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Stump diameter and age affect coppicing of downy birch (*Betula pubescens* Ehrh.)

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Abstract

Downy birch is a primary successional tree species colonizing open areas and thriving on peatlands. Short-rotation coppice management in natural, dense, downy birch stands could be one management option. The effect of stump diameter, stump height and stand age on the sprouting of downy birch was studied by clear-cutting six stands from three age classes (A: 10–12 years, B: 15–16 years, C: 22–24 years) located in northern Finland and measuring the sprouts in the following autumn. The percentage of non-sprouting stumps increased with the stand age (A: 9%, B: 14%, C: 27%). The smallest (< 1 cm) and biggest (> 9 cm) stumps showed higher mortality than medium-sized stumps. Sprouts originated close to the ground level: over 50% were located below 2 cm from the ground level. An increase in the diameter of stumps led to higher numbers of sprouts produced per stump, and higher mean, dominant and cumulative height of sprouts per stump and higher biomass of sprouts per stump. The effect of the diameter on the growth of sprouts depended on the stand age. In the same diameter class, the mean height, dominant height and biomass per stump were higher the younger the stand was. The biomass per stump correlated best with the total height of the sprouts on a stump. The results have implications for strategies in controlling sprouting in coniferous stands and for stand management practices when the aim is to grow downy birch coppices.

Keywords Coppicing · Stump diameter · Damage · Downy birch · Biomass production

Introduction

Birches are the single most important deciduous tree species in most of the Nordic countries. The proportion of birch (silver birch *Betula pendula* Roth, downy birch *Betula pubescens* Ehrh.) out of the total volume is high in Finland (16%), other Nordic (11–16%) and the Baltic (17–28%) countries (Hynynen et al. 2010). Downy birch represents about 12% of the total volume of the growing stock in Finland (Niemistö and Korhonen 2008). According to the Finnish National Forest Inventory, 90% and 98% of the total birch volume consist of downy birch on peatlands in Southern and Northern Finland, respectively (Korhonen et al. 2007). Downy birch is a biologically vigorous, early successional, pioneer tree species thriving on peatlands and in mineral soils with poor drainage. Downy birch is used mainly for pulpwood and energy wood.

Sprouting in deciduous tree species is an induced response to injury or dramatic change in surrounding environmental conditions (Del Tredici 2001). Birch is generally considered a poorly sprouting species. When cut, birches produce stump sprouts from dormant basal buds which activate soon after the cutting of the tree, and in favourable conditions will burst forth from 2 weeks to 1 month (Kauppi et al. 1987, 1988a, b, 1991a). Most of the buds (70–95%) are located underground (Kauppi et al. 1987, 1988b; Johansson 1992a). The origin, structure, development, spatial distribution, number and bursting dynamics are important aspects which all affect coppicing (Sennerby-Forsse et al. 1992). The reduced level of phenolic substances caused by felling the tree is also a precondition for sprouting (Kauppi et al. 1991b). Many external factors and management measures have been shown to have only a minor effect on the number of sprouts per stump, or the number of living stumps in downy birch. For example the cutting season, the size and age of the trees, the stump height and site quality can significantly affect the early height growth of birch sprouts (Mikola

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1942; Andersson 1966; Ethol̩én 1974; Ferm and Issakainen 1981; Ferm 1990; Johansson 1987, 1992b, c; Hytönen 1994; Hytönen and Issakainen 2001). Generally cutting during the active growing period will increase mortality and reduce growth, compared to dormant season cutting (Blake 1981; Blake and Raitanen 1981; Hytönen 1994). Results on the effect of stump height on coppicing of birch have been variable (Mikola 1942; Kvaalen 1989; Johansson 1987, 1992c, Jobidon 1997). There are only few studies comparing the sprouting of downy birch and silver birch. According to Mikola (1942), downy birch sprouts are considerably better than silver birch. Johansson (2008) also reported downy birch to produce more sprouts per stump than silver birch.

