

## Article

# Non-Destructive Evaluation of Downy and Silver Birch Wood Quality and Stem Features from a Progeny Trial in Southern Sweden

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**Abstract:** This study investigated whether improved downy birch could perform as well as improved silver birch, and whether there was sufficient genetic variation and control for non-destructive testing (NDT) values to include them as selection traits in breeding programs. NDT tools were applied to a 15-year-old downy birch family trial intermixed with improved silver birch. Average diameters, fissured bark height, and grain angle were higher for silver than downy birch. The genetic analysis for downy birch provided estimates of narrow-sense heritability ( $h^2$ ) for acoustic velocity and Pilodyn penetration depth that were above 0.3 but had low genetic variation. Grain angle had relatively high genetic variability (18%) and an  $h^2$  of 0.20. A subsample of 49 trees had 4 mm cores x-rayed for wood density estimates, and 34 stems had 12 mm cores macerated for cell measurements. *t*-tests revealed that average wood density and cell measurements were not significantly different between species. For silver and downy birch, fiber length and vessel length increased between inner and outer measurement positions, and fiber length was reasonably correlated with acoustic velocity. Silver birch tended to have denser and stiffer wood, while downy birch had less rough bark and straighter grain, and these results are in agreement with existing knowledge. The  $h^2$  values were similar to those observed in other birch species and indicate there is potential to breed for improved wood density and grain angle in downy birch.

**Keywords:** acoustic velocity; cell dimensions; densitometry; heritability; genetic variability; grain angle



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## 1. Introduction

Birch (*Betula* spp.) is an important tree genus across Europe, Asia, and North America where it is native and widely distributed. In countries where birch is harvested and processed for wood products [1–3], stem properties such as size and form [4–6] affect the monetary value. Stem value can therefore be increased if size or form is improved through either silviculture [7] or breeding [8]. Breeding programs require genetic information specific to a population and trait; these can include heritability (0–1) and genotypic coefficients of variation (%). Here, it is important that a trait is highly (above 0.4) or moderately (0.2–0.4) heritable [9] and that there is variation within the population if it is to be included in a breeding program [10].

The two main species of birch in Sweden, silver birch (*B. pendula* Roth.) and downy birch (*B. pubescens* Ehrh.), have a different number of chromosomes ( $2n = 28$  and  $4n = 56$  [11]), yet hybrids can occasionally occur. Both species are similar in appearance and have slightly different site requirements [7,11,12]; silver birch generally requires better drainage

and site fertility than downy birch. The morphological differences between leaves and shoots are known, but are often difficult to distinguish. The species common name downy birch is from the tiny downy-like hairs that grow on new shoots. Another common feature of downy birch is less rough brown fissured bark [7,11,12]. Both birches are diffuse-porous hardwood trees with vessels distributed throughout each annual ring [13]. Due to phenotypic similarities, they are not differentiated in Sweden's national forest inventory [14].

The wood density of silver and downy birch increases from the pith radially and slightly decreases again nearer to the bark [15]. When considering the wood density along the stem, silver birch has a minor decrease in density with increasing measurement height [16], and this is slightly more pronounced in downy birch [17]. As site and establishment method can affect the wood density and anatomical characteristics of both species [18–20], it is advantageous to compare these species at the same site where conditions are relatively homogenous. Often, silver and downy birch performance has been compared between sites [21], where species differences and site effects were potentially confounded. A lack of active interest in downy birch management and planting, and surviving at wetter and colder climates [11], has likely resulted in downy birch being naturally regenerated on remote, low productivity sites. Active birch management could feature ground preparation to encourage self-regeneration, and should focus on timely thinning to ensure sufficient growing space and sunlight. Ideally, the rotation length would be less than 50 years on sites with reasonable growth [7,12], yet a large proportion of birch in Sweden is in coniferous stands [14] so the rotation length may be longer than is optimal.

The differences between silver and downy birch trait performance [15,17] and growth [21,22] at different sites could be better exploited in breeding programs where populations may be bred for different end uses or deployment zones. Silver birch has been of higher priority in breeding than downy birch [9,22] since on fertile sites it has greater potential for high volume production [18,19], better stem form, and higher wood density [23] than downy birch. Currently, there is an ongoing breeding program for silver birch in Sweden [8]. The breeding of downy birch has been limited to selection of plus trees, i.e., trees with superior growth (diameter, height) and quality traits (straightness, smaller branches) compared to the surrounding trees.

