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Effects of pruning on wood properties of planted silver birch in southern Sweden

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Highlights
- Pruning silver birch trees increased the production of defect-free wood outside the knots.
- Most wood defects were found inside the knots.
- Pruned birch trees provide butt logs with higher value than unpruned trees.

Abstract
Pruning was performed at midsummer in two genetically homogenous and managed planted silver birch stands in southern Sweden – one aged 9 and one aged 10 years. Wood defects were analysed 10 years thereafter, using the five uppermost twigs of the stems up to a height of 30 dm. The number of trees examined at each site was around 70, of which half were pruned. The main findings were that: a) compared to unpruned trees, pruned trees produced more defect-free wood outside the knots; b) most wood defects were found inside the knots; and c) wood defects like rot and bark ingrowth were similar for pruned and unpruned trees, while discolouration was marginally higher for pruned trees inside knots but similar outside knots. Overall, the results confirm previous findings that pruned birch trees will provide butt logs with higher value than unpruned trees.

Keywords wood defects; discolouration; rot; ingrown bark
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1 Introduction

Birch is the most common hardwood species in Sweden and Finland (Swedish Forest Agency 2014; Luke 2015) and is, therefore, an important resource within the forest industry. Large quantities of birch wood are used for pulp production, but the main aim with birch forestry is producing high quality logs, i.e. straight, defect-free stems with large diameters for plywood production, veneer and for use in sawmilling industries. There are normally large differences in price between pulpwood and timber logs, as well as in the prices of timber logs of different quality gradings (cf. Vanhälls Björksåg 2014). This creates incentives for production of high quality timber. This study focuses on silver birch (*Betula pendula* Roth), which is the most frequent birch species in new plantations in Sweden and Finland.

A young silver birch stand should, according to current management recommendations, contain around 1600 trees ha^{-1} after cleaning; this is commonly followed by two thinnings, leaving around 800 and 400 trees ha^{-1}, respectively. The final harvest on fertile sites is scheduled to take place after around 40 years of growth (e.g. Oikarinen 1983; Cameron 1996; Rytter and Werner 1998; Hynynen et al. 2010; Rytter et al. 2014). One drawback with this strategy is that low stocking may lead to reduced wood quality due to the production of thicker branches and greater tapering (Niemistö 1995; Niemistö et al. 1997; Cameron 2002). Shading and competition among trees in well stocked stands leads to faster death and self-pruning of low branches (Niemistö 1996; Rytter and Werner 2007). Knots are generally considered to be the defect with the greatest impact when classifying wood quality. This is consistent with experience from grading of birch logs, where for instance Verkasalo (1997) stated that the number and size of branches are important characters. A lower stocking rate will delay canopy closure, increase branch size and slow down the process of self-pruning (e.g. Cameron 1996; Schatz et al. 2008), while at the same time favouring stem diameter development (Erdmann et al. 1975; Niemistö 1995; Simard et al. 2004; Rytter 2013). Branch traits are considered in birch breeding since branch characters such as angle, thickness and numbers are all under intermediate genetic control (Stener and Jansson 2005). Thus, using genetically improved regeneration material when planting, is one way to increase both yield and stem quality, i.e. straightness and branching (Viherä-Aarnio and Velling 1999; Stener and Jansson 2005). To some extent, this could counteract the impact of the wide spacings. Mäkinen et al. (2003) stated that high-quality timber can only be produced at the expense of stem growth if no artificial measures are carried out.

Artificial pruning is one way to enhance wood quality. The main practical experiences of this originate from Finland where pruning usually is carried out in two phases (Hynynen et al. 2010). On the first occasion 600–700 stems ha^{-1} of birches that are 6–7 m tall are pruned to a length of 2.5–3 m. When the stand height exceeds 10 m, a second pruning takes place, in which 400–500 trees ha^{-1} are pruned to a height of 5–6 m. Pruned stands are, for economic reasons, generally kept for longer rotations than unpruned stands.

Normally, pruning reduces growth increment for some years depending on the proportion of green branches removed (Heiskanen 1958; Vuokila 1976; Kannisto and Heräjärvi 2006). However, this reduction is quite marginal for intermediate prunings, i.e. 20–30% removal of the green crown. Height growth is generally influenced less than diameter growth by a reduced crown (Vuokila 1968; Stoddard and Stoddard 1987) in the same way that light competition reduces stem development (Niemistö 1995; Cameron et al. 1995; Simard et al. 2004; Rytter and Werner 2007).

The wood formed in the stem after pruning will be free of knots and hopefully free of other defects, thus improving lumber quality and enhancing economic value. The main concern with respect to pruning is the incidence of discolouration and rot that may be associated with pruning wounds. Most tree species are sensitive to wounding, as is caused by pruning (Wilkes 1982; Shigo

1984) and this is also the case for birch (Heiskanen 1958, 1964; Vuokila 1976; Verkasalo and Rintala 1998; Kannisto and Heräjärvi 2006). The trees' reactions can take the form of various mechanical (Shigo 1975) and chemical barriers, mostly involving phenolic substances (Shigo 1984). The most effective system to confine infection is the CODIT (Compartmentalisation of Decay in Trees) process which is under strong genetic control (Shigo and Marx 1977; Savill and Evans 1986). The occlusion (wood healing) process, creates a defect zone, including callus and new wood, which should be minimised. The occlusion process is considered to be slow for birch (Nylinder 1952).

