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ORIGINAL PAPER

Relating estimates of wood properties of birch to stem form, age and species

Grace Jones[1] · **Maria Ulan**[2] · **Mateusz Liziniewicz**[3] · **Johan Lindeberg**[4] · **Stergios Adamopoulos**[5]

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Abstract Birch has long suffered from a lack of active forest management, leading many researchers to use material without a detailed management history. Data collected from three birch (*Betula pendula* Roth, *B. pubescens* Ehrh.) sites in southern Sweden were analyzed using regression analysis to detect any trends or differences in wood properties that could be explained by stand history, tree age and stem form. All sites were genetics trials established in the same way. Estimates of acoustic velocity (*AV*) from non-destructive testing (NDT) and predicted *AV* had a higher correlation if data was pooled across sites and other stem form factors were considered. A subsample of stems had radial profiles of X-ray wood density and ring width by year created, and wood density was related to ring number from the pith and ring width. It seemed likely that wood density was negatively related to ring width for both birch species. Linear models had slight improvements if site and species were included, but only the youngest site with trees at age 15 had both birch species. This paper indicated that NDT values need to be considered separately, and any predictive models will likely be improved if they are specific to the site and birch species measured.

Keywords Acoustic velocity · Non-destructive testing · Predictive models · Regression analysis · Wood density

Introduction

Birch (*Betula* spp.) is a genus of angiosperms distributed throughout the northern hemisphere. Arguably, the two most important hardwood species in Swedish forests are silver birch (*B. pendula* Roth) and downy birch (*B. pubescens* Erh.). Birch accounts for over 12% of Sweden's forest volume (SLU 2019), yet it is mostly naturally regenerated material in stands managed for conifers (Götmark et al. 2005) and is perceived as low quality, so may be removed during thinning operations when the birch is still young. The use of Swedish birch for further domestic processing could be increased if more information about wood properties is available (Dubois et al. 2020).

It is desirable to have high-value logs even at the first thinning, meaning they are either larger in size, which reduces costs (Di Fulvio et al. 2011) and increases value (Valkonen and Valsta 2001), or suitable for higher value solid or engineered wood products (Heräjärvi 2004a). Birch at early thinning could also replace some of the currently imported birch, provided it is of sufficient size and quality

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✉ Stergios Adamopoulos
stergios.adamopoulos@slu.se

[1] Teagasc Forestry Development Department, Ashtown Research Centre, Dublin 15 D15DY05, Ireland

[2] Research Institutes of Sweden (RISE), Göteborg, Sweden

[3] The Forest Research Institute of Sweden (Skogforsk), Ekebo 2250, 268 90 Svalöv, Sweden

[4] Department of Forestry and Wood Technology, Linnaeus University, 351 95 Växjö, Sweden

[5] Department of Forest Biomaterials and Technology, Swedish University of Agricultural Sciences, Box 7008, 750 07 Uppsala, Sweden

for sawmills (Woxblom and Nylinder 2010). However, limited information is available regarding wood properties of young birch stems. In a Latvian study (Gailis et al. 2020), the superior genetic material had better financial performance at first thinnings than unimproved material, and improved birch usually grows faster than natural material (Liziniewicz et al. 2022). Faster birch growth rate has also been related to lower density and strength (Dunham et al. 1999), yet few birch studies have combined stem size, form, and wood properties to test if this improved material is suitable for wood products.

Silver birch and downy birch are diffuse-porous hardwood species, and as such, have fairly uniform wood with vessels distributed throughout each annual growth ring (Schweingruber 2016). Due to fairly uniform wood with a narrow portion of latewood in each ring (Luostarinen and Möttönen 2010), it is difficult to distinguish birch ring boundaries (Levanič and Eggertsson 2008; Vanhellemont et al. 2016; Harr et al. 2020). Some studies have observed a negative correlation between ring width and wood density in unimproved (Liepiòð and Rieksts-Riekstiòð 2013) and naturally regenerated material (Bhat 1980; Dunham et al. 1999). Wood density can be important for wood products (Heräjärvi 2004a) as well as pulp and fibre production (Stener and Hedenberg 2003). Silver and downy birch are nearly indistinguishable based on tree form (Atkinson 1992) or wood anatomy (Bhat and Kärkkäinen 1980), so are often treated as a single species for inventory, harvesting, and processing. On most sites, silver birch has faster volume growth (Viherä-Aarnio and Velling 1999) and denser wood (Heräjärvi 2004b) than downy birch, meaning that if downy birch is the same diameter as silver birch it will likely be less dense. This limitation would affect studies that use a birch mixture (Llana et al. 2020), where variability could increase due to including two species, potentially obscuring relationships between size and wood properties.

Non-destructive testing (NDT) of standing tress can allow for faster estimations of wood mechanical properties, such as stiffness, by measuring acoustic velocity (*AV*) with time-of-flight (*ToF*) or resonance devices (Huang et al. 2003). Stiffness also depends on wood density, which can also be measured quickly with NDT tools (Gao et al. 2017). There are numerous examples of relationships existing between stem form traits and NDT values. *AV* measurements can be affected by measurement location within the stem (Wang 2013; Legg and Bradley 2016), grain angle variation due to branches or otherwise (Karsulovic et al. 2000), branch size variables and number (Jones and Emms 2010), or the presence of knots (Palma et al. 2018). Similarly, relationships have been observed between crown metrics and stiffness (Amarasekara and Denne 2002; Kuprevicius et al. 2013), suggesting that more complicated phenotypic relationships could exist between the measured variables.