In conventional silviculture, vigorously sprouting downy birch is often considered in a negative light, especially when regenerating and intermixed with softwoods. The competition offered by fast-growing, deciduous trees of sprout origin often impairs the outcome of forest regeneration. The conifer seedlings run the risk of suffering from shading and mechanical injury inflicted by birch to such an extent that the sapling stand may ultimately be lost and deciduous trees may take over the site. Since controlling for sprouts accounts for a considerable amount of the costs of young stand management, its optimization is an important part of forest regeneration. Thus, most studies dealing with the sprouting of birch have been done to study means for reducing the sprouting (e.g. Ethol̩én 1974; Johansson 1992a, b, c, 2008). Many studies on the coppicing of birch have been done with young 1- to 5-year-old seedlings with stump diameters ranging from 1 to 5 cm (Johansson 1987, 1992b, 2008; Kauppi et al. 1990, 1991a). Such small birches are common in young hardwood plantations and they are removed in early cleaning.

An alternative management option for existing thickets of birch, especially on peatlands, could after clear-cutting be growing of sprout-originated trees applying the principles of short-rotation management instead of soil preparation, planting, weed control and young stand treatment. Establishment of dense downy birch stands on marginal sites, such as cutaway peatlands, has been successful with ash fertilization and natural regeneration or sowing (e.g. Huotari et al. 2008; Hytönen et al. 2016). Energy wood production by growing dense downy birch stands with rotations of 23–26 years, assuming that second birch rotation can be achieved through sprouting, has been calculated to be economically feasible on cutaway peatlands (Jylhä et al. 2015). Additionally, for dense downy birch stands on peatlands, the most profitable management option is to grow them for energy without thinnings until whole-tree final cutting at the stand age of 40–45 years (Niemistö et al. 2017). If sprouting is successful, a second rotation birch stand could be established without costs, provided the development of the sprouts is favourable. However, at the moment in practical forestry coppice regeneration of downy birch is not used. Re-sprouting after harvest and maintaining productivity over multiple cutting cycles is fundamental to short-rotation coppice forestry, which utilizes the exceptional growth rates of stump sprouts or root suckers. Since the economic rotation length of short-rotation birch exceeds 20 years (Jylhä et al. 2015), results on coppicing of very young trees may not be applicable. Older and bigger birches could sprout better than small and young trees due to increasing number of buds with increasing stump diameter, or their sprouting could be poorer due to increased bark thickness or formation of bud clusters (Kauppi et al. 1987, 1988a, b). Thus age and diameter could have independent effect of on sprouting.

The main objective of the present study was to investigate the effect of stump diameter and tree age and their interaction on the coppicing of downy birch. Sprouting success was assessed in several ways including: the number of dead stumps, the number of sprouts per stump, the mean height of the sprouts, the height of the tallest sprout on a stump, the total cumulative height of the sprouts on a stump and the biomass of sprouts on stump. Additionally, the location of the sprouts in the stump and the effect of damage to stump were studied.

Materials and methods

Two naturally regenerated dense unthinned downy birch stands from each of the three age classes (A: 10–12 years; B: 15–16 years, C: 22–24 years) were selected from the same cutaway peatland area located in northern Finland at Liminka, (Hirvineva, 64°48′N, 25°24′E). The depth of the residual peat layer varied from 18 to 60 cm. The estimates of the stand ages were based on the mean biological age of dominant trees on each sampled stand. Their ages were determined from increment cores taken from the base and by adding 2 years to the number of annual rings. The age variation within the dominant trees was small, mostly 2–3 years, indicating that the stands were even-aged and had been established in a short period of time. The mean age of the dominant trees in the six stands varied from 10 to 24 years, and their mean height from 2.8 to 9.0 m (Table 1). Each of the stands was clear-cut (size 520–1800 m^2) in the spring (6th of May 2011).