Previous studies of silver birch have reported reasonable heritability estimates for wood density [24,25], yet downy birch is less commonly studied and is seldom compared to silver birch with the same growing conditions. It can also take a long time to see any results. Therefore, early selection is often applied in breeding programs to shorten breeding cycles. Instead of waiting for trees to reach harvest age, measurements are taken in young stands as indicative of later performance, either relying on trait performance being correlated between ages (age-age correlation [26]) or to improve early trait performance (e.g., survival, initial growth, corewood properties) [8]. The superior genotypes in birch breeding programs are often selected within 15 years of planting and selection is strongly focused on growth parameters, i.e., height and diameter [8].

Previous studies of wood properties in breeding programs have relied on the destructive measurement of sample material [24] or the application of non-destructive testing (NDT) tools [25,27,28]. The use of NDT tools is beneficial as the tree or sample is not destroyed by the measurements, however the relationships with destructively assessed wood properties are imperfect. NDT measurements are practical in breeding programs when applied early to shorten the selection cycle, and since the trees continue to grow, later measurements can also occur. Acoustic velocity (AV) has been used to estimate birch wood stiffness through time of flight (ToF) tools [29–31] and was found to be correlated to fiber length for *B. platyphylla* [29]. Penetration depth provides an estimate of hardness [32], and birch hardness is positively correlated with wood density [15,33]. Stiffness, expressed as modulus of elasticity (MOE), is an important wood trait relating to wood strength and stability. Estimation of MOE also requires a measure of wood density, which for birch has previously been obtained from wood cores or discs [33], and penetration depth [25,27].



The seeds collection was carried out in the archive. Open-pollinated (OP) seeds were collected from 37 plus-trees and created pure half-sib families with known mother but unknown father. Later, pollen from five plus-tree was collected and mixed in the way that each clone had the same proportion of pollen in the mixture. The mixture was used in controlled crosses (CC) with 30 plus-trees as mothers, creating 30 families with known mother and unknown father, which might be one of the five pollen donors included in the pollen mix. All in all, 67 families were created from the 42 plus-trees. The measurements of height and diameter at the ages of 5 years and 10 years showed no differences between OP and CC groups, so for the purpose of this study, both groups were considered together.

The silver birch seedlings represented six half-sib families from six plus-trees. Seeds were collected in a clone archive in southern Sweden. All in all, 61 silver birch seedlings were produced and planted in the experiments.

In both experiments, there were 1145 improved downy birches, 174 improved silver birches, 83 unimproved downy birches planted (representing local stand), and 22 seedlings lost their identity; there were 9 to 45 seedlings per cross. Both experiments were fenced before planting and were established in a single tree plot design where each seedling was randomly planted over the experimental area.

### 2.1. Measurements

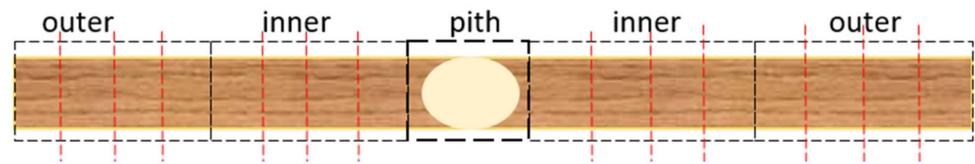
The measurements for this study were taken in autumn 2018 when the stands were 15 years old. Diameter at (1.3 m) breast height (DBH) and the height of rough fissured brown bark were measured for all trees. Height of fissured brown bark was measured until color and structure of bark was not clearly white and smooth, respectively. Straightness, branch angle, branch thickness, and branch frequency were ranked from 1 to 9 for all trees. A numbered ranking where higher scores are better is commonly used for field assessments in tree breeding programs in Sweden, even though the process of ranking is known to include bias due to subjective operator judgment [24,36,37]. Trees were ranked for the lowest 8 m of the stem where straightness related to stem deviation from a central vertical axis and branch angle and thickness scores were for the worst branch. These rankings were performed by the same person for all trees to minimize measurement bias.

The NDT tools applied here were a Pilodyn 6J Forest densitometer (PROCEQ, Zurich, Switzerland) to measure needle penetration depth, a wedge grain angle meter, and a TreeSonic Timer (FAKOPP Enterprise, Agfalva, Hungary) to measure time-of-flight (ToF), later converted to acoustic velocity (AV). These same tools have been applied elsewhere to assess genetics trials [38–41] and their working principles are outlined in numerous reviews [42–45]. Measurements of penetration depth and grain angle were performed at DBH height. ToF sensors were placed at 0.8 m and 1.8 m. ToF was measured on the south stem face, while the Pilodyn and grain angle meter were applied to both stem faces to avoid branches or defects. North and south grain angle measurements were averaged to obtain a single grain angle measurement per stem. ToF was measured for stems greater than 70 mm in DBH, while grain angle and penetration depth were measured for all stems.