Stem form and wood mechanical properties generally vary by site, stand, age and species (Heräjärvi 2001; Poorter et al. 2012). Previous studies of wood density variation from pith to bark have been for fewer than 20 birch trees at a given site (Johansson et al. 2013; Lundqvist et al. 2013), and for one study only 5 logs were measured (Dobrowolska et al. 2020). Another study on hardwood species, which included 5 birch stems, found diameter to be an important factor for predicting bending strength from *AV*, but did not separate silver and downy birch (Llana et al. 2020). This study provided an opportunity to test potential relationships between wood traits and stem form at three sites with young birch trees, where the sample size was large, i.e. greater than 50 trees per site. It was also of interest to know if these relationships were consistent between sites, species and age.

Materials and methods

Data collection

Material was collected from two sites planted with the same 22 full-sib silver birch families at age 19. A third site planted with progenies from selected downy birch and silver birch plus-trees was collected at age 15. All sites are located in southern Sweden with the experimental design and genetic analysis outlined elsewhere (Jones et al. 2021, 2023). Here, the emphasis was on modelling relationships between NDT measurements, and stem form and wood density variables (Table 1) as the genetic analyses found small and insignificant phenotypic correlations between traits.

Silver birch sites were initially measured in May 2018, with stem diameter at a height of 1.3 m from the stem base (*DBH*) measured in the north–south direction with calipers. Fissured bark height was measured with a tape measure to the point where smooth bark dominates, and straightness was scored on a scale of 1–9 where 9 is the best quality and 5 is approximately average. The 1–9 scale was also used to score branch frequency (*BrFreq*), branch angle (*BrAng*) and branch diameter (*BrThick*) for the lowest 8 m stem section. If no branches were visible below 8 m, stems were recorded as branchless or pruned (y/n), and branch quality above 8 m was scored in the next part. Summing the three branch criteria (*BrFreq*, *BrAng*, *BrThick*) gave a single branch score (*BrScore*), where stems without branches below 8 m were given a score of 12 for BrFreq. This resulted in a *BrScore* variable with a maximum possible value of 30.

In September 2018, the NDT tools were used at the two full-sib silver birch sites, and in October at the third site. Measurements and samples were shifted slightly up or down to avoid defects, and repeated if any issues occurred. A Fakopp TreeSonic Timer (FAKOPP Enterprise, Agfalva, Hungary) was applied between 0.8 and 1.8 m on the southern

Table 1 Summary of measurements, codes, units, and details

Measurement type	Code	Units	Details
Unique tree code	*TreeID*	name	Each tree's specific site, experiment, and position
Diameter	*DBH*	mm	Diameter at 1.3 m height
Fissured bark height	*FBH*	cm	Height where smooth bark dominates
Straightness	*Str*	1–9	Visually scored
Pruned	*Prun*	y/n	If there are no branches below 8 m
Branches: angle, frequency, thickness	*BrAng*, *BrFreq*, *BrThick*	1–9	Visually scored where 9 is best
Overall branch score	*BrScore*	3–30	Summed branch angle, frequency and thickness 12 for frequency if pruned = y
Pilodyn values	*PilSth* & *PilNth*	mm	Depth of Pilodyn penetration on south (Sth) or north (Nth) stem face
Pilodyn density	$DENS_{Pilo}$	kg m^{-3}	Pilodyn penetration depth inverted
Time-of-Flight	*ToF*	µm m^{-1}	TreeSonic reading for 0.8–1.8 m south stem face
Acoustic velocity	*AV*	m s^{-1}	ToF (µs to travel 1 m) inverted
Grain angle	*GA*	Degrees (°)	North and south grain angle averaged
Absolute grain angle	*GAD*	Degrees (°)	GA converted to an absolute value
Itrax ring width	*RW*	mm/100	From Itrax and LIGNOVISION™ radial profiles
Basal area increment	*BAI*	cm^2	Calculated for each year from Itrax ring widths
Itrax ring density	$DENS_{Itrax}$	kg m^{-3}	From Itrax and LIGNOVISION™ radial profiles
Ring number	*NR*	years	Age of ring = ring number from pith

stem face to get a time-of-flight (ToF) value for each stem. The Pilodyn 6J Forest (PROCEQ, Zurich, Switzerland) densitometer and a wedge grain angle gauge were applied to the north and south stem faces at 1.3 m. Two Pilodyn penetration values were taken per stem face (*PilSth* and *PilNth*), and the average of north and south grain angle readings was used as the average stem grain angle (*GA*). These NDT tools were applied to either a sample of stems with *DBH* above 60 mm, or all stems at the third site with a *DBH* above 70 mm.

A subsample of 5 mm diameter cores was taken to measure radial wood density ($DENS_{Itrax}$) profiles. Trees were random subsample of stems with NDT values. The borer was applied parallel to the stem on the south stem face at 1.3 m to collect 58 cores from Hyssna, 72 cores from Brunsberg, and 30 silver birch and 30 downy birch stems from Nybro. These cores were then air dried and glued to wooden pine boards and sawn across the fibres to a thickness of 2 mm. The X-ray principle underlying the Itrax scanning X-ray densitometer (Cox Analytical Systems, Mölndal, Sweden) scanning of wood is described elsewhere (Bergsten et al. 2001; Jacquin et al. 2017). Cores were mounted into a metal frame 8 h before scanning to condition to the relative humidity (RH) of the Itrax chamber. Temperature and RH were recorded at the start and end of each Itrax batch run. A sample of known thickness and material density was scanned during each batch run to calibrate the light intensity (LI) values. All Itrax images were processed to have noise removed. The computer programme LIGNOVISION™ (Rinntech, Heidelberg, Germany) was used to get an average LI value for a user defined ring. The sampling window width was constant (set to 0.5 mm) so that the length of a line drawn from one ring boundary to the next was recorded, alongside the average LI for this sampling window. Actual sample thickness (mm) was measured with digital calipers to 3 dp and used for conversion of LI values into density (kg m^{-3}), alongside operating RH, temperature, sample thickness, and batch-specific scaled LI values from the calibration sample. This produced radial profiles for ring width (*RW*) and wood density ($DENS_{Itrax}$).