The trees were dormant at the time of cutting. Daily mean temperatures in April were 3.6 °C and in May before cutting 3.2 °C. All the stands were cut manually using a motor saw, except for the two oldest stands, which were cut by a harvester. After cutting the trees were removed from the study areas. The summer following the clear-cutting was warmer than the 10-year average (d.d. 1382 vs. 1210 d.d. in 2006–2016). Additionally, the precipitation in June–August

Table 1 Stand density, mean height and leafless above-ground biomass of the stands before cutting and number of measured stumps, their mean diameter, number of measured downy birch sprouts and number of sample plots

Age	Age class	No. stems (ha^{-1})	Mean height (m)	Biomass (Mg ha^{-1})	No. measured stumps	Mean diameter (SD and range) of the measured stumps (cm)	No. measured sprouts	No. sample plots (size, m^2)
10	A	129,100	2.8	26.8	262	1.0 (1.0; 0.2–5.2)	978	4 (30)
12	A	57,800	3.6	29.3	183	2.4 (1.6; 0.2–8.3)	1255	3 (40)
15	B	30,200	5.2	55.9	193	2.7 (1.6; 0.2–7.5)	1229	1 (50)
16	B	45,400	4.8	33.6	423	2.6 (2.3; 0.4–18,8)	2058	2 (100)
22	C	10,600	9.0	66.9	92	5.5 (3.5; 1.1–16.3)	688	3 (150)
24	C	12,200	9.0	76.2	105	8.2 (4.2; 3.0–20.0)	666	1 (100)

was higher than the average (239 mm vs. 209 mm in 2006–2016).

The sprouting was measured in November, after the first growing season. Circular sample plots (1–4 in each stand, size 30–150 m^2 depending on density of stands) were established on each of the study stands. Since the aim was to measure similar number of stumps from each stand, larger sized sample plots were established in the centre of the clear-cut older stands. In the younger and denser stands, 3–4 smaller plots distributed uniformly over the clear-cut areas were established. All stumps within the sample plots were measured for their diameter and height. Mortality of stumps was visually assessed by determining the presence or absence of living sprouts. Stumps without sprouts were classified as dead. Total number of measured stumps was 1258 (Table 1). During harvesting, some stumps were damaged and the damage class of all stumps was assessed (1 = no damage, 2 = slight damage, 3 = large damage). The number and height of all sprouts in the stumps were measured. Total number of measured sprouts was 6874. Since some stumps may have many short sprouts and some stumps have only few longer sprouts, mean height of sprouts is not always a good indicator of sprouting success. Thus also the height of the tallest sprout on each stump (dominant sprout) and the total cumulative height of all sprouts in each stump were calculated. From 111, 146 and 35 birch sprouts in age classes A, B and C, respectively, the location of sprouts in the stump was measured as distance from ground level. One sprout per stump was selected using systematic sampling. Sprouts locating underground were marked as originating from 0 cm from the ground.

Altogether 30 birch sample sprouts covering the height variation were taken for modelling the biomass production. The base diameter of the sample sprouts varied from 0.2 to 1.6 cm and their height from 27 to 187 cm. The leafless sprouts were transported to laboratory, and their dry mass was determined after drying at 105 °C to constant weight. The biomass of the sprouts was estimated with allometric model based on the sample tree data

$$Y = 0.0001432 * X^{2.496}.$$

In the model, Y = dry mass (g) and X = height of sprouts (cm). The model had an R^2 value of 89.2% and was corrected after logarithmic transformation linearizing the allometric equation with s^2/s. The biomass of the sprouts in each stump was calculated with the model based on sprout height.

