

Site and size but not species mixture drive wood properties of second-growth western redcedar

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Abstract

Wood properties are key determinants of wood quality, influencing strength, stiffness, and dimensional stability. However, these properties can be affected by multiple silvicultural practices, including the choice of species composition, planting density, fertilization, and tree breeding. Understanding these effects is crucial, as wood resources in the Pacific Northwest forests are shifting to managed second-growth forests. This study investigated the effects of species mixture, site, and tree size on basic density, microfibril angle (MFA), wall thickness, and cell radial diameter of second-growth western redcedar, a species that produces high-value wood, across two locations with similar productivity in British Columbia, Canada. Increment cores were collected from 72 trees covering a range of sizes and analysed using SilviScan. Species mixture with other conifer species was quantified as the proportion of western redcedar basal area within the plot surrounding each sampled tree. Analysis of variance was used to evaluate mixture effects, and nonlinear mixed-effects models were applied to assess site and size influences. Results showed no mixture effect for any of the wood properties examined. The northern site showed higher values for all properties, except radial diameter. Small and medium trees had higher basic density and wall thickness, and lower MFA, traits associated with stiffness and mechanical performance. Only small trees showed significantly smaller radial diameter. Our results support the use of western redcedar mixtures with other conifers, which could increase resistance to disturbances without negatively affecting the studied wood properties.

Introduction

Wood quality is a widely used term, referring to the properties that influence its performance and value for a specific end use (Jozsa and Middleton 1994). A good understanding of wood as an integrated system is therefore essential, as wood quality is assessed through multiple internal properties. Although certain wood quality traits are species-specific, growing conditions play a key role in shaping wood quality. However, in response to increasing concerns about climate change and the need to reduce carbon emissions, wood has gained prominence as a renewable, carbon storing material capable of substituting for more emission intensive products such as steel, cement, and plastic (Leskinen et al. 2018). The carbon stored in harvested wood products, coupled with the lower energy requirements of their manufacture, makes them an important component of climate mitigation strategies (Buchanan and Honey 1994; Eriksson et al. 2012). As a result, the demand for wood is projected to increase substantially (Xue et al. 2024), driving the transition to managed second growth forests.

This transition usually involves shorter rotation periods, as well as changes in planting densities, species composition, and species proportions, designed to accelerate growth and maximize yield, which can strongly influence wood formation and therefore wood quality (Macdonald and Hubert 2002). Shorter rotations generally result in a higher proportion of juvenile wood, characterized by larger microfibril angles (MFA) and reduced density, leading to lower mechanical performance and reduced structural stability (Kennedy 1995; Macdonald and Hubert 2002). Similarly, stand density and initial spacing influence growth rates and wood structure; narrower spacing often promotes slower diameter growth,

higher wood density, and lower MFA, while wider spacing can result in lower wood density and greater variability in fiber characteristics (Fabris 2000). The species composition within a stand further adds complexity by introducing interspecific interactions between tree species (Pretzsch et al. 2017). Mixed species stands, compared with monocultures, are associated with a wider range of ecological functions and ecosystem services, yet they may also alter light availability, nutrient use, and competition dynamics, influencing wood formation in different ways among species and environments. Some studies reported reduced wood density in mixtures (De Araujo et al. 2015; Zeller et al. 2017), whereas others report the opposite (Krajnc et al. 2021). Tree size, which often reflects differences in growth rate, further contributes to variation in wood properties. The research findings confirm that faster growing trees generally form lower density wood, thinner cell walls, larger tracheid dimensions, and higher MFA, whereas slower growing trees tend to produce denser, mechanically stronger wood (Herman et al. 1999; Hong et al. 2014; De Araujo et al. 2015; Magalhães 2021). However, this trend is not true in all cases and can be opposite for certain species (Rosner et al. 2007; Kojima et al. 2009; Mäkinen and Hynynen 2014; Rungwattana and Hietz 2018). Site conditions, such as soil fertility, temperature, precipitation, and elevation can also shape wood anatomical traits, though their effects are often inconsistent among species and regions (Antony et al. 2011; Barrios et al. 2017; Magalhães 2021). These contrasting results highlight the need to understand better how growth environment and stand structure influence multiple wood properties simultaneously.