Equations for conversions

For grain angle (*GA*), an absolute value was used to express the deviation in angle from 0° without the positive or negative symbol (GAD). The following formula given in Chen et al. (2015), was used for converting Pilodyn values to approximate wood density ($DENS_{Pilo}$) in kg m^{-3}:

$$DENS_{Pilo} = \frac{1}{(PilSth + PliNth)/2} \times 10,000 \tag{1}$$

AV (m s^{-1}) was calculated using the *ToF* data to convert microseconds per metre (µs m^{-1}) to metre per second (m s^{-1}):

$$AV = \frac{Distance\ between\ probes\ (m)}{Fakopp\ (microseconds)} \times 10^6 \tag{2}$$

Basal area increment (*BAI*) was estimated by the formula:

$$BAI_t = \left(\pi \times r_t^2\right) - \left(\pi \times r_{t-1}^2\right) \tag{3}$$

where r for a given ring number, year or age (t) is the sum of all ring widths up to and including the year of interest for a given tree. The radiuses were converted to centimetres (cm), squared, multiplied by pi (π), and then the previous year's ($t-1$) value was subtracted, to give an individual tree's *BAI* in cm^2 for a given year (t). The average *BAI* values are plotted by year, species and site in the Appendix (Fig. S1).

Modelling wood properties

For each ring number, the mean *RW* and $DENS_{Itrax}$ were calculated with standard deviations by site and species. These were calculated from both north and south values (see Appendix, Tables S1 and S2). Pearson's correlations between years for $DENS_{Itrax}$ and for *RW* were calculated using a significance level of $\alpha = 0.05$ to test if the correlations were significant. Data were also pooled across sites and species as the results were similar regardless of cardinal direction, site, or species. The resulting correlations (see Appendix, Tables S3 and S4) indicated potential autocorrelation in any fitted models, similar to the results of Bouriaud et al. (2004).

Models were produced to make inferences about the relationships between measurements and to better understand the variables affecting $DENS_{Itrax}$ by age (ring number, *NR*). Mixed effects models were built in *R* generally of the same form as Eq. 4, where, *S* represents the factor of site or species:

$$DENS_{Itrax_{ij}} \sim RW_{ij} + Direction + Age_{ij} + S + (1|TreeID_i) \tag{4}$$

R summary values also provide correlations between model variables. Values in Eq. 4 are for a specified ring *j* of a given tree *i*, where the discrete model parameters affect the model intercept (*Direction*, *S* and *TreeID*) and slope (*Direction* and *S*). The end term in Eq. 4 is R notation to show that *TreeID* is a random effect. The random factor of year (or ring number within year) did not significantly improve the model, as it explained less than 10% of residual model variance. The year variable was included as a fixed effect and as an interaction term with ring number (Age). However, any variation explained by a year term was already explained by Age and site, so it was dropped from later models. Data subsets were also used to see if model form varied by site or species.

Similar models were built between measured variables in case relationships between NDT values were more complex than Pearson's correlations, which were generally below 0.3 in strength. Relationships were not greatly improved by including multiple variables. In general, additive models could be built to explain additional variation of the dependent variable, and so *AV* was selected as the dependent variable to illustrate the results of model building. Added variables usually accounted for additional variation in the dependent variable, yet no interactive effects were observed. Here, the final models included variables that had *p*-values below the significance level $\alpha = 0.01$, in an attempt to avoid over parameterisation. Variables were dropped if their *p* value was above 0.01 in an iterative process whereby the variable with the highest *p* value was dropped and the model statistics were recalculated until all remaining variables had *p*-values below 0.01. Interaction terms were tested, but generally had a higher *p* value than when included seperately. "Optimal models" were built in the same way using a subset of the data which included a single site, or a single site and species. These optimal models were then tested using other site subsets.

The final model parameters and form are tabulated in the results. Model fit was test using k-fold cross validation in the caret R-package with *k* set to 10. Three model types (linear regression, random forests, and neural network) had similar results, and so only simple linear models (lm) were used. Model metrics included: *R*-squared, root mean square error (RSME), and mean absolute error (MAE) with 10 resamples per iteration resulting in 100 values per model and metric. Maximum, minimum, median, first quartile (25%), and third quartile (75%) of the 100 values for each model type and metric were then plotted for the 5 numbered models for both *AV* and $DENS_{Itrax}$.

Results

Modelling NDT values

Most variables followed the normal distribution law, with the occasional outlier. Variables with skewed distributions included *FBH*, which was curtailed at 0 cm, and branch attributes, which were discrete variables (scored 1–9). Outliers were removed to determine if they had undue influence on the model fit. Hyssna and Nybro each had an identified outlier with an *AV* value above 5500 m s^{-1}, which were excluded after the first model was built. This decision was based on visual inspection of the residuals and it slightly improved correlations and *R* values (Table 2). *DBH* was correlated (above 0.5) with *FBH* at all sites and had *p*-values above 0.01 when *FBH* was included in a model. Compared to *GA*, using GAD slightly improved model fits, had lower *p*-values, and changed the estimated coefficients to be larger and positive. When all data were pooled across sites, Pearson's correlations and *R* values slightly increased. Any model using the total dataset was improved by adding a term for site; this was only done once to show that the site accounted for a large amount of variation in AV. $DENS_{Pilo}$ and *PilSth* were highly correlated, so *PilSth* was used for the below models as *AV* was measured on the southern stem face.

