1728.52*	< 0.001
Fibre length:width -ratio	32.9 ± 0.05	32.5 ± 0.04	10.946*	0.001

factors and density were analysed on an individual tree basis, however, in order to find the variation of fibre properties within a sample tree and, furthermore within regeneration method, the fibre properties were analysed at a fibre level. Pearson correlations were calculated for width of annual rings, fibre length and fibre width.

3 Results

3.1 Height and Diameter of Trunks, Width of Annual Rings and Wood Density

The main trunks of sprout-originated birches were larger than those of seed-originated trees regarding both height and breast height diameter (Table 1). However, the differences in height were not statistically significant, but the diameter without bark was about 35% larger in sprout-originated than in seed-originated trunks. The variation in height and diameter of the sample trees was slightly larger in seed-originated birches than in sprout-originated ones (Table 2).

Average widths of the annual rings were larger in sprout- than in seed-originated birches (Fig. 2, Table 1), and this difference was also statistically significant for the individual annual ring groups 1, 4, 5 and 6. The variation of ring width was also larger in sampled sprout- than seed-originated birches (Table 2). However, the annual ring width had no correlation with fibre dimensions within either of the regeneration methods. The regeneration method also had no significant impact on the average wood density measured at 12% MC (Table 1).

3.2 Length and Width of Fibres

Fibres were significantly longer, on average (Table 1), but fibre length varied less from pith to bark in sprout-originated than in seed-originated birches (Fig. 3). The fibre length in seed-originated birches became larger than in sprout-originated trees around the cambium age of 10–12 years. The differences in the average fibre length between the regeneration methods were proved statistically significant within each annual ring group. Similar to tree growth, the variation of fibre length was larger in seed-originated than in sprout-originated birches (Table 2).

Fibres were also wider, on average, in sprout- than in seed-originated birches (Table 1). In addition, in seed-originated birches a decrease in fibre width was observed from ring group 1 to 2 whereas in sprout-originated ones no such diminishing was observed. Fibre width increased until 10–15 years of age (Fig. 4). Unlike fibre length, the variation of fibre width was larger in sprout- than in seed-originated birches (Table 2).

Furthermore, fibre length and width correlated positively in both sprout-originated (r = 0.367,

Table 2. Differences of the analysed properties within regeneration methods. At tree level (n = 5) the statistical comparison was made with t-test, while at annual ring (n = 100 for seed-originated trunks, n = 110 for sprout-originated trunks) and fibre (n ≥ 4000 for each annual ring group of an individual) levels Kruskall-Wallis test (χ^2-values, marked with *) was used.

Measured property	Seed-originated		Sprout-originated	
	t /χ^2	*p*	t /χ^2	*p*
Height, m	53.85	<0.001	6.96	0.002
Diameter without bark, mm	18.72	<0.001	11.12	<0.001
Density at 12% MC, kg/m^3	53.31	<0.001	63.18	<0.001
Width of annual rings, mm	15.40*	0.004	22.11*	<0.001
Fibre length, mm	1334.31*	<0.001	184.51*	<0.001
Fibre width, µm	272.58*	<0.001	734.99*	<0.001
Fibre length:width -ratio	1358.39*	<0.001	48.23*	<0.001

$p < 0.001$) and seed-originated ($r = 0.322$, $p < 0.001$) birches, and the length/width-ratio of fibres was larger in seed- than in sprout-originated birches from the cambium age of 4–6 years (annual ring group 2) towards the bark (Fig. 5). The ratio also increased up to the age of about 20 years in both regeneration methods, but then stabilising in sprout-originated trees. Similar to tree growth and fibre length, the variation of the ratio was large, particularly in seed-originated sample trees (Table 2).