Out of the stems with a DBH above 70 mm, 30 silver birch and 30 downy birch trees were randomly selected for wood density measurements. A 4 mm diameter increment borer (Haglöf, Långsele, Sweden) was used to collect cores from the north to the south stem face through the pith. Cores were later scanned using the Itrax scanning densitometer (Cox Analytical Systems, Mölndal, Sweden). This method is outlined by Hallingbäck, et al. [46] and, alongside the subsequent ring analysis in LIGNOVISION™ (Rinntech, Heidelberg, Germany), is the same method as in Jones et al. [25]. Each core was processed to create a wood density radial profile; the average of all ring densities for a given tree was used.

In addition, 15 silver birch and 19 downy birch stems with DBH above 70 mm were randomly sampled, attempting to measure one tree per species and plot where they were present. More downy birch were sampled since there were a larger number present. Cores were taken using a 12 mm diameter increment borer (Haglöf, Långsele, Sweden) as above. These cores were conditioned to room temperature and then sectioned with the pith and

bark excluded (Figure 2). At least one thin splinter of wood was split from each sampling position (red dashed lines) by following the grain. These thin wood splinters were placed into glass jars labelled with position (inner/ outer) and tree ID for later maceration.



**Figure 2.** Indicative diagram showing 12 mm core sectioning. Dashed black lines show how the quarters were divided to avoid bark and pith, and dashed red lines show the positions where the splinters were taken from. No distinction was made between north and south.

A mixture of equal parts of hydrogen peroxide and acetic acid was used for wood splinter maceration according to a commonly used method [47]. Wood splinters were placed in glass jars with the mixture and left in an oven at 60 °C until they appeared white. At least three slides were made per jar in an attempt to randomly sample intact fibers and vessel elements under the microscope. The light microscope BX63F, equipped with a DP73 color CCD cooled camera (max. 17.28 megapixel) and the software program cellSens DIMENSION 1.18 (all Olympus, Tokyo, Japan), was then used to measure cell dimensions. Fifty (50) fiber lengths, a straight line from end point to end point, and 30 vessel elements (width and length) were measured from each sample. Vessel lengths were measured from end point to end point, and across the mid-point of this line the vessel width was measured [47]. Often additional slides (more than the three minimum) were needed to find 30 vessel elements since vessels were less common. For each tree, 100 fibers and 60 vessel elements were measured making in total 1900 and 1500 fiber length measurements, for downy birch and silver birch respectively, while the vessel element measurements (length or width) were 1140 for downy birch and 900 for silver birch.

## 2.2. Statistical Analyses

In the analysis, if there were multiple measurement of a specific trait, a simple average was used instead. In this regard, north and south Itrax wood density, Pilodyn penetration, grain angle, and cell measurements were all averaged to obtain a single value for each measurement type per stem. Mean values, standard deviations, and phenotypical correlation coefficients (R values, Pearson correlation) between traits were computed in Microsoft Excel (Excel 2016).

The Walsh's two-tailed unpaired *t*-tests were used for comparison of traits between species (Table 1), while a paired *t*-test was used to compare inner and outer cell measurements since inner and outer were for the same trees. The significance level for testing was  $\alpha = 0.05$ , where *t*-test values and correlations were considered significant if their *p*-value was below this value.

Variance and covariance components for genetic analyses were estimated for downy birch for each site using ASREML4.0 [48]. The following linear mix model for single site analysis was fitted:

$$y_{lijk} = \mu + S_i + B_j + F_k + \varepsilon_{ijkl}, \quad (1)$$

where  $y_{lijk}$  is the trait observation of the *l*-th tree (e.g., H, DBH, FBH) from the *i*-th site (1–2), *j*-th plot within site (1–6/14) and *k*-th family (1–67) within plot *j*,  $\mu$  is the trait mean *S* is a fixed site effect, *B* is a fixed plot effect, and *F* is a random half-sib family effect. Variances and covariances were estimated for the traits measured or ranked on all trees. Some traits did not contain enough data for models to converge.

**Table 1.** Summary of measurements, NDT values and cell dimensions for outer wood by species. Standard deviations (St.Dev) and *t*-test results.