Table 2 Model fitting for AV as a function of NDT and stem form values with (a) correlations (top value) between fitted and actual values and multiple R-squared statistics (bottom value) for data subsets, and (b) model parameter estimates with significance values

(a) Correlation (fitted + real) multiple R-squared	19-year-old silver birch		15-year-old birches			All data
Model form/data subset	Hyssna	Brunsberg	Nybro	Silver	Downy	No outliers
$AV \sim FBH + DBH + PilSth + BrScore + GA + Str$ = Brunsberg optimal	0.39	0.55	0.51	0.48	0.55	0.58
	0.16	0.30	0.26	0.23	0.30	0.34
Hyssna (outlier included)						
Nybro (outlier included)	0.33		0.47		0.49	0.72
Total dataset (+ site term)	0.11	NA	0.22	NA	0.24	0.51
$AV \sim FBH + PilSth + BrScore + GA$ = Hyssna optimal	0.38	0.42	0.45	0.35	0.50	0.55
	0.15	0.18	0.20	0.12	0.25	0.31
$AV \sim PilSth + BrScore + GA + Str$ = Nybro optimal	0.34	0.51	0.50	0.39	0.54	0.57
	0.11	0.26	0.25	0.16	0.30	0.32
$AV \sim FBH$[a] $+ BrScore + Str$[b] = Best visual predictors	0.29	0.44	0.44	0.43	0.46	0.47
	0.08	0.19	0.19	0.18	0.21	0.22

(b) Model parameter estimates and significance levels with all data included

Model form	Intercept	FBH	DBH	PilSth	BrScore	GA	Str
(1) $AV \sim FBH + DBH + PilSth + BrScore + GA + Str$	4135.66*	− 0.69*	1.87*	− 43.34*	29.88*	28.97*	22.60*
(2) $AV \sim FBH + PilSth + BrScore + GA$	4246.21*	0.04	NA	− 38.25*	34.25*	27.32*	NA
(3) $AV \sim PilSth + BrScore + GA + Str$	4127.78*	NA	NA	− 39.40*	32.85*	27.33*	33.60*
(4) $AV \sim FBH + BrScore + Str$	3364.06*	− 0.19	NA	NA	35.44*	NA	30.34*
(5) $AV \sim DBH + BrScore + Str$	3344.68*	NA	$0.56^{\bullet}$	NA	33.72*	NA	26.15*

'Optimal' models: all variables are significant at $\alpha = 0.01$

[a] FBH was not a significant predictor for Nybro, but was a significant variable for Nybro Silver.

[b] Str was not a significant predictor for Hyssna at $\alpha = 0.01$.

Significant at: $^{\bullet}$0.1 and *0.01, all data was pooled with no model terms for age, site and species.

Radial profiles and modelling of Itrax wood density values

Profiles of values for ring density ($DENS_{Itrax}$) had higher initial variation, which became relatively stable in the outermost rings (Fig. 1). Ring width (RW) also had higher initial variation but continually declined as ring number increased for all sites and species. When ring averages were plotted with standard deviations, there were slight differences between Hyssna and Brunsberg means at the same cambial age with overlapping deviations (Fig. 1a, b). For both sites, $DENS_{Itrax}$ generally increased and RW decreased with increasing ring number from the pith. Mean $DENS_{Itrax}$ tended to be slightly higher at Brunsberg than Hyssna, while for RW the reverse was true. At Nybro, silver birch (Fig. 1c) and downy birch (Fig. 1d) performed similarly with overlapping standard deviations. Mean RW and $DENS_{Itrax}$ values and standard deviations are appended for Hyssna and Brunsberg.

Silver birch ring number (NR) and RW were highly correlated (above 0.5) when $DENS_{Itrax}$ was modelled as a function of RW, site, direction, and NR. This dataset included all silver birch across the three sites where site was a significant model factor (p-value below 0.01) for Nybro but not Hyssna (Table 3). For a subset of Nybro only, species replaced site and was insignificant as a model factor (p-value of 0.2), and cardinal direction was also insignificant. Tree code ($TreeID$) as a random effect accounted for over 40% of the unexplained variance. Site was replaced with a binary factor; site equal to Nybro as True or False (Site = Nybro), which otherwise explained the variance in 'year'.

Modelling with a subset to exclude extreme ring numbers ($NR > 19$) slightly improved significance values, but all values were included in model fitting since the overall trends were unaffected. An interaction term between RW and species was significant, but did not greatly improve model fit and had similar p-values to just RW. The estimated coefficient was lower for "RW: Species = Downy" (− 0.069) than for "RW" (− 0.079) and "RW: Species = Silver" (− 0.081). Basal area increment (BAI) was another significant model term but was excluded from the final model; it was highly correlated with RW and NR (0.6) and had lower p-values than either.