4 Discussion

Sprout-originated downy birches surpassed the growth of seed-originated ones 25 years after regeneration on a relatively fertile soil. These results differ from previous studies in which birch seedlings are reported to reach sprouts in size while still young (Ferm 1990, Paukkonen and Kauppi 1998). In the mentioned studies sprouts originated from seedlings that were coppiced at the age of few years and did not have a large root system of mother trees like in this or in a previous study (Hytönen and Kaunisto 1999). Although the large root biomass of coppice stands is of major importance in the carbon balance (Huotari et al. 2009), downy birch is able to store some carbon in the roots even during the same growing season when the trees are coppiced (Luostarinen and Kauppi 2005), which refers to its good regeneration ability. Furthermore, coppiced birches continue their growth longer in August than seed-originated ones, which results in increased height growth due to differing carbohydrate dynamics of the roots (Kauppi et al. 1990, Luostarinen and Kauppi 2005). In addition to the slightly greater height growth, the measured sprout-originated main stems of birches also had larger diameters and greater amounts of generally thicker annual rings than the single seed-originated trunks. Consequently coppicing also resulted in greater amount of above-ground biomass, which is obviously an advantage for coppice stands regardless of which purpose the biomass is used.

According to the results of this study, the average wood density did not differ significantly between seed- and sprout-originated downy birches, although differences in radial growth existed. In some previous studies correlation between the growth rate and the wood density is observed to be negative in birch (Bhat 1980, Björklund and Ferm 1982), whereas in other studies the effect of growth rate on density of birch wood is concluded as insignificant (Hakkila 1966, Nepveu and Velling 1983). The earlier studies of *Eucalyptus* and *Populus* species also report very small differences in wood density between sprout- and seed-originated trunks or a slight decrease in sprout-originated trunks (Blankenhorn et al. 1988, Sesbou and Nepveu 1991, Sharma et al. 2005). Thus, the slight difference in the wood

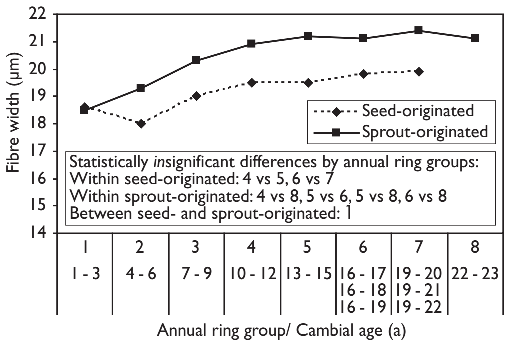

Fig. 4. Average fibre width (µm) by regeneration method, annual ring group (1–8) and cambial age (1–23). Standard errors of the means were not included, because they were very small and therefore indistinguishable from the figure.

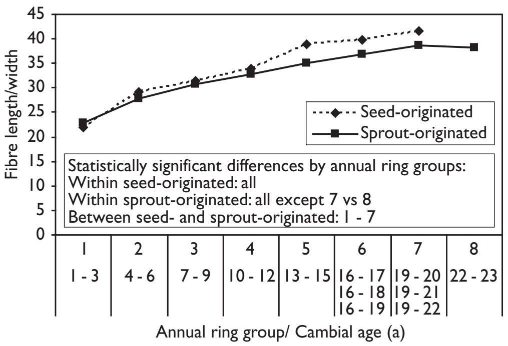

Fig. 5. Average fibre length/width –ratio by regeneration method, annual ring group (1–8) and cambial age (1–23). Standard errors of the means were not included, because they were very small and therefore indistinguishable from the figure.

density between the seed- and sprout-originated trees is only of minor importance regarding the usability of downy birch wood as raw material for any use.