Trait	Code	Units	Downy Birch			Silver Birch			Walsh's <i>t</i> -Test	
			<i>n</i>	Mean	St. Dev	<i>n</i>	Mean	St. Dev	Test Stat	<i>p</i> -Value
Height at age 5	H <sub>5</sub>	cm	1036	358	12	145	447	12	9.86	0.00
Diameter at age 10	DBH <sub>10</sub>	mm	1006	50	21	141	79	27	12.26	0.00
Diameter at age 15	DBH <sub>15</sub>	mm	716	73	26	118	110	33	11.83	0.00
Fissured bark height	FBH	cm	710	14	13	118	69	33	18.08	0.00
Grain angle	GA	°	623	−1.7	1.6	106	−2.0	1.5	2.36	0.02
Acoustic velocity	AV	m s <sup>−1</sup>	389	3873	15	103	3892	16	0.69	0.49
Pilodyn penetration	Pilo	mm	647	17.8	2	112	17.4	2	1.81	0.07
Wood density	DENS <sub>trax</sub>	kg m <sup>−3</sup>	26	399	28	23	408	28	1.26	0.21
Fiber length (outer)	FL <sub>O</sub>	μm	19	987	74	15	994	101	0.35	0.73
Vessel element length (outer)	VL <sub>O</sub>	μm	19	729	63	15	706	81	0.83	0.41
Vessel element width (outer)	VW <sub>O</sub>	μm	19	86	8	15	94	16	1.72	0.10

Estimates of heritability ( $h^2$ ) were obtained for each trait using variance components from univariate single-site analysis. Standard errors were estimated by using the Taylor series expansion method [48]. The individual-tree narrow-sense heritability for each trait was estimated by:

$$\hat{h}^2 = \frac{\hat{\sigma}_A^2}{\hat{\sigma}_P^2} = \frac{4 \times \hat{\sigma}_f^2}{\hat{\sigma}_f^2 + \hat{\sigma}_\varepsilon^2}, \quad (2)$$

where  $\hat{\sigma}_A^2$  is an additive genetic variance,  $\hat{\sigma}_P^2$  is a phenotypic variance,  $\hat{\sigma}_f^2$  is a family variance, and  $\hat{\sigma}_\varepsilon^2$  is a total error variance. Each trait's genotypic coefficient of variation (GCV) and phenotypic coefficient of variation (PCV) were calculated using the following formulas:

$$CV = \frac{\sqrt{\sigma_G^2}}{\bar{x}} \times 100 \quad (3)$$

$$PCV = \frac{\sqrt{\sigma_P^2}}{\bar{x}} \times 10, \quad (4)$$

where  $\bar{x}$  is a trait's mean value,  $\hat{\sigma}_G^2$  is the genotypic variance, and  $\hat{\sigma}_P^2$  is phenotypic variance (as above). Phenotypic correlations ( $r_P$ ) and genotypic correlations ( $r_G$ ) between traits were calculated as:

$$r_{(xy)} = \frac{\hat{\sigma}_{(xy)}}{\sqrt{\hat{\sigma}_{(x)}^2 \times \hat{\sigma}_{(y)}^2}}, \quad (5)$$

where  $\hat{\sigma}_{(x)}^2$  and  $\hat{\sigma}_{(y)}^2$  are the estimated genetic variances for traits  $x$  and  $y$ , respectively, and  $\hat{\sigma}_{(xy)}$  is the estimated genetic covariance between traits  $x$  and  $y$ .

Scatterplots—with trend lines and correlation values (R v.4.2.2)—and boxplots were produced in R (R Core Team, Vienna, Austria, 2019 [49]).

### 3. Results

Silver birch height at age 5 (447 cm) was greater than that of the improved downy birch (358 cm) (Table 1). Improved downy birch diameters at age 10 (50 mm) and 15 (73 mm) were lower than for silver birch (79 mm and 110 mm). Fissured bark height was nearly four times higher for silver birch (70 cm) than for improved downy birch (17 cm). Grain angle was larger for silver birch (−2.0°) than for downy birch (−1.7°). All these differences were statistically significant according to Walsh's *t*-test at an alpha value (significance level) of 0.05.

Silver birch had slightly higher values for acoustic velocity (3892 m s<sup>−1</sup>), Pilodyn penetration (17.4 mm), and wood density (408 kg m<sup>−3</sup>) than downy birch (3873 m s<sup>−1</sup>, 17.8 mm, and 399 kg m<sup>−3</sup>); however, these differences were non-significant based on *t*-test statistics. The average outermost cell measurements for improved downy birch (987 μm

for fiber length, 729  $\mu\text{m}$  for vessel length and 86  $\mu\text{m}$  for vessel width) were not significantly different to those for silver birch (994  $\mu\text{m}$ , 706  $\mu\text{m}$  and 94  $\mu\text{m}$ , respectively) based on *t*-test results.