For the final model (Model 5), all data was included, site was a binary factor, and the only random effect was $TreeID$,

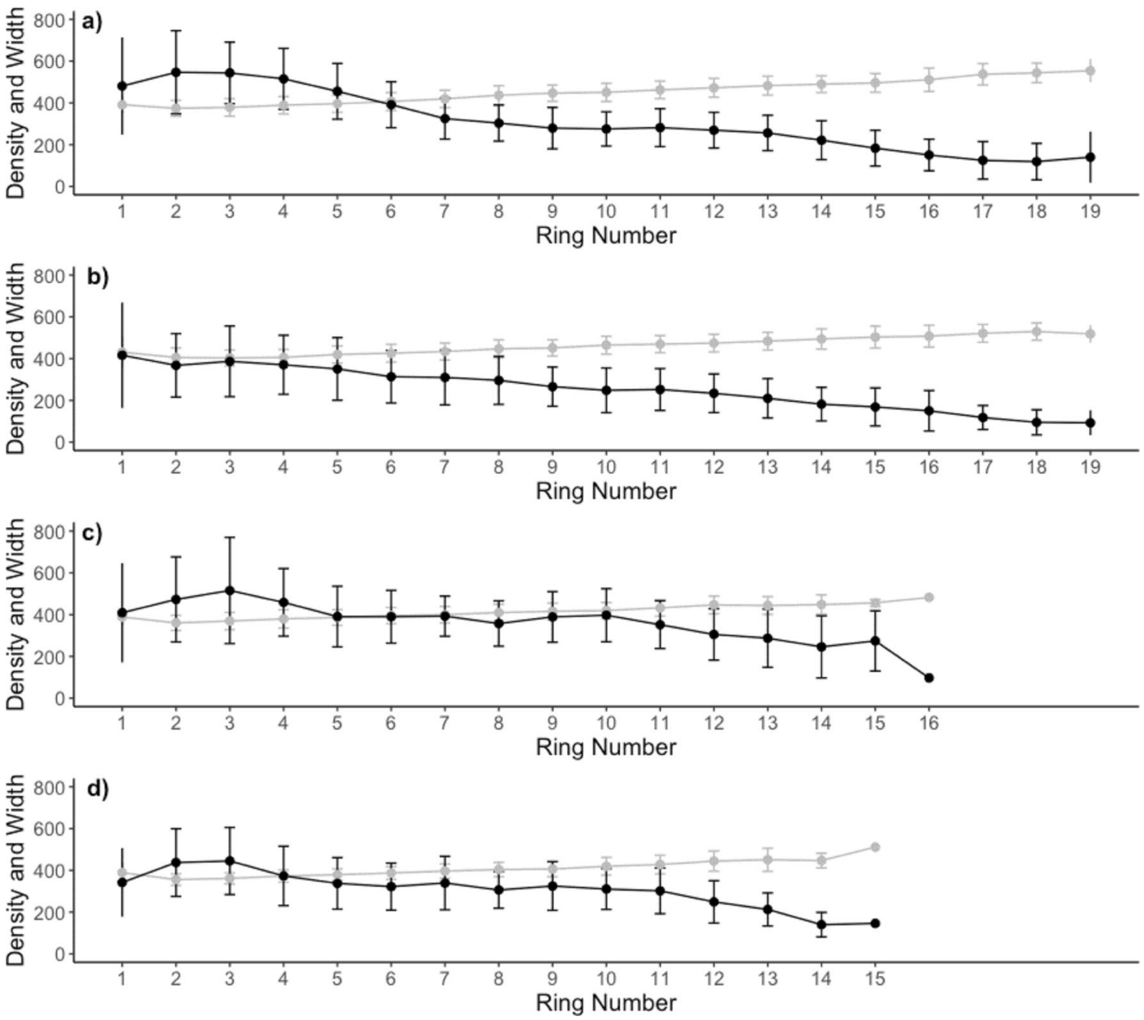

Fig. 1 Radial profiles of Itrax ring Density ($DENS_{Itrax}$, grey, kg m^{-3}) and ring width (*RW*, black, mm/100) for silver birch at Hyssna (**a**), Brunsberg (**b**) and Nybro (**c**), and downy birch at Nybro (**d**). Points are averages and bars are standard deviations

Table 3 Model fitting for Itrax ring density ($DENS_{Itrax}$) with model parameter estimates and their significance listed by model number. Remaining model variance is split into random effects of *TreeID* and residual variance

Model number	Model parameter estimates and significance (*)							Variance Random Effects (*TreeID*/ Residual)
	Intercept	*BAI*	*RW*	Direction (south)	*NR*	Site = Hyssna	Site = Nybro	
Model 1	418.30*	− 1.43*	0.61*	− 7.96*	7.28*	− 8.55•	− 34.26*	821/1013
Model 2	405.50*	− 1.49*	− 0.61*	− 7.99*	7.31*			1020/1013
Model 3	410.70*		− 0.80*	− 8.12*	6.50*			1027/1022
Model 4	424.20*		− 0.79*	− 8.09*	6.49*	− 9.90•	− 35.78*	812/1022
Model 5	420.00*		− 0.79*	− 8.09*	6.49*		− 31.43*	825/1022

Model form: $DENS_{Itrax} \sim BAI + RW +$ Direction $+ NR +$ Site + (1|TreeID).

Significance at •0.1 and *0.01

i.e. "Site-Experiment-Plot-Row-Position". The coefficient estimate for *RW* means that with all other variables constant, if a ring's width is 1000 (10 mm) then it's subsequent $DENS_{Itrax}$ estimate is approximately 50 kg m^{-3} lower than a 5 mm ring. Nybro had slightly lower $DENS_{Itrax}$ values overall, as evidenced by its negative parameter estimates and lower trend line (Fig. 2). Generally, later rings (pink-purple colours in Fig. 2) had values further along the trend-lines while the earlier rings (red-yellow colours in Fig. 2) were closest to the x-axis.