The objective of this study was to analyse the wood quality 10–11 years after pruning in two young plantations of silver birch containing genetically improved reforestation material. It was hypothesised that pruned birch trees have fewer wood defects and, thus, a higher wood value than unpruned trees.

2 Material and methods

2.1 Material

Two sites were included in the study. Site 1, Järpås, Lidköping 58°14´N, 12°35´E, 65 m a.s.l., 1.7 hectare, is located on former agricultural land, and site 2, Bökö, Osby 58°16´N, 13°35´E, 115 m a.s.l., 2.0 hectare was established on forest land. Both sites are basically progeny trials including open-pollinated progenies from the same, around 300, phenotypically selected plus trees from southern Sweden. The material represents a somewhat better population than southern Swedish silver birch growing stock in general. The planting at both sites was carried out in spring 1995 with 1-year-old container-grown plants in a randomized block design, including 1–2 progenies per block, at a spacing of 2 × 2 m. The progeny trials were transformed to silvicultural trials in 2002 (site 1) and 2003 (site 2) in which the thinning treatments light, ordinary and heavy thinning are tested. Each treatment is tested in net plots of 28 × 24 m (672 m^2) at both sites and the plots for each treatment were distributed over 4 and 3 blocks at sites 1 and 2, respectively. The thinnings are performed as a reduction of the stem number from initially over 2000 trees ha^{-1} to a final density of 450–500 trees ha^{-1} at the end of the rotation (Table 1), by thinning on two (heavy), three (ordinary) and four (light) occasions. The thinning follows silvicultural standards, i.e. unvital, damaged and low stem quality trees are removed in the first place, followed by the removal of trees competing with the main stems, i.e. the trees that should be kept until final harvest.

2.2 Method

Six out of up to 14 planted rows per plot were randomly chosen at both sites for the pruning study. In three of these rows, all trees were pruned up to a height of 30 dm, leaving a green crown of at least 50% and in the other three rows, no pruning was performed. The pruning was carried out in June 2003 (site 1) and June 2004 (site 2) using a standard pruning saw and all branches were cut just outside the branch collar. To avoid negative effects of split branches, saw strokes were first applied to the lower side of the branch, followed by final strokes on the upper side.

Trees from the latest thinning, performed in June 2013 (site 1) and May 2015 (site 2), were used in the study, where 3–4 trees from both pruned and non-pruned rows of each plot were sampled for analysis of the pruning effect. One or two thinnings (depending on thinning regime) had been undertaken previously (Table 1), in which non-vital, damaged and low stem quality trees were removed. Thus, the sampled trees included vital and well-growing trees. The lower stem section up to 30 dm in height was examined for each sampled tree and the five knots/twigs located as high as

Table 1. Three thinning treatments tested at each site, 1) heavy thinning, 2) ordinary thinning and 3) light thinning. Means for tree height (H), stem number (N), basal area (BA) and tree diameter (D_g, tree of mean basal area) refer to the situation prior to thinning.

Year	Stand age (yrs)	Heavy thinning				Ordinary thinning				Light thinning			
		H (m)	N (stems ha^{-1})	BA (m^2 ha^{-1})	D_g (cm)	H (m)	N (stems ha^{-1})	BA (m^2 ha^{-1})	D_g (cm)	H (m)	N (stems ha^{-1})	BA (m^2 ha^{-1})	D_g (cm)
Site 1 – Järpås													
2002	9	8.9	2433	12.2	8.0	9.0	2429	12.5	8.1	8.7	2407	12.2	8.0
2007	14	15.2	726	10.5	13.6	14.9	1154	14.3	12.6	14.7	1566	17.1	11.8
2012	19	18.7	711	15.3	16.6	18.4	804	15.8	15.8	17.8	990	16.7	14.7
Site 2 – Bökö													
2003	10		2053				2103				2138		
2008	15	13.5	804	9.9	12.5	12.8	1260	12.2	11.1	12.7	1577	14.5	10.8
2010	17	14.7	804	11.7	13.6	13.9	1260	14.0	11.9	14.4	1106	14.0	12.7
2014	21	16.6	804	15.9	15.7	16.7	809	15.1	15.4	16.4	1106	18.9	14.7