For analysing mortality of the stumps, they were classified into diameter classes and mortality percentage in each diameter class was calculated. Subsequently the effect of age class and diameter class and their interaction was analysed by analysis of variance. A one-way analysis of variance was used to test the differences in stump height and the location of the sprouts between the stands. The analysis of stump damage on sprouting was confined to the two oldest stands since stumps in age classes A and B did not have any severe damages and only 4.4% of the stumps had slight damage. In all other calculations, damaged stumps were excluded and results are presented for undamaged stumps. The effect of age and stump diameter and their interaction on the measured sprouting characteristics was studied by analysis of variance using general linear model. In the model, stand age was fixed factor and stump diameter was used as covariate. Correlation coefficients between the biomass of sprouts per stump and other sprouting characteristic were calculated. When testing figures in percentage form, variance stabilizing transformation of square root arcsine was used. To compare the means of the results, a significance level of $p \leq 0.05$ was used. All statistical analyses were carried out using IBM SPSS Statistics 22 software.

Results

Mortality of stumps

Not all the birch stumps sprouted. The mean mortality of the stumps was 9.3%, 14.5% and 27.1% in age classes A, B and C, respectively. The stump diameter class had a significant effect on the mortality of the stumps ($p = 0.002$), but the effect of age class was not significant ($p = 0.315$). Significant interaction between diameter class and age class ($p = 0.039$)

indicated that the effect of diameter on mortality depended on age. When the diameter of stumps increased, the mortality of older stumps increased more than mortality of younger stumps (Fig. 1a). Very small stumps (< 1 cm in diameter) and large stumps (> 9 cm in diameter) sprouted poorer than stumps in between.

Height of the origin of sprouts

The mean height of the origin of the sprouts in the stumps varied from 2 to 4 cm from ground level. The stand age class ($p = 0.488$) or stump diameter class ($p = 0.992$) did not affect the origin of the sprouts. Most of the sprouts originated quite close to the ground level or even below it: 22% were originated from ground level or below ground and over 50% of the sprouts originated less than 2 cm from ground level (Fig. 2). The share of the sprouts locating above 10 cm from ground level was 3%. The mean height of the stumps in the study stands varied from 9 to 18 cm. Stump height did not correlate with the height of the origin of sprouts ($p = 0.853$). Nor did the height of origin of the sprouts correlate with the height of sprouts ($r = 0.145$).