The following genetic analysis is only for the downy birch material. Narrow-sense heritability ( $h^2$ ) was 0.262 for height at age 5 and 0.212 for diameter at age 10 (Table 2). Heritability for quality traits was similar to that of growth traits except Pilodyn penetration (0.599) and acoustic velocity (0.328).

**Table 2.** Downy birch variables and units with summary statistics and breeding values.

Trait *	Unit	Mean	CVP (%) **	Min	Max	$h^2$	SE *** of $h^2$	CVG (%) ****
H <sub>5</sub>	cm	358	32	1	62	0.262	0.091	13.6
DBH <sub>10</sub>	mm	50	41	1	110	0.212	0.079	8.0
DBH <sub>15</sub>	mm	73	36	4	143	0.310	0.113	8.7
BAng	class	4.1	24	2	8	0.178	0.092	3.7
BThk	class	5.1	15	2	8	0.178	0.092	2.9
BFrq	class	4.6	22	2	8	0.201	0.093	4.3
FBH	cm	14	84	2	90	0.318	0.118	22.7
STR	class	4.1	31	1	8	0.290	0.107	7.3
Pilo	mm	17.8	11	13	23.5	0.599	0.165	3.3
GA	°	1.95	71	2.75	−10.7	0.197	0.096	18.0
AV	(m s <sup>−1</sup> )	3873	5.8	2907	6944	0.328	0.153	1.5

\* H<sub>5</sub> = height at age 5, DBH<sub>10 or 15</sub> = diameter at age 10 or 15, BAng = branch angle, BThk = branch thickness, BFrq = branch frequency, FBH = fissured bark height, STR = straightness, Pilo = Pilodyn penetration, GA = grain angle, AV = acoustic velocity. \*\* CVP = Phenotypic Coefficient of Variation. \*\*\* SE = Standard Error. \*\*\*\* CVG = Genetic Coefficient of Variation.

Phenotypic correlations between growth traits were stronger than for quality traits. Phenotypic correlations between growth and quality traits were moderate, except for growth traits and straightness, which were between 0.60 and 0.69. Pilodyn penetration had phenotypic correlations between 0.27 and 0.45 with size traits, 0.19 with fissured bark height, and 0.25 with straightness. There was a strong correlation between Pilodyn penetration and wood density (−0.64) and between acoustic velocity and fiber length (0.59, Table 3).

Genotypic correlation between height at age 5 and diameter (DBH) at age 10 was 0.79. The genotypic correlations were low between growth and quality traits—except straightness and Pilodyn penetration—and the correlations were stronger for diameters. Grain angle was moderately genotypically correlated with diameter at age 10 and 15.

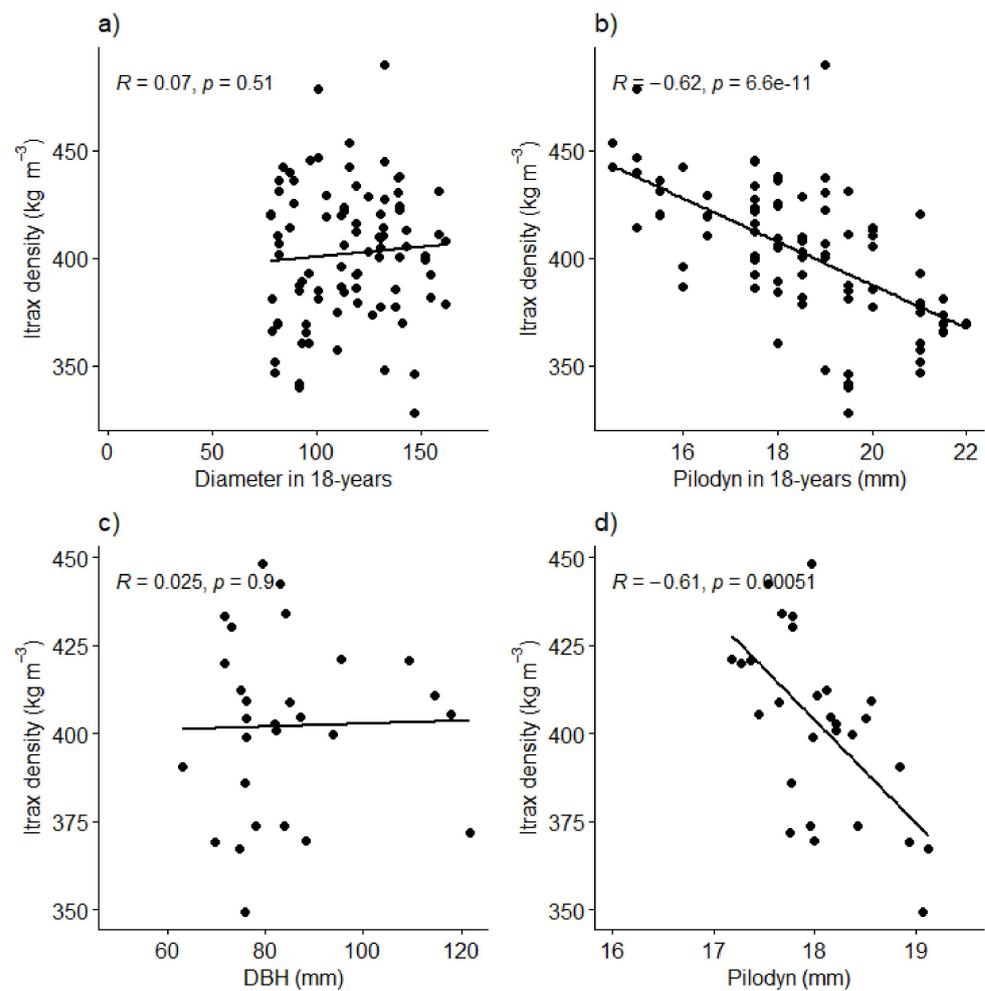
No correlation was found between Itrax wood density and diameter at age 15 both for individual genotypes (Figure 3a) and for full-sib families (Figure 3c). There was a significant negative phenotypic correlation ( $\alpha = 0.05$ ) between Itrax wood density and Pilodyn penetration for both individual genotypes and families (Figure 3b,d). The correlation coefficient was about −0.6 in both instances.