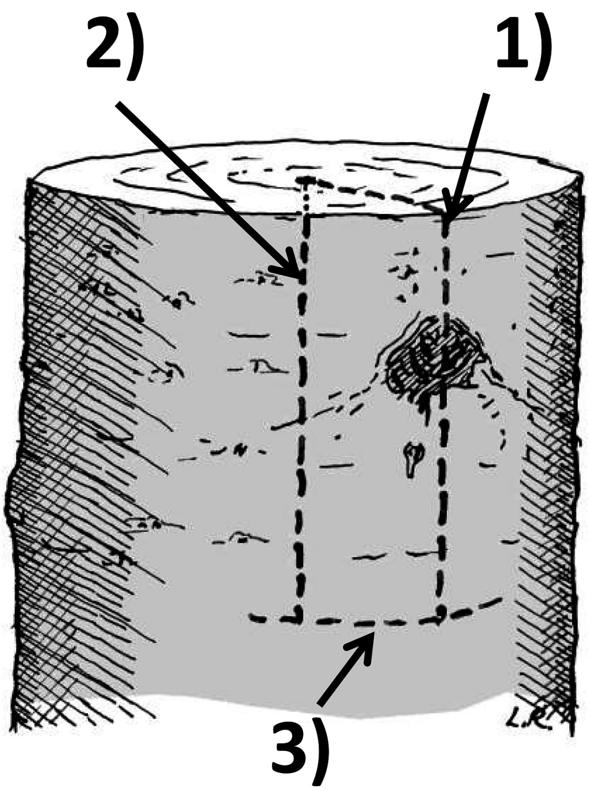

Fig. 1. Illustration of how the knot samples were produced. A vertical cut with a chain saw was directed through the centre of the knot towards the pith (1). A second vertical cut directed towards the pith was made a few cm from the first (2). A third cut released the sample, shaped like a slice of cake. Picture taken from Rytter and Jansson (2009).

possible on each stem section were selected. Before assessments, the cardinal north was noted for each twig, after which the top of the log was cut off 5–10 cm above each specific knot/twig, using a chain saw. Then, the chain of the saw was put a little to the side of the centre of the twig/knot, parallel to its length extension and directed towards the pith (Fig. 1). Thus, a section resembling a slice of cake was produced for each knot. Every sample was photographed and given a unique identification number. Cardinal point and the height above ground was recorded. The total number of sampled trees at site 1 was 67, of which 33 were pruned; 70 trees were sampled from site 2, of which 33 were pruned.

The traits used in the analyses are described in Table 2. The different wood traits related to the knot were recorded from the vertical side of each section (Fig. 2). The thickness of the knot was measured in the vertical direction from where it ended or where it passed through an imagined line along the inner limit of the bark, but excluding the commonly found protuberance. The knot angle was assessed as the angle from the horizontal line (0°). Discoloured wood only refers to a change of colour compared to ordinary wood, while rot is a structural change, i.e. the wood that has started to break down.

The length of new wood outside the knot (cicatrised wood) was measured after differentiation of the wood into defective (Dist1) and defect-free (Dist2) wood. The fault-free wood was given as the distance from the end of the discoloured, cicatrised wood to an imaginary line along the stem surface. Most twigs (ca 90%) from the unpruned trees had fallen off due to natural pruning before the time of sampling. This made it possible to estimate "Dist1" and "Dist2" for unpruned trees as well. The length of the stem swelling (protuberance) which is normally found outside the knot, was not included, since it is of no use for log production. Finally, the horizontal distance from pith to the imaginary line along the stem surface was recorded (Radius), as well as the length of ingrown bark on the upper and lower sides of the twig/knot.

Table 2. Description of traits. Illustrations are presented in Fig. 2.

Trait	Unit	Description
CardP	N, E, S, W	Cardinal point of the twig. Every twig was designated to one of the four points.
KnAng	Degrees (90°)	Knot angle from a horizontal line (Fig. 2, no 2)
Radius	mm	Horizontal distance from pith to trunk surface, excluding the protuberance, (Fig. 2, no 5 in the lower illustration)
Dia	mm	Tree diameter at 13 dm above ground in autumn 2012 (age 19) at site 1 and 2014 (age 21) at site 2
TwHght	cm	Height from ground to the twig
KnDia	mm	Diameter of the knot at the outer end or trunk edge (Fig. 2, no 1)
Dist1	mm	Length of new wood with wood defects (Fig. 2, no 3)
Dist2	mm	Length of defect-free new wood (Fig. 2, no 4)
Dist3	mm	Total length of new wood (Dist1 + Dist2)
BrkUp	mm	Length of ingrown bark above the knot (cf. BrkLow)
BrkLow	mm	Length of ingrown bark below the knot (Fig. 2, no 6)
ColIn	%	Proportion of wood discolouration within the knot (Fig. 2, no A)
ColOut	%	Proportion of wood discolouration outside the knot (Fig. 2, no B)
RotIn	%	Proportion of wood rot within the knot (Fig. 2, no A)
RotOut	%	Proportion of wood rot outside the knot (Fig. 2, no B)