Wood density, MFA, cell-wall thickness, and cell radial diameter are key determinants of wood quality because they influence stiffness, strength, dimensional stability, and water transport. Wood density has become the most widely studied wood property because it integrates variation in multiple underlying anatomical traits. It is frequently associated with both mechanical performance and hydraulic behaviour across species and environments (Lachenbruch and McCulloh 2014). MFA is another very important trait, referring to the orientation of cellulose microfibrils in the secondary cell wall relative to the longitudinal axis of the cell (Barnett and Bonham 2004). Cell wall thickness and radial diameter are fundamental anatomical traits as well, particularly for xylem hydraulic function. Radial diameter usually determines hydraulic efficiency, whereas cell wall thickness contributes to hydraulic safety by increasing resistance to conduit collapse and embolism (Bouche et al. 2014).

All these traits are structurally linked: a higher proportion of thick-walled latewood cells increases wood density (Krajnc et al. 2021), while MFA is generally lower in latewood and higher in thin-walled earlywood tracheids (Fabris 2000). Wood density therefore largely reflects the percentage of cell wall material, and is determined by the ratio between cell wall thickness and radial diameter (Lundgren 2004). In addition to determining mechanical and hydraulic performance, these anatomical traits also provide valuable insights into past and present environmental conditions. Because wood formation is highly sensitive to temperature, precipitation, and soil water availability, variations in these traits across growth rings can record climatic fluctuations and physiological stress. This makes them important indicators for reconstructing past climates and evaluating the capacity of trees to adapt to ongoing climate change (Salimath et al. 2025). For example, Drew et al. (2012) found that wood density, cell radial diameter and MFA were significantly correlated with temperature, stream flow, and a drought index, highlighting their

potential to capture climate variability. Lu et al. (2015) found that MFA and radial diameter were negatively correlated with temperature and positively correlated with precipitation during the growing season, whereas wood density showed an opposite trend. Another recent study showed that conduit dimensions may integrate long-term physiological stress rather than reflecting only short-term climatic variation, where trees that later experienced drought-induced decline had persistently smaller xylem conduits for decades prior to mortality and reduced anatomical plasticity compared with healthy trees (Dow et al. 2026). Understanding how these physical properties vary and respond to environmental conditions and management practices is therefore important for predicting wood quality.

Western redcedar (*Thuja plicata* Don), hereafter referred to as redcedar, is a key tree species native to western North America, valued for its ecological and economic contributions (Antos et al. 2016), and cultural importance to Indigenous communities (Hebda and Mathewes 1984). Redcedar does not usually form monocultures but rather tends to be a component of mixed-species stands. Redcedar is highly valued for its decay-resistant heartwood, low density, straight grain, high dimensional stability, and ease of machining, making it important for siding, decking, and other outdoor applications (Minore 1983; McDonnell et al. 2024). In contrast to other commercial species, however, little is known about the responses of redcedar wood properties to stand and site characteristics in second-growth forests.

The aim of this study was to investigate the effects of species mixture, site, and size class on wood density, MFA, cell-wall thickness, and radial diameter in second-growth redcedar from two sites with similar productivity (medium to high site index) in British Columbia, Canada. Understanding how these wood properties interact and how they are impacted by multiple factors will improve predictions of second-growth redcedar's wood quality and inform silvicultural strategies that balance growth efficiency and enhanced resilience to disturbances with product performance.