Fiber length was positively correlated with vessel length ( $R > 0.6$ ) and vessel width (above 0.2), which were additionally correlated with each other ( $R > 0.2$ ) despite varying by radial position (inner/outer) and species (Table 4). Acoustic velocity and outer average fiber length were positively correlated ( $R = 0.56$  and  $0.69$ ) for downy birch and silver birch, respectively. For the average inner fiber lengths, the correlation with acoustic velocity was lower ( $R = 0.53$  and  $0.43$  respectively). Similar correlations with acoustic velocity existed for average vessel length and width but were inconsistent between inner and outer values. Vessel measurements were somewhat correlated with Pilodyn penetration, although this varied by species and position.

**Table 3.** Genotypic correlations (lower triangle) and phenotypic correlations (upper triangle) between measured variables for downy birch \*.

Traits **	H <sub>5</sub>	DBH <sub>10</sub>	DBH <sub>15</sub>	Bang	BThk	BFrq	FBH	STR	Pilo	GA	AV	DENS <sub>Itrax</sub>	FL <sub>O</sub>
H <sub>5</sub>	1	0.86	0.79	0.26	0.22	0.42	0.34	0.60	0.27	0.11	0.21	0.15	0.32
DBH <sub>10</sub>	<b>0.79</b>	1	0.96	0.26	0.10	0.33	0.45	0.67	0.45	0.12	0.07	0.01	0.15
DBH <sub>15</sub>	0.77	0.99	1	0.26	0.12	0.32	0.49	0.69	0.39	0.12	0.12	0.07	0.12
Bang	<b>0.61</b>	<b>0.59</b>	<b>0.58</b>	1	0.34	0.35	0.08	0.20	0.13	0.09	0.25	0.04	0.17
BThk	<b>0.68</b>	<b>0.25</b>	<b>0.08</b>	<b>0.29</b>	1	0.38	0.02	0.23	−0.05	0.08	0.33	0.07	0.29
BFrq	0.26	−0.11	−0.06	<b>0.25</b>	<b>0.68</b>	1	0.06	0.36	0.04	0.11	0.41	0.07	0.03
FBH	<b>0.12</b>	<b>0.23</b>	<b>0.32</b>	<b>0.09</b>	−0.15	−0.17	1	0.25	0.19	0.12	−0.04	0.26	0.10
STR	0.30	0.58	<b>0.51</b>	<b>0.33</b>	<b>0.09</b>	−0.02	−0.31	1	0.25	0.12	0.28	−0.13	0.12
Pilo	<b>0.35</b>	<b>0.51</b>	<b>0.45</b>	<b>0.38</b>	−0.29	−0.20	<b>0.30</b>	<b>0.28</b>	1	0	−0.18	−0.64	−0.05
GA	<b>0.15</b>	<b>0.33</b>	<b>0.50</b>	<b>0.32</b>	−0.13	−0.12	−0.11	−0.22	−0.11	1	0.25	0.20	−0.12
AV	−0.25	NC	NC	−0.17	−0.14	−0.29	NC	NC	−0.82	0.35	1	0.11	0.59

\* Numbers in bold are from multivariate models, otherwise from bivariate models, NC = model did not converge. \*\* H<sub>5</sub> = height at age 5, DBH<sub>10or15</sub> diameter at age 10 or 15, Bang = branch angle, BThk = branch thickness, BFrq = branch frequency, FBH = fissured bark height, STR = straightness, Pilo = Pilodyn penetration, GA = grain angle, AV acoustic velocity.