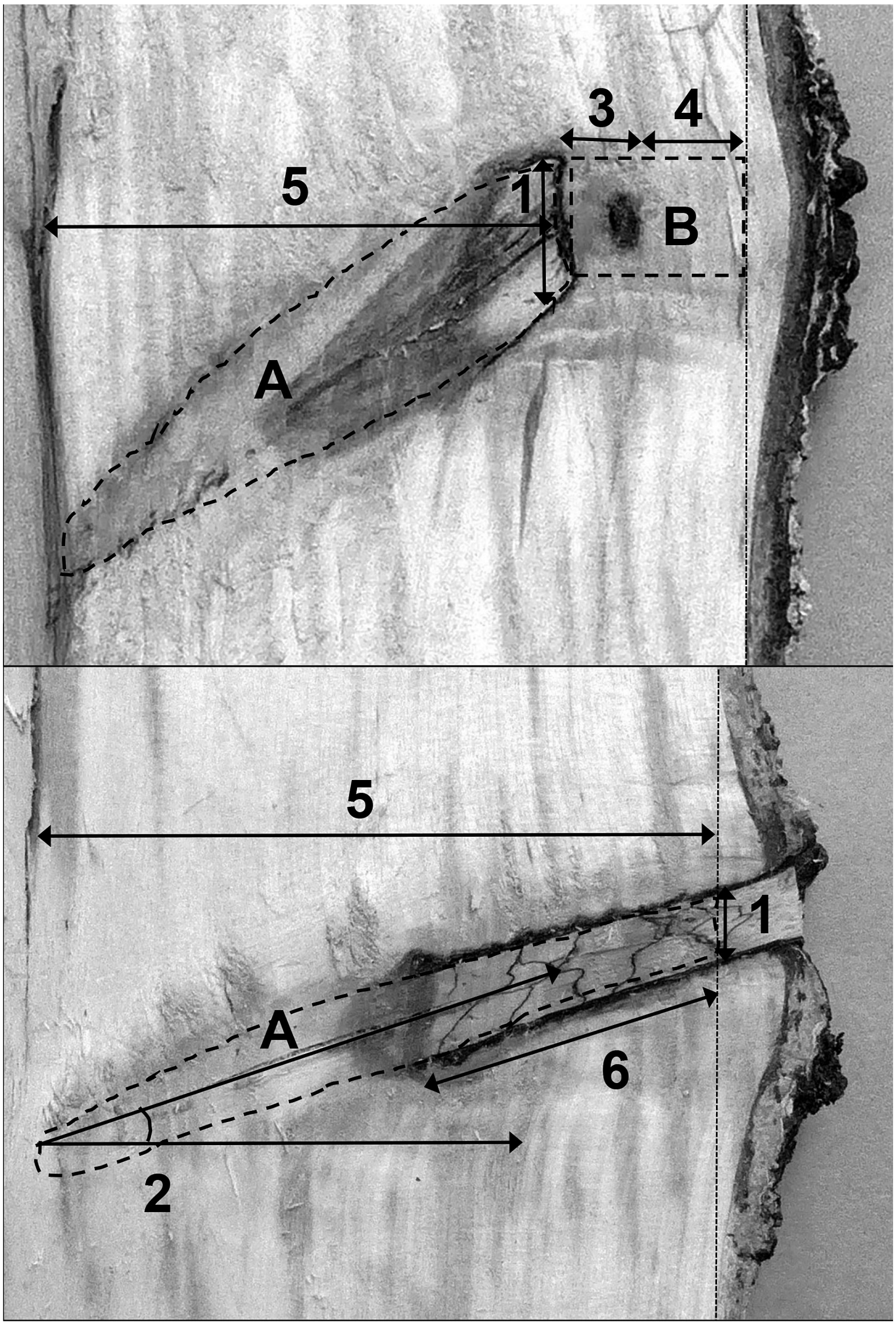

Fig. 2. Example of measurements of traits in pruned (top picture) and unpruned (bottom picture) trees: 1 = vertical knot thickness; 2 = knot angle; 3 = discoloured wood and wood with rot in the horizontal direction; 4 = defect-free wood outside the knot; 5 = distance from pith to knot end; 6 = length of ingrown bark; A = area within the knot from which areas affected by discolouration and rot were estimated as a percentage; B = area between knot end and vertical trunk edge (excluding the protuberance commonly found outside a twig) from which areas affected by discolouration and rot were estimated as a percentage.

2.3 Statistical analysis

The statistical analysis was based on the five individual knots for each tree. All knots were described as fresh. Thus, no dry knots were included. The basic model (1) used for each separate site was:

$$Y_{ijklm} = Block_i + Thin_j + Plot_{ij} + Prun_k + Thin_j \times Prun_k + Sub\text{-}plot_{ijk} + Tree_l\left(Sub\text{-}plot_{ijk}\right) + e_{ijklm} \quad (1)$$

where Y_{ijklm} = observation *ijklm*, $Block_i$ = random effect of block *i*, $Thin_j$ = fixed effect of thinning treatment *j*, $Prun_k$ = fixed effect of pruning treatment *k*, $Sub\text{-}plot_{ijk}$ = ($Block_i \times Thin_j \times Prun_k$), $Tree_l$ = fixed effect of tree *l* and e_{ijklm} = random error term for observation *ijklm*, NID($0,\sigma_e^2$).