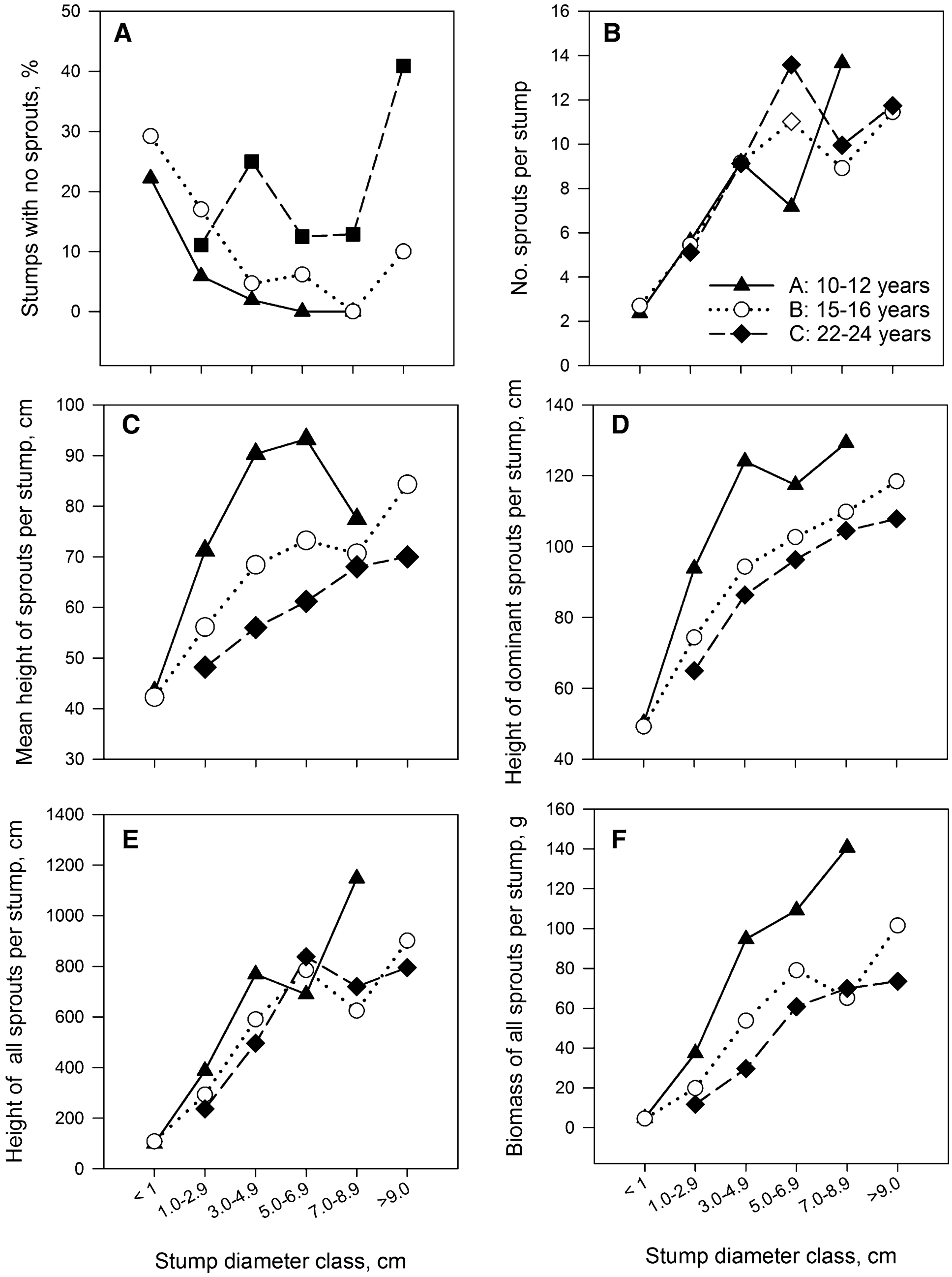

Fig. 1 The effect of stand age and stump diameter on the share of stumps without sprouts (**a**), number of sprouts per stump (**b**), mean height of sprouts per stump (**c**), mean height of tallest sprouts per stump (**d**), cumulative height of all sprouts per stump (**e**) and biomass of all sprouts per stump (**f**). In the analysis of share of stumps without sprouts, all stumps were included. All other analysis included only stumps with sprouts

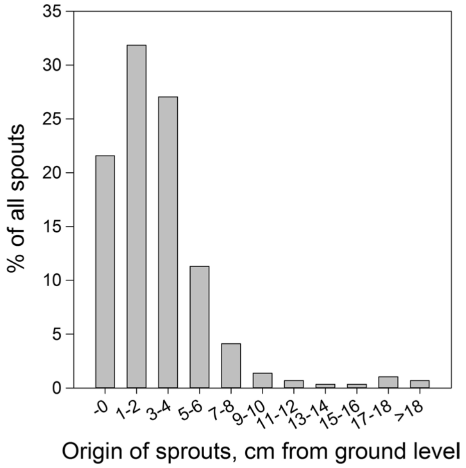

Fig. 2 Height of location of the sprouts from ground level in diameter classes

Stump damage

The stands cut manually by motor saw (age classes A and B) had only a small number of damaged stumps. However, it was possible to analyse the effect of damage on the sprouting in the two oldest stands (age class C) cut with a harvester causing damage when driving on the stumps. In these stands, 27.5% and 23.9% of the stumps were recorded with light and severe damage, respectively. The mortality of stumps was equally distributed in the different damage classes (no damage, slight damage, severe damage) ($\chi^2 = 2.600$, $p = 0.273$) indicating that damaging of stumps did not increase mortality.