Methods

Study sites, sampling and data collection

This study was conducted in two forest stands located at different latitudes (Hushamu: 50°36'52" N, 127°46'43" W; Malcolm Knapp: 49°20'06" N, 122°32'35" W) within the Coastal Western Hemlock biogeoclimatic zone in British Columbia, Canada. Both stands were naturally regenerated following wildfire, resulting in even-aged structures with trees approximately 70–90 years old. Redcedar represented a substantial proportion of the overall stand composition at both sites (Table 1), with the other most common species in the plots being western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), amabilis fir (*Abies amabilis* (Dougl.) Forbes), Sitka spruce (*Picea sitchensis* (Bong.) Carr.), and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco).

Table 1

Site description and biometric measurements of western redcedar sample trees. Cw is western redcedar, Hw is western hemlock, other species are: amabilis fir, Sitka spruce, Douglas-fir. Small, medium, and large indicate DBH classes. DBH is the diameter at breast height measured at 1.3 m.

Variable	Hushamu	Malcolm Knapp
Site characteristics		
Elevation (m)	115–150	350–400
Aspect	S-SW	W
Slope (%)	10–30	20–50
Mean annual temperature (°C)	8.2	8.5
Mean annual precipitation (mm)	3357	2527
Basal area (m ² /ha)	32–144	45–124
Stand composition (%)	55Cw 30Hw 15other	74Cw 22Hw 4other
Biometric measurements		
DBH small (cm)	28.5–32.0	28.5–31.8
DBH medium (cm)	38.0–42.2	37.8–41.4
DBH large (cm)	47.8–52.0	47.6–52.2
Tree height small (m)	22.7–29.9	22.6–28.7
Tree height medium (m)	24.1–32.8	23.4–31.0
Tree height large (m)	27.1–32.4	25.5–31.0

At both sites, three diameter classes were defined (30, 40 and 50 cm), and 12 redcedar trees were randomly selected within each class. This resulted in a total of 72 sampled trees. Trees with structural defects (e.g., forks, crooks), excessive lean, or visible pathological signs were excluded. For each sample tree, a circular plot was established with the tree at the center, sized to include at least 15–20 live neighboring trees. Plot radii were 3.99 m and 5.64 m for areas of 50 and 100 m², respectively. All trees within each plot were identified by species, and their DBH was measured for competition analyses.

Detailed biometric measurements were recorded for each sample tree (Table 1), and increment cores were taken for fiber property analysis. Cores were extracted at breast height, aligned perpendicular to the slope to minimize compression wood and maintain consistency between sites, using a 12 mm increment borer. Knots were avoided, and each core was taken from pith to bark. Immediately after collection, the cores were placed in a freezer until laboratory processing and analysis.

Sample preparation and tree core analysis

Tree cores were first conditioned at 40% relative humidity and 20°C temperature until they reached 8% moisture content (dry basis). The cores were extracted with acetone, then air-dried and reconditioned under the same conditions. Each core was cut into strips of 2 x 7 mm (tangentially x longitudinally) using a twin blade saw. The cross-section of each strip was sanded to obtain a smooth surface for image analysis. Strips were then analysed by SilviScan, using optical microscopy, X-ray densitometry (25 µm resolution) and X-ray diffractometry (1 mm resolution), to determine basic density, MFA, wall thickness and radial diameter.

Data analysis and modeling

Competition and species composition

To evaluate whether neighboring tree species composition influenced western redcedar wood properties, we quantified competitive environment based on field plot data. Neighboring trees were divided into two groups: “redcedar” and “other species.” For each sample tree, the basal area of all neighbors within the plot was calculated, and the proportion (%) of redcedar neighbors relative to total basal area was derived. To facilitate interpretation, these proportions were categorized into three classes, each including 12 target trees, representing increasing dominance of redcedar: low (higher mixture with other species), medium, and high (predominantly redcedar).

We then tested for differences in the four measured wood properties (basic density, MFA, wall thickness, and radial diameter) across the three mixture classes using one-way analysis of variance (ANOVA).