**Figure 3.** Relationship of individual tree wood density (Itrax density) against diameter at age 15 (a) and Pilodyn penetration depth (b). Relationship of average family wood density and average family diameter (c), and average family Pilodyn penetration depth (d). Solid line is linear relationship between traits, R value is correlation coefficient and *p*-value a significance for the relationships.

**Table 4.** Correlation between anatomical and quality traits measured with different NDT tools for downy birch (upper triangle) and silver birch (lower triangle).

Trait *	FL <sub>I</sub>	VL <sub>I</sub>	VW <sub>I</sub>	FL <sub>O</sub>	VL <sub>O</sub>	VW <sub>O</sub>	DBH <sub>15</sub>	GA	AV	Pilo
FL <sub>I</sub>	1	0.91	0.44	0.61	0.52	0.27	0.18	−0.09	0.53	0.24
VL <sub>I</sub>	0.61	1	0.52	0.72	0.66	0.33	0.34	−0.01	0.54	0.23
VW <sub>I</sub>	0.21	0.35	1	0.43	0.43	0.43	0.40	0.19	0.48	0.24
FL <sub>O</sub>	0.63	0.68	0.60	1	0.72	0.26	0.12	0.04	0.56	0.15
VL <sub>O</sub>	0.51	0.64	0.45	0.85	1	0.20	0.17	−0.01	0.44	0.53
VW <sub>O</sub>	0.04	0.25	0.05	0.39	0.35	1	0.32	0.16	0.40	0.30
DBH <sub>15</sub>	−0.19	0.32	0.32	0.16	0.08	0.13	1	0.48	0.25	0.23
GA	−0.14	0.08	0.21	−0.09	−0.12	−0.19	0.59	1	0.66	−0.08
AV	0.43	0.56	0.34	0.69	0.64	0.45	0.38	−0.12	1	−0.05
Pilo	0.00	0.32	0.41	0.06	0.13	−0.03	0.20	0.30	−0.15	1

\* FL<sub>I</sub> = fiber length inner, VL<sub>I</sub> = vessel element length inner, VW<sub>I</sub> = vessel element width inner, FL<sub>O</sub> = fiber length outer, VL<sub>O</sub> = vessel element length outer, VW<sub>O</sub> = vessel element width outer, DBH<sub>15</sub> = diameter at age 15, GA = grain angle, AV = acoustic velocity, Pilo = Pilodyn penetration.

There were significant differences between near the pith and outer measurements ( $p < 0.05$ ). The differences between species were mostly insignificant (Table 1). Fiber length had similar mean values for downy and silver birch for both inner and outer wood, and

the values increased between the two positions (Figure 4). In both species, average vessel length increased slightly in the outer samples. Vessel width for both species had minor changes from inner to outer sampling position. For each species, the differences between inner and outer measurements were significant based on the results from paired *t*-tests, yet the difference between species by position was inconsistently significant and the ranges of values overlap (Figure 4).



**Figure 4.** Boxplots showing average (midline), quartiles (box), range (vertical lines), and outliers (points) for fiber length, vessel element length or vessel element width for inner and outer measurements, for silver birch (grey) and downy birch (black).

#### 4. Discussion

In our study, the breast height diameter (DBH) of downy birch was 33% lower than that of silver birch at age 15. The fertile site with good drainage conditions was more favorable for silver birch. A Finnish study across a range of sites had similar results, with downy birch only achieving 60 or 80% of silver birch's volume growth at the same site [22]. However, there may be no volume growth difference at moist sites with high peat content [21], where silver birch seems to perform worse, and so our results are valid only for sites with conditions similar to those of the test site. Moist or infertile sites could be planted with downy birch since it is possible that volume will be as high as it is for silver birch, grain angle would be straighter, rough bark would be less, or other species differences may be better exploited. At present, size is the main determinant of log value, and it may be that segregating stands by likely wood properties is of limited interest to birch wood processors.

Downy birch had similar mean wood density (related to most other wood properties), Pilodyn penetration depth (related to wood density and hardness), and acoustic velocity (related to stiffness) to silver birch at this site. Grain angle was closer to 0° for downy birch than silver birch, where grain angle values closer to 0° are considered better quality wood. The species differences in this study are in agreement with other species comparisons, where silver birch has higher wood density, hardness [15], stiffness, and strength [17], than downy birch. Based purely on volume growth, silver birch tends to outcompete downy birch [15], and that was also true at this site.