Damaging of the stumps did not reduce the number of sprouts per stump (Table 2). However, the effect of damage on mean and dominant height of the sprouts was significant, but not on cumulative height of sprouts per stump. The mean height of sprouts per stump recorded to have slight damage was the shortest. Even though the effect of stump damage on biomass per stump was also significant (Table 2), Tukey's multiple range test did not find significant differences between the mean values.

Number of sprouts per stump

Age class ($p < 0.001$), stump diameter ($p < 0.001$) and their interaction ($p < 0.001$) had significant effect of the number of sprouts per living stump. The mean number of sprouts per stump increased with the increase in stand age (A: 5.9, B: 6.9, C: 10.3). The number of sprouts per living stump increased with increasing diameter in all age classes up to 5 cm (Fig. 1b). Further increase in stump diameter from 5 to 9 cm did not increase the number of sprouts per stump in the two oldest age classes.

Height of sprouts

The mean height of sprouts was 20–30 cm shorter than the height of the tallest sprouts on stump (A: 60.2 vs. 79.4 cm, B: 60.8 vs. 91.8 cm, C: 73.0 vs. 98.5 cm). The height of all sprouts on a stump was 7–9 times higher than the mean height of sprouts (A: 403 cm, B: 427 cm, C: 625 cm). The age class had a significant effect on the height of the tallest sprouts on stump ($p = 0.003$) and height of all sprouts per stump ($p < 0.001$), but not on the mean height of sprouts ($p = 0.450$). Stump diameter and interaction between stump diameter and stand age class had a significant effect on mean height of sprouts ($p < 0.001$), tallest sprouts on stump ($p < 0.001$) and height of all sprouts per stump ($p < 0.001$). The height of sprouts increased with the increase in diameter, the youngest age class produced the tallest sprouts and the oldest shortest (Fig. 1c–e). The total cumulative height of all sprouts per stump increased with an increasing stump diameter up to 3–5 cm and stayed at the same level in the two older age classes (Fig. 2e). However, significant diameter stand age interaction showed that the effect of diameter depended on age.

Table 2 The effect of the stump damage class on the number of sprouts per stump, mean height of sprouts per stump, height of all sprouts on a stump and the biomass of all sprouts on a stump

Variable	Damage class			*F*	*p*
	No	Slight	Severe		
No. sprouts per stump	10.4 (0.8)a	9.7 (1.0)a	8.9 (1.1) a	0.581	0.561
Mean height of sprouts per stump (cm)	65.2 (2.3)a	51.4 (2.7)b	59.9 (4.0)a	6.794	0.002
Height of dominant sprouts per stump (cm)	98.9 (3.8)a	77.7 (4.9)b	85.1 (5.4)ab	6.330	0.002
Total height of all sprouts per stump	675 (56)a	547 (74)a	504 (64)a	2.160	0.119
Biomass of sprouts per stump (g)	58.8 (6.8)a	37.3 (7.5)a	37.1 (7.1)a	3.231	0.043

Only living stumps from stand age class C (22–24 years) included in the analysis. The standard error is shown inside brackets. The means marked with the same letters do not differ from each other at the 0.05 significance level

Biomass

The total biomass of all the sprouts per stump increased with the increase in stand age ($p \leq 0.001$) (A: 31.4 g, B: 44.6 g, C: 58.5 g) and diameter ($p > 0.001$). Also the interaction between diameter and stand age class was significant ($p < 0.001$). The stumps of equal diameter produced more biomass in the youngest age class (A: 10–12 years) than in the two older age classes and difference between age classes increased with increasing diameter. The amount of biomass per living stump correlated best with the total height of all the sprouts per stump (Table 3). Mean dominant height (height of the tallest sprout per stump) correlated better with biomass on the stumps than the mean height of the sprouts.

The total biomass in the study areas after one growing season was highest in the youngest age class (A: 2.8 Mg ha^{-1}) and decreased with an increase in the age class (B: 1.1 Mg ha^{-1}; C: 0.3 Mg ha^{-1}). The biomass on an area basis was related to the number of stems in the stands (Table 1).