For the overall results for both sites model (2) was used:

$$Y_{hijklm} = Site_h + Block_{hi} + Thin_j + Plot_{hij} + Prun_k + Thin_j \times Prun_k + Sub\text{-}plot_{hijk} + Tree_l\left(Sub\text{-}plot_{hijk}\right) + e_{hijklm} \quad (2)$$

where Y_{hijklm} = observation *hijklm*, $Site_h$ = fixed effect of site *h*, $Block_{hi}$ = random effect of block *i* for site *h*, $Thin_j$ = fixed effect of thinning treatment *j*, $Prun_k$ = fixed effect of pruning treatment *k*, $Sub\text{-}plot_{hijk}$ = ($Site_h \times Block_i \times Thin_j \times Prun_k$), $Tree_l$ = fixed effect of tree *l* and e_{hijklm} = random error term for observation *hijklm*, NID($0,\sigma_e^2$).

The analysis started with testing the effects of cardinal point (CardP), knot angle (KnAng), stem radius (Radius), tree diameter (Dia), twig height on the trunk (TwHght) and knot diameter (KnDia) by using Eq. 1 and 2. Only KnDia exhibited significant differences for pruned and unpruned trees. Thus, to avoid any systematic influence of knot diameter, additional calculations were performed where KnDia was included as a covariate in Eq. 1 and 2.

Data pertaining to CardP, TwHght, length of new wood with defects (Dist1), ingrown bark above and below the knot (BrkUp, BrkLow), wood discolouration within the knot (ColIn), and

Table 3. Number of observations (N), arithmetic means (Mean), standard deviations (Std), minimum (Min) and maximum (Max) values for different traits at each site, based on individual knot/twig data. Description of traits are given in Table 2.

Trait	Unit	Site = 1 (Järpås)					Site = 2 (Bökö)				
		N	Mean	Std	Min	Max	N	Mean	Std	Min	Max
Dia	mm	335	141	20.0	102	179	348	138	18.7	91	273
Radius	mm	335	59	8.8	38	84	348	54	7.9	33	73
TwHght	cm	335	238	37.0	150	300	348	240	37.8	140	300
KnDia	mm	335	12.1	5.8	2	40	348	10.8	6.7	2	55
KnAng	°	335	42	9.1	7	64	348	41	10.2	11	65
Dist1	mm	335	0.9	1.9	0	12	348	0.7	1.7	0	10
Dist2	mm	335	9.1	8.1	0	32	348	6.0	6.8	0	30
Dist3	mm	335	10.1	8.1	0	32	348	6.6	7.2	0	30
BrkUp	mm	335	11.1	11.4	0	66	348	18.9	23.6	0	105
BrkLow	mm	335	5.3	5.7	0	32	348	6.1	6.9	0	35
ColIn	%	335	30	14.7	0	90	348	29	18.2	0	100
ColOut	%	335	4.9	12.0	0	90	348	4.0	13.0	0	100
RotIn	%	335	7.9	9.5	0	40	348	11.5	11.9	0	100
RotOut	%	335	0.0	0.0	0	0	348	0.7	6.4	0	100

Table 4. Statistical results for difference in pruning treatments and least-square means of pruned and unpruned trees for different traits for each site (Eq. 1) and for both sites (Site 1+2, Eq. 2). A "x" in the column "Covar" indicates the result when the covariate KnDia was included in Eq. 1 and 2. Bold figures are significant at the 5%-level. Description of traits are given in Table 2.