Wood properties

Preliminary analysis showed that wood properties vary between the two sites and among tree size classes. Consequently, size class was used as an indicator of growth rate within the stand, with large trees growing faster than those in the medium or small classes.

Model selection was based on preliminary exploratory analysis of the radial profiles. Basic density, MFA and wall thickness displayed similar radial patterns and were therefore modeled using the equation applied by Jordan et al. (2005):

$$1. f(\text{Ring}) = \frac{\beta_0}{1 + e^{\beta_1 \text{Ring}}} + \beta_2$$

where Ring is the ring index from pith (cambial age), β_0 is the initial value parameter, β_1 is the rate parameter, and β_2 is the lower asymptote.

In contrast, radial diameter displayed a different radial pattern and was modeled using a power function:

$$1. f(\text{Ring}) = \alpha \cdot \text{Ring}^\beta$$

where α is the scale parameter, Ring is the ring index from pith, and β is the growth rate.

We fitted all models using nonlinear mixed-effects models using the “nlme” package (Pinheiro et al. 2024) of R 4.4.1 (R Core Team 2024), with tree as a random effect.

We started with one parameter varying randomly with tree, sequentially adding the second and third parameters, and selected the best random-effects structure based on Akaike’s Information Criterion (AIC). Next, dummy variables of site (Hushamu being the reference site) and size class (large being the reference size class) were added as fixed effects to assess their influence on all model parameters. Once the best model for each wood property was determined, we added autocorrelation and weighted variance structures in the model to account for within-tree autocorrelation across growth rings and to improve the model fit. Model adequacy was assessed by visually evaluating diagnostic residual plots. Figures were produced in R using the ggplot2 package.

Results

Effect of species composition on wood properties

There was no significant effect of redcedar neighbor proportion on the basic density, MFA, and radial diameter, based on ANOVA results (Fig. 1). Wall thickness at Malcolm Knapp showed a suggestive trend ($p = 0.056$). Post-hoc Tukey analysis found a significant difference in wall thickness between the medium and high proportion classes ($p = 0.045$), highlighting a specific difference between these groups. The overall results did not show any significant effect of redcedar proportion classes. Consequently, mixture was not included in further analyses.

Site and size influence on wood properties

Site showed a significant effect ($p\text{-value} < 0.05$) on the initial value (β_0) and lower asymptote (β_2) parameters of the basic density model (Table 2). The initial value was higher, and the asymptote was lower at Malcolm Knapp compared to Hushamu (Fig. 2). Size class had a significant effect on the initial value and lower asymptote parameters as well. Medium trees had a higher initial value (β_0) than large trees (reference level). Both medium and small size trees showed higher lower asymptote (β_2) values compared to large ones (Fig. 2).

Site significantly affected all MFA model parameters. The initial value parameter was higher at Malcolm Knapp than Hushamu. The rate of decrease and lower asymptote parameters were lower at Malcolm Knapp. Size class significantly affected the initial value and lower asymptote. Medium and small trees had higher initial values and lower asymptote values than large size trees.

Site had a significant effect only on the asymptote parameter of wall thickness, being lower at Malcolm Knapp compared to Hushamu. Size class influenced the rate of decrease and the asymptote parameters. Medium trees showed a lower rate of decrease and both medium and small size trees had higher asymptote values than large size trees.

Site significantly influenced the scale (α) and growth rate (β) parameters of radial diameter. The scale parameter was higher at Malcolm Knapp, while the growth rate parameter was lower compared to Hushamu (Table 2, Fig. 2). Size class significantly affected only the scale parameter, with small size trees having lower values compared to large size trees.

Table 2

Estimated parameters, standard errors, and goodness-of-fit measures for models of wood properties. Only significant parameter estimates are presented. Dummy variables of site (reference level – Hushamu) and size class (reference level – large) were included in each model. MK is Malcolm Knapp site, β_0 is the initial value parameter, β_1 is the rate of decrease, β_2 is the lower asymptote, α is the scale, β is the growth rate, and Φ is the autocorrelation parameter.