Discussion

The birch stands were cut at the beginning of May when the trees were still leafless and the growing season had not yet begun. Generally, the beginning of the growing season is considered a time when cutting birches leads to poorer growth of the sprouts than cutting done in other seasons (Ferm and Issakainen 1981; Hytönen 1994; Etholén 1974; Johansson 1992b, c). For sustainable short-rotation coppice forestry, a high number of sprouting stumps is a prerequisite and the amount of dry mass produced by the sprouts in the stumps is a good indicator of sprouting success. However, in conventional forestry, on the other hand, a low number of sprouting stumps is desired and the dominant height of the sprouts and their number is more important than the biomass. Sprouting success was assessed in several ways in this study including: the number of dead stumps, the number of sprouts per stump, the mean height of the sprouts, the height of dominant sprouts, the total cumulative height of the sprouts on a stump and the biomass of sprouts on stump. The study revealed that sprouting of downy birch is affected both by age of trees and stump diameter.

Table 3 Correlation coefficients between the biomass of the sprouts per stump and the number of the sprouts, the mean height of the sprouts, height of dominant sprouts and height of all the sprouts on a stump

Stand age class	Number of sprouts per stump	Mean height of sprouts	Height of dominant sprouts	Height of all sprouts on a stump
A	0.762***	0.612***	0.755***	0.920***
B	0.629***	0.596***	0.741***	0.891***
C	0.610***	0.642***	0.762***	0.865***

Stars indicate statistical significance: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$

The number of non-sprouting stumps in this study was affected by stump diameter, but the effect of stump diameter depended on the age class. The higher the stump diameter and the older the stand the higher was the mortality. The high mortality of thinnest stumps (< 1 cm) is probably associated with low number of buds in thin stumps. Mortality of thickest stumps (> 9 cm) especially in the oldest stand was high. Thus when short-rotation management principles are applied in birch stands, growing the birch to over 10–15 cm in diameter could already increase the mortality (Mikola 1942; Ferm et al. 1985) to such an extent that the biomass production decreases. Repeated coppicing and short rotations can also increase the stump mortality. The mortality of birch stumps has been observed to increase more with each successive coppice cutting the shorter the rotation is (Hytönen and Issakainen 2001).

The mortality was in line with earlier studies reporting the number of non-sprouting birch stumps to be generally within the range of 10–40% (Moilanen and Oikarinen 1980; Ferm and Issakainen 1981; Hytönen 1994; Kauppi et al. 1988b; Johansson 1987, 1992c, 2008; Hytönen and Issakainen 2001). Kvaalen (1989); however, reported only 1–2% initial mortality for silver birches after cutting.

The weakening of birch coppicing ability in older trees has been associated with an increase in bark thickness, which is supposed to reduce the number of buds and prevent them penetrating the surface (Mikola 1942). However, according to Kauppi et al. (1988b) birch bark does not grow in such thickness that it would prevent bud growth. When the trees grow, the primary buds branch and form clusters of secondary buds located in the axis of their scales. Although branching increases the bud number in the stump, the formation of bud clusters is not favourable for coppicing (Ferm and Kauppi 1990) and it is considered to be the major cause of weakened sprouting ability in older trees (Kauppi et al. 1988b).

Generally, the method of cutting the birch (axe, billhook, manual saw, chain saw) or artificial damaging of the stump following cutting has not affected the number of sprouting stumps or the growth of the birch sprouts (Mikola 1942; Ferm and Issakainen 1981). This was mostly true also in this study where damage to the stumps did not affect the number of sprouts per stump. However, damaging of the stumps decreased the mean height of sprouts per stump and their biomass. This could be due to damage caused to the root systems by harvesting machine driving over the stumps.