The tenfold cross validation values minimum R-squared values were much higher for models predicting density compared to *AV* (Fig. 3). The $DENS_{Itrax}$ models seemed to perform well since even the minimum R-squared values were above 0.3 and RMSE and MAE seemingly normally distributed. $DENS_{Itrax}$ had higher error relative to the mean values compared to *AV*, even when the number of model variables increased. The results of this show that mean error values were generally below 10% of the mean value (model intercept). The maximum RSME for *AV* was 4224.6 ± 68 m s^{-1} and for $DENS_{Itrax}$, and the maximum RMSE was 410.7 ± 51 kg m^{-3}.

Discussion

Managing birch stands for different wood product segments requires the development of models that relate site, species, and size characteristics to subsequent birch wood mechanical properties. Sampling strategies could be altered where stem form factors affect the variation or measurement of NDT values, e.g. to sample across diameter, straightness, or branch attribute classes. Such guidance is already available for NDT measurement in some coniferous (Toulmin and Raymond 2007; Wilhelmsson et al. 2002) and broadleaved species (Raymond and MacDonald 1998), but less so for birch where management history may be unknown. Models can also be applied in reverse, where related characteristics could be used as indicative of each other, and so fewer measurements are taken overall. Here, there is the opportunity to more efficiently capture information about birch wood properties in standing stems by identifying related properties and sources of variation. Later work could then test model prediction accuracy using the identified variables, and compare them between sites.

This investigation built models, which increased the amount of variation explained for *AV* values, but most of the variables considered had an additive effect and no significant interaction terms were observed. This means that although each additional model parameter improved the model fit, models with complex relationships did not reduce the number of variables needed. Furthermore, since significant predictor variables for *AV* (based on their model *p*-values) varied by site, it could be worth applying site-specific models in future studies. The best models predicting *AV* generally included *PilSth*, *Branches* and *GA*. Nybro was the only site with silver and downy birch, and ignoring the effect of species resulted in slightly lower correlations and model

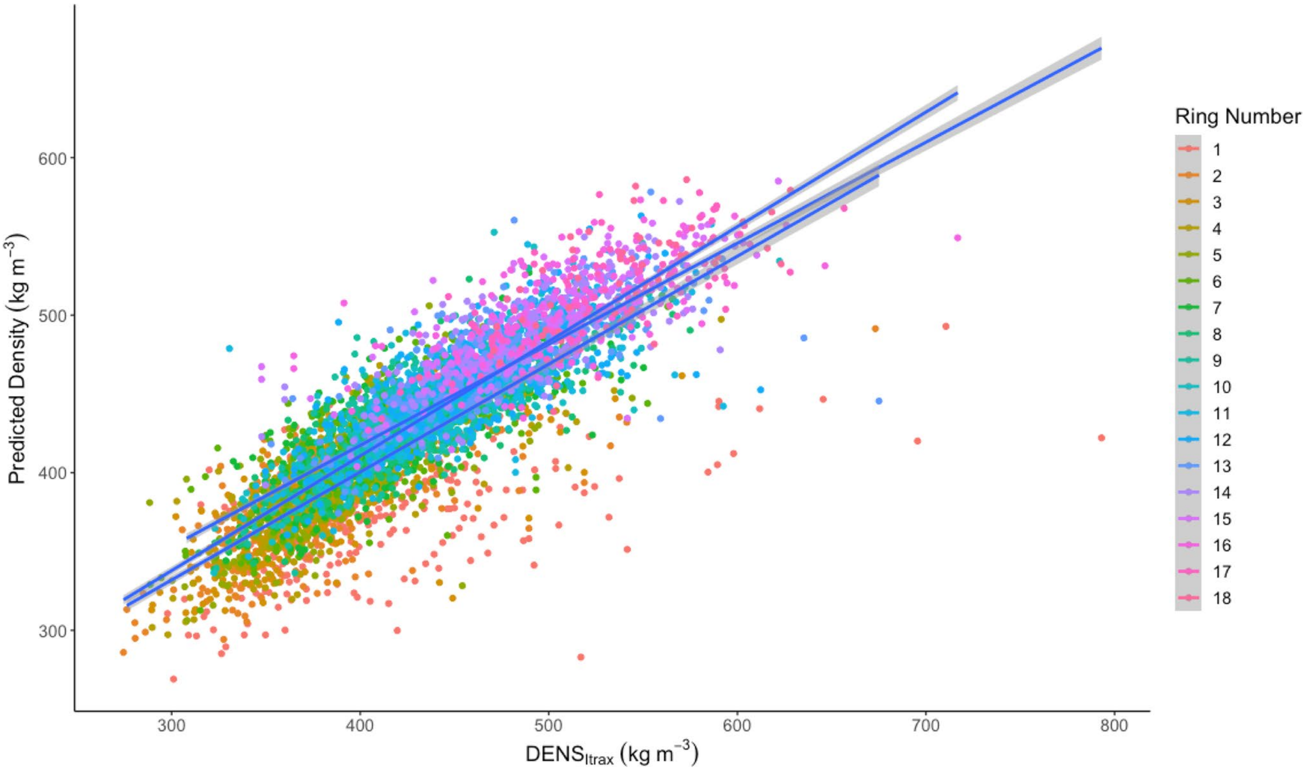

Fig. 2 Predicted ring density against actual Itrax ring density ($DENS_{Itrax}$) for ring numbers 1–18 only. Linear trend lines are for each site: Nybro (lowest), Hyssna (steepest) and Brunsberg (longest)