Trait	Covar	Unit	Site 1				Site 2				Site 1+2				
			p-value	Means		p-value	p-value	Means		p-value	p-value		Means		p-value
			Pruning	Unpruned	Pruned	KnDia	Pruning	Unpruned	Pruned	KnDia	Pruning	Site	Unpruned	Pruned	KnDia
CardP		(1–4)	0.802	2.9	2.9		0.951	2.4	2.4		0.893	**0.003**	2.6	2.6	
KnAng		°	0.530	42.0	42.0		0.118	40.0	43.0		0.094	0.733	41.0	42.0	
Radius		mm	0.760	58.4	58.9		0.602	53.8	54.7		0.597	**0.028**	56.1	56.7	
Dia		mm	0.869	141.0	141.0		0.842	139.0	138.0						
TwHght		cm	0.423	236.0	239.0		0.539	239.0	241.0		0.308	0.416	237.0	240.0	
KnDia		mm	0.100	11.5	12.7		**0.006**	9.1	12.8		**0.0005**	0.113	10.3	12.7	
Dist1		mm	0.439	0.9	1.1		**0.028**	0.4	1.0		**0.024**	0.181	0.6	1.0	
Dist1	x	mm	0.582	0.9	1.0	**0.019**	**0.046**	0.4	0.9	0.369	0.067	0.219	0.6	1.0	**0.016**
Dist2		mm	**0.048**	7.7	10.7		**0.003**	2.9	9.4		**0.040**	**0.0002**	5.3	10.0	
Dist2	x	mm	**0.024**	7.4	11.0	**<0.0001**	**0.001**	2.6	9.8	**<0.0001**	**0.031**	**<0.0001**	5.0	10.4	**<0.0001**
Dist3		mm	**0.035**	8.6	11.8		**0.003**	3.3	10.3		**0.034**	**<0.0001**	6.0	11.0	
Dist3	x	mm	**0.019**	8.3	12.0	**<0.0001**	**0.002**	3.0	10.7	**0.001**	**<0.0001**	**0.028**	5.7	11.3	**<0.0001**
BrkUp		mm	0.268	10.1	12.1		0.136	21.4	16.4		0.397	**0.006**	15.7	14.2	
BrkUp	x	mm	0.356	10.3	11.9	**0.004**	0.053	22.4	15.2	**0.002**	0.145	**0.005**	16.3	13.6	**<0.0001**
BrkLow		mm	0.732	5.2	5.5		0.149	6.8	5.3		0.950	0.660	6.0	5.4	
BrkLow	x	mm	0.737	5.2	5.5	0.950	0.512	6.4	5.8	**<0.0001**	0.654	0.532	5.9	5.6	**0.0008**
ColIn		%	**0.003**	26.0	34.0		0.167	26.6	32.6		**0.003**	0.891	26.0	33.0	
ColIn	x	%	**0.004**	26.3	33.6	**0.0002**	0.244	27.0	32.0	0.082	**0.008**	0.977	26.7	32.8	**0.0005**
ColOut		%	0.208	4.0	6.1		0.335	3.1	4.8		0.096	0.535	3.6	5.5	
ColOut	x	%	0.281	4.2	5.9	**0.022**	0.298	3.0	5.0	0.580	0.142	0.578	3.7	5.4	0.298
RotIn		%	0.153	8.8	6.8		0.506	11.0	12.2		0.637	0.103	9.9	9.4	
RotIn	x	%	0.126	8.9	6.7	0.150	0.819	11.4	11.8	**0.041**	0.377	0.094	10.1	9.2	**0.006**

wood rot within and outside the knot (RotIn, RotOut) deviated from normal distributions and were transformed using log and square root algorithms. These transformed values had only marginal effects on the results when compared to the original values. Thus, the presented results refer only to the original untransformed values.

Correlations among traits were calculated within each site. The statistical analyses were carried out using the Proc MIXED or Proc CORR procedures, supplied in Version 9.4 of the SAS System.

3 Results

Tree growth (Dia) was of similar magnitude at both sites, as were the means for the different knot and wood defect traits (Table 3), despite the two-year difference in age. However, for the traits length of defect-free wood (Dist2), total length of new wood (Dist3), length of ingrown bark above the knot (BarkUp) and proportion of rot within the knot (RotIn), the differences between sites were more pronounced.

The statistical tests showed that the basic traits such as cardinal point, knot angle, radius, diameter at breast height, twig height and knot diameter had no significant effect with respect to pruning at site 1, while at site 2 and thus also in the combined analysis of sites 1 and 2, the effect was significant for knot diameter (Table 4). The latter resulted, as mentioned previously, in the inclusion of trait KnDia as a covariate in the statistical analysis. This covariate trait was significant in the analysis of most traits but the pruning effect (Table 4) was only marginally influenced.

Dist1, i.e. the overgrown length, including wood defects, from the end of the knot to the beginning of the area without any wood defects (Fig. 2) was generally small (around 1 mm) but had a tendency to be larger for pruned trees (Table 4). The new wood produced after pruning without wood defects (Table 4, Dist2) was significantly greater for pruned trees compared to unpruned trees. The absolute lengths were around 7 mm at site 1 and 3 mm at site 2 for unpruned trees and the corresponding figures were 11 and 10 mm for pruned trees. When expressed in relative terms, i.e. in relation to the stem radius at the position of each knot, the figures were 13% and 5% for unpruned trees and 17% for pruned trees.

Table 5. Correlations between different traits at site 1. Bold figures are significant at the 5% level. Description of traits are given in Table 2.

Trait	KnAng	Dist1	Dist2	Dist3	BrkUp	BrkLow	ColIn	ColOut	RotIn
KnDia	**0.52**	**0.15**	**–0.22**	**–0.18**	**0.14**	0.01	**0.24**	**0.14**	0.07
KnAng		0.06	–0.04	–0.03	**0.34**	**–0.11**	0.06	0.05	–0.01
Dist1			**–0.11**	**0.13**	0.07	0.06	**0.13**	**0.75**	0.06
Dist2				**0.97**	0.03	–0.07	**0.22**	**–0.18**	**–0.13**
Dist3					0.05	–0.05	**0.25**	0.00	**–0.11**
BrkUp						**0.27**	**0.11**	0.05	**0.33**
BrkLow							0.04	0.09	**0.48**
ColIn								**0.15**	**–0.23**
ColOut									0.09

Table 6. Correlations between different traits at site 2. Bold figures are significant at the 5% level. Description of traits are given in Table 2.