The average fibre length observed in this study was clearly smaller than the fibre lengths measured previously for downy birch of a similar age (Kujala 1946, Ollinmaa 1958, Bruun and Slungaard 1959, Lönnberg 1975). This could be due to genetic variation observed among birch stems (Lepistö 1980) or even to the location of samples on the southern, i.e. more sunny side of the trunk (Zobel and van Buijtenen 1989, Kärkkäinen 2007). The fibre length in this study was close to fibre lengths measured for two species of *Eucalyptus* and *Populus* of 4–15 years of age (Jorge et al. 2000, Muneri and Raymond 2001, Klasnja et al. 2003). The increase of fibre length in downy birch is reported to continue until 35 years of age (Kujala 1946), or even until 45 years when the length reaches 1.3 mm (Bhat 1980). In comparison, the lengthening of fibres in sprout-originated birches of this study settled by the cambial age of 22–23 years, and in seed-originated trunks it slowed down markedly by the age of 20. In previous studies of some *Eucalyptus* species, the effect of the regeneration method on fibre lengths has varied, fibres of sprouts being either longer or of the same length than those of seed-originated ones (Sesbou and Nepveu 1991, Sharma et al. 2005). In sprouts of poplars, fertilization has even reduced the length of fibres and thickness of cell walls (Luo et al. 2005). In fact, the trees may have an optimal growth rate for fibre length which has been found for quaking aspen (*Populus tremuloides*) as fibre length decreased at both low and high circumferential growth rate (Fujiwara and Yang 2000). The stabilisation of the fibre length in sprout-originated birches at the cambial age of slightly over 20 years makes the fibre length comparable to that of fast growing tropical hardwoods used for fine papers (Karlsson 2006).

In this study fibre widths were near (Bruun and Slungaard 1959) or smaller (Lönnberg 1975) than those measured in downy birches of about the same age, and fibre widths were larger in sprout- than in seed-originated trunks. This difference also remained until 20 years' of cambial age, even though the increase in fibre width started to stabilise after 12 years. Similar differences in fibre width between young sprouts and seedlings of downy birches have previously been interpreted as a result of physiological changes in roots or rapidly expanding leaf area of sprouts as no differences in auxin concentrations between seedlings and sprouts were observed during the same season when cut (Rinne et al. 1993). In general, auxin that is produced in apical meristems causes tracheid enlargement (Kozlowski and Pallardy 1997) and during a period of several years auxin may become more significant in coppiced trees, which are more bush-like than seedlings (Kauppi 1989). Thus smaller amounts of branches, leaves and apicals in seedlings than in sprouts may explain the decrease in fibre width from the annual ring group 1 to 2. However, an observation on increasing fibre width in wood of seed-originated 45-year-old downy birch to more than 28 μm also exists (Bhat 1980). The difference observed here, regarding fibre width of seed- and sprout-originated downy birches, is also consistent with observations of some eucalypts (Veenin et al. 2005).

The fibres were slightly wider in relation to the length in sprout-originated than in seed-originated trunks, the length increasing more than the width. Low fibre width is connected to good surface quality of paper as well as to the good formation of paper in the process, and long fibres form stronger paper than short ones (Karlsson 2006). Consequently the ratio of the width to the length in this study was better in seed- than in sprout-originated trunks, even though the differences were minor and therefore hardly significant for the industry. Longer rotations could, however, be favourable for sprout-originated trees in which wood properties were more homogenous and stabilised at a younger age. In sprout-originated birches the slowing down of fibre lengthening occurred coincidently with the fibre width reaching its maximum. The comparable phenomena have been associated with changes leading to wood maturation (Ridoutt and Sands 1993, Bonham and Barnett 2001, Veenin et al. 2005). Thus, the commencement of wood maturation may vary depending not only on species but also on the origin of the stem.

As a conclusion, both the length and width of fibres were exceptionally small in this study in comparison to the earlier results for downy birch. In addition, the very small differences in both fibre properties and wood density have no marked effects on the use of the wood as a raw material. However, the smaller differences in growth parameters and in fibre length from pith to bark, and early stabilizing of fibre width suggest that wood matures earlier in sprout- than in seed-originated trunks. Consequently, coppicing justifies its place as a regeneration method for downy birch, which also grows on untypical forest sites such as former mires. Coppicing has also low costs and easiness in regeneration, it results in high production of biomass, and for these reasons its significance may increase in the future.

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