Heritabilities for height and diameters were 0.2–0.3 (genetic coefficients of variation were above 8%) suggesting it is possible to improve downy birch volume through breeding. Similar heritabilities were observed for straightness, fissured bark height, and grain angle. Straightness has been commonly used as selection criteria in many breeding programs and leads to an improvement of overall quality of stems. Grain angle measurement was quick, and this trait could potentially be improved by breeding. Pilodyn penetration and acoustic

velocity had moderate heritability estimates and low variation, making these traits less suitable for selection criteria in a breeding program. Still, Pilodyn penetration could likely be used as assessment criteria due to quick measurement time and high heritability. Due to low genetic variability of the Pilodyn measurement, genetic gains may be lower and more difficult to obtain than for other traits. Including a measure of hardness or density could help to avoid inadvertently reducing wood density. Earlier studies on silver birch families [25] or clones [24] also observed an unfavorable genotypic correlation with stem diameter (for hardness [25] or density [24], respectively). Further studies are needed to ensure there are no genotype-by-environment interactions [50], as the results are only for a single site and population.

Moderate genotypic correlations between diameter and Pilodyn penetration (0.4–0.5) suggest that, as observed for coniferous species [9,51], selection for diameter may inadvertently reduce wood density. For silver birch, this decrease in wood density was considered insignificant [24], yet for solid wood products, higher wood density may be desirable. Finnish researchers have also observed a correlation between hardness and density for birch [15], so it is reasonable to assume that Pilodyn penetration reflects wood density in this study. An extremely low correlation between Itrax wood density and breast height diameter at age 15, and no clear linear trend between the two variables, may partially be explained by trees with a diameter below 70 mm being excluded from the coring subsample. Here, diameter should reflect growth rate as all trees are the same age, yet there was no phenotypic correlation between average Itrax wood density and diameter.

Fiber length, vessel length, and vessel width increased from inner to outer sampling positions. Correlations between cell measurements were highest for vessel length and fiber length, followed by cell measurements and acoustic velocity. Other researchers have similarly found a relationship between fiber length and acoustic velocity [29,52,53]; in this paper, the correlations were higher for outer fiber length. The results indicate that the difference between innerwood and outerwood cell dimensions could be minor or non-existent; this trend has also been observed by other authors [18,54–56]. The range of fiber lengths, vessel lengths, and vessel widths was similar to those observed by Fabisiak and Helińska-Raczkowska [55] who had a smaller sample size than in our study. Some of the differences between studies could also be attributed to using average values for each stem to calculate their average ( $n = 3$ ); they also did not sample every ring when averaging, further reducing their variation. Stener and Hedenberg [24] sampled 30 clones of 10-year-old silver birch and had an average fiber length on 0.87 mm, which is close to the inner wood mean values in our study. Bhat and Kärkkäinen [13] also found similar mean vessel diameters, 70  $\mu\text{m}$  and 74  $\mu\text{m}$  for silver and downy birch, respectively.

The differences between downy and silver birch in this study are likely due to inherent differences between species, as site conditions and establishment were fairly homogenous for all stems. This is unique, since many studies comparing the two species use unmanaged material, and often make comparisons across sites. It may be that a greater historic emphasis on improving silver birch [57] resulted in superior performance compared to downy birch, yet this is for a single site so could vary under different site conditions. The observed differences may otherwise be due to silver birch already having worse grain angle, higher wood density, and faster growth than downy birch in natural populations for given growing conditions. The advantage for continuing to breed downy birch is to maintain high levels of genetic diversity, which is important for breeders, and for deployment to a wider range of site conditions [58,59]. Site conditions affect not only birch form and wood [19,20,23] but also survival rates [60]. Therefore, testing across sites is essential to identify any genotype by environment interactions. Downy birch has been observed to perform similarly to silver birch at poorer sites, and a broad range of growing conditions should be tested to see if downy birch has an advantage at wet low nutrient sites.

## 5. Conclusions

Silver birch was generally thicker in diameter, had greater modulus of elasticity (MOE), and greater wood density than downy birch, which is in agreement with other studies. It is possible that downy birch's grain angle and Pilodyn penetration (wood density) could be improved through breeding. It is unlikely that acoustic velocity (stiffness) can be easily included as an assessment criteria in a downy birch breeding program. For silver and downy birch, fiber length and vessel length increased between inner and outer measurement positions, and fiber length was reasonably correlated with acoustic velocity.

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