Wood property	Parameter	Estimate	Std. Error	p-value
Basic density	β_0 MK	50.890	23.480	0.0303
	β_2 MK	-13.550	4.330	0.0018
	β_0 Medium	64.680	29.380	0.0277
	β_2 Medium	14.120	5.250	0.0072
	β_2 Small	30.570	5.340	< 0.001
	Φ	0.422		
	Variance power	-0.167		
	AIC	46206.95		
	logLik	-23085.47		
MFA	β_0 MK	6.230	1.950	0.0014
	β_1 MK	-0.106	0.022	< 0.001
	β_2 MK	-6.810	1.130	< 0.001
	β_0 Medium	5.066	2.390	0.0342
	β_2 Medium	-2.734	1.370	0.0463
	β_0 Small	13.712	2.420	< 0.001
	β_2 Small	-5.130	1.380	0.0002
	Φ	0.688		
	Variance power	0.021		
	AIC	24579.48		
	logLik	-12272.74		
Wall thickness	β_2 MK	-0.041	0.021	0.0472
	β_1 Medium	-0.287	0.107	0.0074
	β_2 Medium	0.064	0.025	0.0106
	β_2 Small	0.162	0.025	< 0.001

Wood property	Parameter	Estimate	Std. Error	p-value
	Φ	0.534		
	Variance power	2.019		
	AIC	-5786.253		
	logLik	2911.126		
Radial diameter	α MK	1.388	0.285	< 0.001
	β MK	-0.008	0.003	0.0163
	α Small	-1.622	0.349	< 0.001
	Φ	0.484		
	Variance power	-0.135		
	AIC	15759.31		
	logLik	-7866.653		

Discussion

We investigated how species mixture, site, and tree size class influence four key wood properties (basic density, MFA, cell wall thickness, and cell radial diameter) in second-growth redcedar across two sites with similar productivity in British Columbia, Canada. The results showed that stand mixture did not significantly affect any of the properties examined, while both site and tree size had significant effects on the nonlinear mixed-effects models describing radial trends in these traits. Overall, our findings highlight that wood property variation in redcedar is primarily shaped by environmental and growth rate differences rather than species composition.

Mixture effect

The absence of mixture effects on any of the wood properties, except for a suggestive difference in wall thickness at Malcolm Knapp (Fig. 1), indicates that neighboring species composition had little influence on the wood formation of redcedar. This contrasts with patterns observed in other tree species, where mixture often affects wood properties. For example, Zeller et al. (2017) reported lower ring density in mixed stands of Scots pine and European beech compared to monocultures, and De Araujo et al. (2015) found reduced density and increased MFA in trembling aspen when mixed with white spruce. In contrast, Krajnc et al. (2021) found that mixture increased density in pubescent oak and black pine. More recently, Zhang et al. (2025) suggested that species diversity can enhance wood formation at the cellular level by increasing xylem cell production and wall thickness.

Mixture may also influence the variability of wood properties among individual trees, as Pretzsch and Rais (2016) suggested that greater variation in stand conditions can be reflected in a broader range of wood-quality traits. In this study, however, the spread of basic density, MFA, wall thickness, and radial diameter did not appear consistently greater in the low or medium redcedar proportion classes, which represent greater mixture around the sampled trees, compared with the high cedar proportion class (Fig. 1). This suggests that neighbouring species composition did not strongly increase the variability of redcedar wood properties within the sampled conditions. Another possible explanation is that the range of species composition represented at the two sites may not have been sufficient to produce detectable effects on redcedar wood properties, as redcedar accounted for 55% of stand composition at Hushamu and 74% at Malcolm Knapp (Table 1).