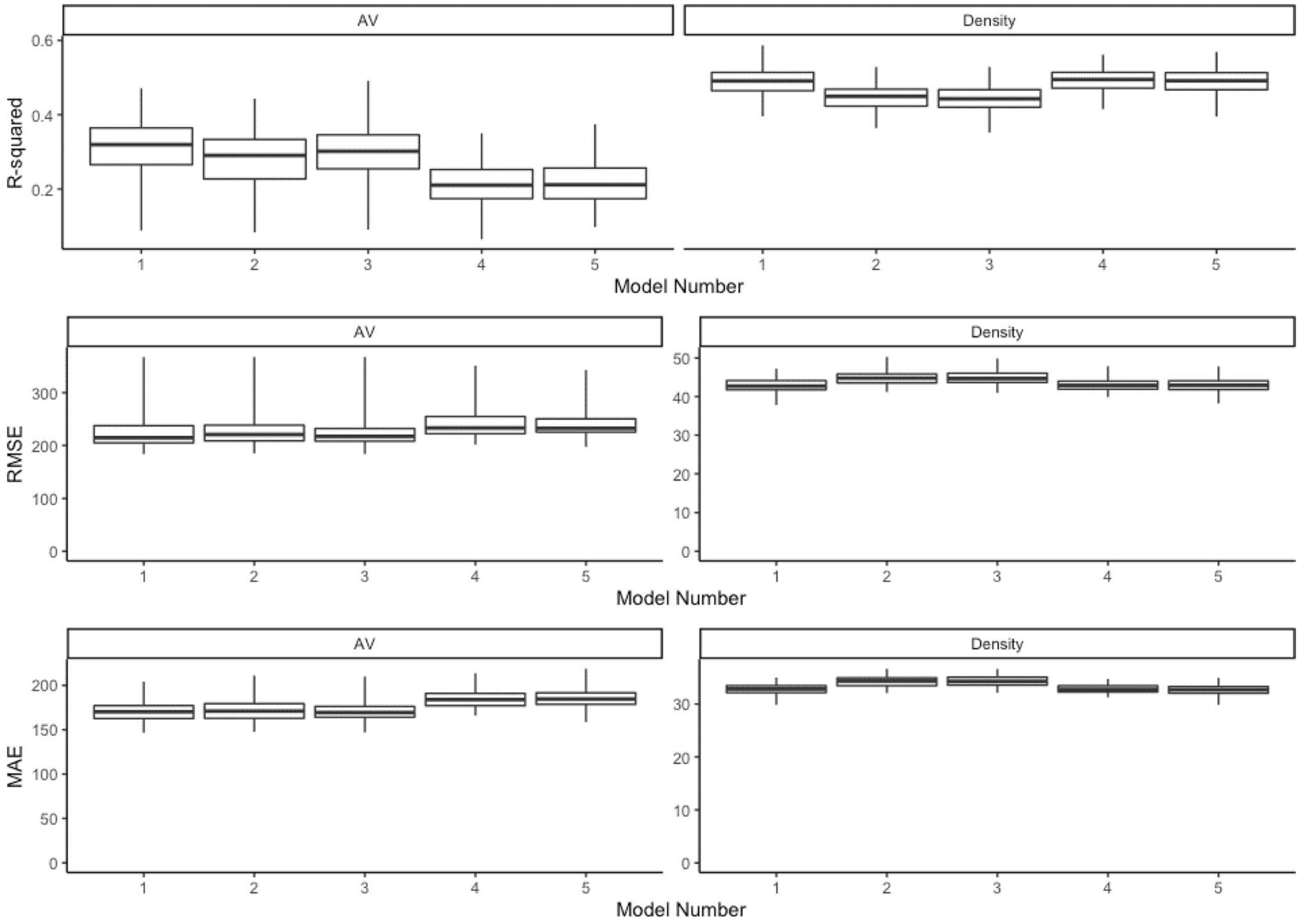

Fig. 3 Linear model outputs for each model using the total dataset for either *AV* or $DENS_{Itrax}$, model number 1–5 along the x-axis. Vertical lines represent the range of values, whereas horizontal lines are quartiles: 25%, 50% and 75% of values. Plots show R-squared, root mean square error (RSME), and mean absolute error (MAE)

R-squared values. Age was also difficult to account for since its effects were likely explained by the variable "site". This extra information only slightly improved the model and is often not available for studies of birch. A Finnish study by Heräjärvi (2004a) found only a minor relationship between birch bending strength and density, so it may be that density is not as large a determinant of strength for birch as for other species (Niklas and Spatz 2010). Numerous traits should be included for further work predicting birch *AV* as no single variable was consistently highly correlated, and the variables were independent of each other.

When considering variables which can be visually assessed for silver birch, *FBH* consistently had negative parameter estimates and significant *p*-values for predicting *AV*. Branches and straightness were also always positive estimates, yet their *p*-values were above $\alpha = 0.01$ for Hyssna and Nybro silver birch. Processors may however be pleased that straightness and branching scores were positively related to AV, since these are already prioritized in birch stem quality grading (Heräjärvi and Verkasalo 2002; Johansson 2008; Kilpeläinen et al. 2011; Skovsgaard et al. 2021). It is important to emphasize that these traits have not been sufficiently studied to claim that they represent *AV* and related fiber traits, for example microfibril angle and grain angle (Huang et al. 2003). Branches and straightness could actually have an effect on *AV* measurement method. Conversely, *DBH* being excluded from models of *AV* does not mean that the two traits are unrelated, especially since *FBH* and *DBH* were positively correlated. The k-fold cross validation also illustrated how the models predicting *AV* were dependent on the data used to train them. Although their performance varied between iterations, it seems likely that predictions would be within 10% of the overall median *AV* value. For forest managers this suggests reliable models can be built, but applying them to new sites and populations may require calibration.