Trait	KnAng	Dist1	Dist2	Dist3	BrkUp	BrkLow	ColIn	ColOut	RotIn
KnDia	**0.40**	0.07	–0.09	–0.07	**0.13**	**–0.25**	0.05	–0.02	0.09
KnAng		–0.02	**–0.13**	**–0.13**	**0.41**	**–0.20**	**–0.12**	–0.02	**–0.15**
Dist1			**0.12**	**0.36**	–0.10	0.04	0.08	**0.69**	**0.11**
Dist2				**0.97**	**–0.16**	**–0.09**	**0.18**	0.00	0.02
Dist3					**–0.17**	–0.07	**0.19**	**0.17**	0.04
BrkUp						**0.20**	**0.22**	–0.10	**0.11**
BrkLow							**0.42**	0.10	**0.53**
ColIn								0.07	**0.64**
ColOut									0.09

Overall, there was more ingrown bark on the upper side (BrkUp, 10–22 mm) than on the lower side (BrkLow, 5–7 mm) of the knot (Table 4). No significant effect was found among pruned and unpruned trees, although there was a tendency to be less bark damage on pruned trees at site 2. There was also a significant site effect, where ”BrkUp” at site 2 was significantly larger than for site 1.

The discolouration percentage was larger within the knot (ColIn, 26–34%) compared to the area outside the knot (ColOut, 4–6%) (Table 4). Pruned trees tended to be more discoloured and this was statistically significant at site 1.

The rot outside the knot (RotOut) was mostly close to 0 (Table 3) and was not analysed further. The wood with rot damage inside the knot (RotIn) was around 6–12% of the defined area (Table 4). There were no significant pruning effects.

The correlations for the most relevant traits for the two sites are presented in Tables 5 and 6. They refer to both pruned and unpruned trees at each site, since separate correlations for each of these material groups differed only marginally. The correlations were generally weak, except for those between Dist1 × ColOut and Dist2 × Dist3, that were strong to very strong. The latter relationship is obvious, since the traits represent very similar characteristics. The correlation between colouration and rot within the knot (ColIn, RotIn) were both significant but showed contrasting results at the two sites.

4 Discussion

Our main findings were that pruned trees in relation to unpruned trees a) had significantly more newly produced wood without defects outside the knot, b) tended to be more discoloured within the knot, c) had similar lengths of ingrown bark and d) did not differ with respect to rot damage (Table 4).

These results, 10–11 years after pruning, are partly in accordance with our expectations, i.e. pruning produced faultless wood, and wood defects such as in-grown bark, discolouration and rot were of the same level for pruned as for unpruned trees. The pruning was performed in mid-summer, mainly on thin branches and it was undertaken carefully just outside the bud collar without leaving any residual stub, i.e. according to current recommendations (Hynynen et al. 2010). This was a way to minimise the risk of developing wood defects. The wounds were related to the thickness of the branches. However, our results did not show any significant effect in relation to knot diameter, as shown in Tables 4–6. The main reason for this is probably that knot diameters in general were modest. Even though maximum knot diameters of up to 55 mm were found (Table 3), more than 94% of the knots were less than 25 mm and at least 86% were less than 20 mm for both pruned and unpruned trees at both sites. There are reports stating that green crown pruning of birch should be performed on branches up to around 20 mm in diameter. Thicker branches cicatrise more slowly and, thus, the risk of discolouration increases (e.g. Verkasalo and Rintala 1998; Kannisto and Heräjärvi 2006). Furthermore, the development of knot-free wood will be postponed.

The new wood without defects produced after pruning (Table 4, Dist2) was significantly larger for pruned trees (ca 11 mm) compared to unpruned trees (3–7 mm). The difference in lengths of fault-free new wood for pruned and unpruned trees was not as large as expected. However, it should be noted that 34% (site 1) and 68% (site 2) of the knots of unpruned trees had no defect-free wood at all (Dist2 = 0), while the corresponding figures for pruned trees were 13% and 9%. In a study of pruning of hybrid aspen (Rytter and Jansson 2009), where a similar methodology was used as in this study, the length of fault-free wood was much larger for pruned (33 mm) than for unpruned trees (3 mm) 10 years after pruning. Hybrid aspen, however, grows at least twice as fast as silver birch (Rytter and Stener 2014).