This limited responsiveness may be linked to the ecological characteristics of redcedar. Redcedar is highly shade-tolerant and can persist for long periods under competitive, low-light conditions, reflecting its stress-tolerant strategy and ability to maintain growth across a wide range of environments (Antos et al. 2016). This ecological adaptation likely explains the absence of significant neighbor effects on its wood properties. Although a significant difference in wall thickness was observed between medium and high cedar proportion classes, particularly at Malcolm Knapp, this effect was not accompanied by changes in density or MFA. The high cedar proportion class at Malcolm Knapp included stands approaching pure cedar composition (82 – 100% cedar), which may increase intraspecific competition. However, given that most wood properties were unaffected, mixture appears to have had only a limited influence on wood formation of redcedar.

Site effect

Site had a significant influence on all wood properties. Overall, trees at Malcolm Knapp started with higher initial basic density and higher initial MFA compared with Hushamu. Wood density and MFA are generally negatively related, with higher MFA often associated with lower density (Barnett and Bonham 2004). The coexistence of relatively high density and high MFA in the innermost rings at Malcolm Knapp therefore suggests that additional factors may have influenced this pattern. One possible explanation could be the presence of compression wood, which in conifers is characterized by both higher wood density and higher MFA compared with normal wood (Auty et al. 2013). However, visual inspection of the cores revealed no evidence of compression wood, suggesting that it was unlikely to be a major driver of the observed pattern. Instead, the elevated MFA near the pith is consistent with the greater proportion of juvenile wood typically found in the innermost rings (Jordan et al. 2005), whereas the higher initial density at Malcolm Knapp may reflect differences in site conditions. The higher elevation at Malcolm Knapp (Table 1) may have been associated with slower early growth rates, contributing to the formation of denser wood, although genetic or microsite effects established during early stand development may also have played a role.

Over time, however, basic density, MFA, and wall thickness stabilized and became lower at Malcolm Knapp compared with Hushamu. Radial diameter showed an opposite trend: trees at Malcolm Knapp

consistently exhibited larger radial diameters across the profile, despite slightly lower overall growth rates than those observed at Hushamu.

Regional variation in wood properties between sites may reflect differences in environmental conditions such as precipitation, elevation, and aspect. Environmental conditions have been shown to influence wood properties across multiple species. For example, Antony et al. (2011) reported higher specific gravity in loblolly pine in two southeastern regions, likely due to a longer growing season and a higher proportion of latewood. Topaloğlu et al. (2016) found that wood density increased and vessel diameters decreased with altitude in Oriental beech. Similarly, Xie et al. (2024) observed altitude-related variation in tracheid dimensions, although density itself was less responsive in that case. Water availability has also been shown to influence wood structure. In larch, reduced precipitation initiated the latewood formation (Antonova and Stasova 1997), which is generally associated with higher density and smaller tracheid diameter. In contrast, irrigation experiments in loblolly pine demonstrated increases in whole-core specific gravity and latewood proportion under higher water availability (Gonzalez-Benecke et al. 2010), indicating that site moisture conditions can modify xylem structure, although responses may vary among species. More detailed relationships have been reported for seasonal precipitation. Van der Merwe et al. (2023) found that greater spring precipitation was associated with lower-density wood and a lower latewood proportion in *Pinus patula*, whereas summer precipitation was positively correlated with both wood density and latewood proportion. However, site responses are not consistent across species; for example, Magalhães (2021) found no significant site effect on density in Lebombo ironwood. In the present study, redcedar exhibited lower mature basic density, thinner cell walls, lower MFA, and wider radial diameter at the southern site (Malcolm Knapp), despite its higher elevation and lower precipitation (Table 1).