According to this study, the effect of stump height on sprouting is small, since 53% of the sprouts originated

2 cm or lower from the ground level and only 3% originated above 10 cm from the ground. Thus leaving 10 cm stumps would not practically affect spouting at all, and even very low stumps would not considerably reduce the number of sprouts. Low stumps could even be beneficial for later development of the sprouts since shoots located close to the ground are more likely to be connected to individual roots than to the root system as a whole (Ferm and Kauppi 1990) and this is believed to give some advantage in terms of availability of water and metabolites. Even though the major part of the buds (70–95%) are located below the soil surface (Kauppi et al. 1987, 1988b; Johansson 1992a), still 44% of the sprouts in this study originated from buds located over 2 but below 11 cm from ground level. Even though buds located below ground level produce abundantly sprouts, the number reaching the soil surface is much smaller (Kauppi et al. 1987, 1988b) and even one third of birch sprouts can originate from buds locating above-ground (Ferm and Kauppi 1990). Thus, cutting the tree very close to ground level (0 cm stump) could reduce the number of sprouts per stump or the number of trees producing sprouts but cutting trees leaving such low stumps would be quite difficult in practical forestry operations. However, the effect of stump height on sprouting has been quite variable on other studies (Mikola 1942; Johansson 1987, 1992c) and the initial effect of stump height on sprouting may also change over subsequent years (Kvaalen 1989; Jobidon 1997).

In this study, the tree-to-tree variation in sprouting was quite high. Stumps with same diameter produced variable number of sprouts. The main reason for this is that the number of buds varies markedly from one tree to another so that it can range from 0 to several hundred in 15–40-year-old downy birch trees (Kauppi et al. 1987, 1988b). The number of sprouts per stump increased with the increasing diameter and age of the stumps. Probably bud cluster formation, associated with decline in sprouting ability in older birches (Kauppi et al. 1988a, b) had not advanced considerably even in the oldest age class. In line with this study, Johansson (1987, 2008) found increasing number of sprouts per stump with the increases in the stump diameter from 1 to 5 cm. The effect of diameter is explained by the increase in the number of buds with the increasing diameter of the stumps (Johansson 1992a). However, when stump diameter in the two oldest age classes exceeded 5 cm the number of sprouts per living stump did not increase any more.

With the increase in stump diameter, the height of sprouts (mean height, dominant height, total height of all sprouts) increased. At similar stump diameter, younger trees produced taller sprouts than older trees. In young stand cleaning in conventional silviculture cutting trees when they are still thin would decrease height growth and decrease competition inflicted by birch sprouts on conifer seedlings. The height of dominant sprout is more important than the mean height of sprouts, since the tallest sprouts have the highest risk for causing shading or mechanical injury.

When managing coppiced stands for production of lignocellulosic biomass growth is important sprouting characteristic. The dry weight of sprouts on a stump increased with increases in stump diameter from 1 to 2 cm in accordance with Johansson (1987). This study showed that increase continues at least up to 9 cm and depends on stand age. Younger stumps of the same size produced more biomass than older stumps. Thus fast-growing young stands producing stumps sized 9 cm would be ideal for short-rotation management of birch. The total biomass of the sprouts on an area basis in the study stands was related to the number of trees in the stands. Since the young stands had more stumps per hectare than the older stands, they had higher biomass on area basis.

With the increase in diameter, the number of sprouts and their height and biomass increased in all stand age classes. The effect of age was in this study seen foremost in the increase in mortality of stumps in the oldest age class. Also when comparing stumps of equal size, the height of sprouts and their biomass was the higher the younger the stand was. When short-rotation management of birch is considered, the oldest stands (22–24 years old) had the highest numbers of non-sprouting stumps, which is questionable for the sustainability of the coppice system. With similar stump diameter older trees also produced less biomass than younger trees. This favours coppicing of young trees. However, since the effect of diameter on the number of sprouts and their growth is high, the oldest stands, having higher average stump diameter than young stands, produced similar or even slightly higher number of sprouts per stump, had the similar mean height and biomass of sprouts per stump than younger stands. Thus, age in the range of 10–25 years does not limit coppice management provided that the diameter of stumps remains under 10–15 cm.

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