Modelling for $DENS_{Itrax}$ resulted in more robust models. *NR* (age) had a larger effect on ring density than cardinal direction, and both variables were significant in the final model. One site (Nybro) had consistently lower $DENS_{Itrax}$

predictions, and so a binary term was important in final models, which likely accounted for the lower site age. It is possible that Nybro was unique due to an interaction between year and age, however testing this would require the inclusion of climate variables. Although the oldest rings are likely an artefact of measurement, the numbering still provides an indication of increasing cambial age increasing density and reducing *RW*, as has been observed previously for birch stems (Vanhellemont et al. 2016; Dobrowolska et al. 2020). *RW* remained significant even when age was accounted for in the model. Similar to previous findings, it seems that birch growth rate is negatively related to wood density (Dunham et al. 1999; Liepiòð and Rieksts-Riekstiòð 2013). This is evidence that faster growth before age 20 may slightly reduce wood density. The benefit of faster growth may exceed any negative consequences of reduced birch wood density, as other researchers have considered a 10% reduction of birch wood density to be of minor importance (Dunham et al. 1999). It should be mentioned that relationships between growth and wood density depend on the species and the site concerned, but also on how growth is expressed (Zobel and van Buijtenen 1989; Long and Vacchiano 2014).

One possible issue with this analysis is that *TreeID* may have accounted for some of the variation due to site and species, so neither terms were significant in the final model. Nybro was significant, but this reflects either the younger age, the presence of downy birch stems or the effect of different cambial ages during different seasons (climate was not studied here). $DENS_{Itrax}$ estimates were nested by *TreeID*, as is common practice for studies that include tree ring data to avoid overestimating significance values. Other studies have included an autocorrelation term, which changes how the residuals are calculated (Bouriaud et al. 2004). Adding an autocorrelation or lag variable did not greatly change model parameter estimates, but complicated the interpretation of the results and affected the model residuals. $DENS_{Itrax}$ models consistently had good performance even when the model was trained on a subset of observations. This suggests that ring wood density has a general relationship with $DENS_{Itrax}$, cardinal direction, and *NR* (age or year). However, this is only for the young material studied in this paper, and further work should look to include managed mature birch stands.

The results of this analysis have limited applications for modelling birch wood's mechanical properties, or the measured NDT values, as the intention was to check for any complex underlying phenotypic relationships between traits assessed in previous birch genetics trials. The difficulties faced in building a better model may help future researchers or forest managers who are considering a similar task for stands of birch. Building a model to predict stiffness or *AV* at the individual tree level may require too many inputs to be practically feasible in field. The k-fold validation had irregular R-squared values, so it may be that there is no systematic relationship between *AV* and the other measured variables. There were some good candidate variables, which could be measured in further work, and *FBH* is one such variable.

Models fit the data slightly better when a term for species was included, despite species being an insignificant predictor for $DENS_{Itrax}$ (at $\alpha = 0.01$). This is one of the few opportunities to model using such a large dataset of birch measurements where stand history is known. Unfortunately, it is possible that the genetics trials had better form than unmanaged or naturally regenerated stands, reducing any differences between birch species or stem form classes. A wider range of sample stems may show clearer differences between stem types and species. The homogenously managed sites have however provided one of the few birch wood ring density studies using material with a known management history and a large sample size ($n > 30$). This dendrochronological series of ring widths and densities was only for the first 15 to 19 years of growth, and therefore provides information on young managed stands. The earliest rings often account for most of a stem's volume, and as this is arguably where the poorest quality wood occurs (Moore and Cown 2017), so it may be the best place to target if trying to improve stem density.

The error terms for $DENS_{Itrax}$ models would likely be lower if non-linear models were used, which included the random effects of *TreeID*. Simple linear models still provided reasonable estimates, and fitted values were consistently correlated with actual values without a *TreeID* term in the model. Other researchers have also used a linear model for modelling radial profiles in *B. platyphylla* stems, but used a non-linear relationship in the mature wood (Erdene-Ochir et al. 2021). Instead, this study focused on European birches which were under 20 years old, so it is likely that their wood density will continue to increase (Dobrowolska et al. 2020) and their ring width will continue to decrease (Vanhellemont et al. 2016). For other researchers who lack a validation dataset or have a small sample size, the methods used in this study provide a framework for building and validating models for predicting stem wood properties.

Conclusion

In this study, iterative model building and testing was applied to find relationships between measurements for young birch stems in southern Sweden, with these models tested using k-fold cross validation. There is insufficient evidence of a strong relationship between the assessed stem form metrics (*DBH*, *FBH*, straightness and branching score) and stem AV. Other NDT values (Pilodyn penetration depth and *GA*) were similarly related to *AV*, but this relationship did not greatly improve when additional variables were accounted for. The measured variables explained some of the variation in *AV*, but their importance varied by site and species. For models predicting Itrax ring density ($DENS_{Itrax}$), the model terms *NR* (age), *RW* and cardinal direction had significant *p*-values. *RW* had a consistently significant influence on $DENS_{Itrax}$ estimates, even when the effects of cardinal direction and age were accounted for. This is in contrast to the general belief that diffuse-porous species' wood density is independent of growth rate. Silver birch and downy birch could generally be treated as a single species, which may help other researchers attempting to build predictive models for birch wood mechanical properties.

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