Discoloured wood is one of the major defects that has a great impact on the value of logs. Pruned trees had around 7% more discoloured wood within the knot than unpruned trees in this study, while there were no differences for the wood outside the knot (Table 4). Schatz et al. (2008) reported that pruned branches of birch had colour defects in all directions inside the stem. The most obvious directions were tangential (47%), but the discolouration did not reach the knot-free sapwood. This agrees with our results, since the cicatrised distance with wood defects (Dist1) was small (Table 4). This is also supported by Ohman (1968) and Skilling (1958), who stated that discolouration and decay in pruned hardwoods is rare beyond the annual ring in which the twig was pruned. Heikinheimo (1953) found obvious colour defects after green crown pruning of birch. For branches thicker than 10 mm, the wood surrounding the branch was discoloured for around 50% of the branches. In our study the defective wood was only found within the knot. On the other hand, Heikinheimo (1953) commented that the trees used in his study were growing slowly (1 mm year^{-1}) and he speculated that the defects would be less severe in faster growing trees.

Many reports stress the importance of careful pruning. For instance, Heiskanen (1958) stated that colouration defects originating from pruned branches in birch are mainly a result of bark injuries, as a consequence of bad pruning work. Vuokila (1976, 1982) delivered the same message. Furthermore, Schatz et al. (2008) showed that pruning with secateurs was less harmful with respect to discolouration than using a saw. The pruning technique in this study was, in our judgement, performed appropriately (see section 2.2), suggesting no or a very low impact on the result due to incorrect pruning.

Rot is also a serious wood damage problem that may be connected to artificially or self-pruned trees. In our study rot damage was rare outside the knot and not common inside the knot either (6–12%, Table 4) and there were no differences between pruned and unpruned trees. In the study by Heiskanen (1958), examining 74 pruned/unpruned birches from 22 stands, rot was the most common defect. However, rot was not found beyond the annual ring of the pruning year, i.e. a similar result to ours. Schatz et al. (2008), on the other hand, showed that minor proportions of rot can be found outside the knots in birch. Despite the rot damage results, Heiskanen (1958) concluded that the economic value of all pruned trees was higher than that of unpruned trees and that defects caused by rot and discolouration after pruning had not in any case decreased the value of the veneer produced from the wood.

Ingrown bark is another character that reduces wood quality. It is caused by the formation of new annual rings outside the dead and dying twig so that bark is included. The amount of ingrown bark was of approximately the same magnitude as reported in a pruning study of hybrid aspen (Rytter and Jansson 2009). However, in contrast to that study, we found no differences between pruned and unpruned trees. One reason for this may be that the hybrid aspen study included trees with dry twigs, which cause greater bark ingrowth problems than fresh twigs.

There are reports showing that the speed of occlusion (healing time) depends greatly on the rate of stem diameter growth, when proper pruning techniques are used (Roth 1948; O'Hara et al. 1996). This finding is supported by our results, if we consider occlusion to be closely related to the new wood produced after pruning. "Dist2" and "Dist3" (Table 4) were significantly larger at site 1, located on former agricultural land compared to site 2, located on forest land. Thus, site 1 is the more fertile site, with higher growth potential than site 2. This is also indicated by the diameters presented in Table 3, which are similar, although the diameter at site 1 refers to an assessment conducted 2 years earlier than that at site 2. In addition, previous estimates of productivity (Lars Rytter, pers. comm. in 2016) have shown yields of around 9.5 m^3 of stemwood ha^{-1} yr^{-1} for site 1 compared to around 7.5 m^3 of stemwood ha^{-1} yr^{-1} for site 2.

Similar diameters at breast height (Table 4) for pruned and unpruned trees indicate that there was no reduction in growth after pruning. The trees were pruned to a height of 3 m, having an average height of 8–9 m at site 1 (Lars Rytter, pers. comm. in 2016). Thus, the proportion of green crown was about 55–60% in relation to the total tree height. This exceeds the critical level of around 50–55%, which is needed for unreduced continuous growth of deciduous trees (Niemistö 1996; Cameron 1996; Rytter and Werner 1998).

The relationship between colouration and rot within the knot (ColIn, RotIn) exhibited different trends for the two sites (Tables 5, 6). We consider the correlation from site 2, where the proportion of colouration within the knot tended to increase with higher proportions of rot, to be the most reliable of the two. The result for site 1, was based on a quite uneven distribution of observations, where most assessments resulted in low scores. Removing the very few observations with high scores resulted in a correlation that was not statistically significant.

Pruning has the potential to encourage the subsequent rapid formation of faultless wood, in which wood defects like in-grown bark, discolouration and rot, can largely be avoided. From the results, it can be concluded that pruning may marginally increase wood discolouration, but if knots are small, this should not be a significant problem, especially since the defect mainly affects the inside of the knot. Thus, overall, our results, here represented by managed silver birch plantations, confirm previous findings that pruned birch trees will eventually provide butt logs of higher value than those from unpruned trees. The conclusion drawn from the existing information is, therefore, that defect-free wood from birch is produced outside the pruned knots and that the amount of high quality wood is favoured by early pruning as long as the green crown is not reduced to an extent which limits growth.

This study is based on a large sample from a homogenous population, having the same genetic background and forest management. This should strengthen the reliability of the conclusions. It should be noted that the results are closely related to the pruning recommendations (Hynynen et al. 2010) in use today.

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