The radial patterns observed may also reflect known anatomical trends in conifers. In most conifers, wood density generally increases from pith to bark as the proportion of latewood rises and tracheids become smaller in diameter, with thicker cell walls (Lachenbruch et al. 2011). However, Cupressaceae species, including redcedar, often display a contrasting radial profile, as shown in Fig. 2. According to Schimleck et al. (2022), this “type 3” pattern is characteristic of several Cupressaceae species, in which specific gravity declines from pith to bark. This reflects a transition from denser, mechanically stronger corewood to lighter, hydraulically efficient outerwood. The higher density near the pith may reflect hydraulic constraints during early development, as described by Lachenbruch et al. (2011). Because young trees have limited access to stored water, early-formed xylem may prioritize structural reinforcement through smaller and thicker-walled tracheids, leading to denser corewood. Schimleck et al. (2024) interpret this pattern as characteristic of Type 3 Cupressaceae species. As trees mature, the formation of lower-density outerwood may enhance hydraulic conductivity and growth efficiency (Jagels et al. 2003; Poorter et al. 2010).

In addition, other unmeasured factors may have contributed to the observed site differences. Although Van der Merwe et al. (2023) found that climatic variables explained more variation in wood properties than the measured soil properties in *Pinus patula*, soil characteristics have been shown to influence

wood anatomical traits in other species. For example, Dong et al. (2023) reported positive relationships between soil texture, nutrient concentrations, and wood density in Persian oak. Although both sites regenerated naturally after fire, genetic differences between populations may also play a role. Wood properties such as MFA, cell wall thickness, and tracheid diameter have demonstrated moderate to strong genetic control in Norway spruce (Baison et al. 2020). Therefore, site-level variation in redcedar wood properties likely reflects a combination of environmental influences, developmental patterns specific to Cupressaceae, and potential genetic differentiation between stands.

Size class effect

Tree size class also had a strong effect on wood properties. Small and medium trees exhibited higher basic density and greater cell wall thickness than large trees (Table 2). The higher density observed in smaller trees may be linked to differences in growth patterns among size classes. In conifers, wood density is frequently negatively correlated with ring width (Mäkinen et al. 2007; Franceschini et al. 2013). In Norway spruce, Franceschini et al. (2013) reported a clear negative relationship between annual ring width and ring density, demonstrating that increased radial growth is associated with reduced wood density. They further showed that wider rings were accompanied by a lower proportion of latewood. Similarly, Mäkinen et al. (2007) observed negative relationships between ring width, ring density, and latewood percentage, and noted that faster-growing trees exhibited larger tracheids and lower cell wall proportion. Although ring width and latewood percentage were not quantified in the present study, the higher density observed in smaller trees may be consistent with reduced radial growth over time. Slower growth is often associated with a greater proportion of latewood and higher ring density. In contrast, larger trees, which typically sustain higher growth rates, may produce wider rings with lower density (Macdonald and Hubert 2002). Similar size-related patterns have been reported in other tree species. Zhang et al. (2021), for example, found that basic wood density decreased with increasing DBH class in black spruce. De Araujo et al. (2015) also observed higher mean density in co-dominant than dominant white spruce trees, a pattern consistent with higher density in smaller trees. On the other hand, Magalhães (2021) reported the opposite pattern, with density increasing with DBH. However, in both cases the trends were connected to tree age, which in our case is not applicable as all the sampled trees have similar ages.

MFA was lower in small and medium trees than in large trees across cambial age. In the nonlinear model, the asymptotic parameter (β_2) was significantly reduced for small and medium size classes, indicating that these trees converge toward a lower mature MFA. This pattern is consistent with the higher asymptotic basic density observed in smaller trees. Reduced microfibril angles are characteristic of stiffer and more mature wood (Donaldson 2008) and when coupled with higher density, suggest that small and medium trees produce structurally more rigid mature wood compared with large trees.

Although the proportion of redcedar neighbours did not significantly influence wood properties, tree size class may still reflect differences in competitive status and long-term resource availability that were not captured by the mixture. Smaller and intermediate trees are more likely to experience more shade and

limited water and nutrient resources, which may favor the formation of narrower cells and thicker walls, leading to a higher density.

Only small trees showed significantly smaller radial diameter – the scale parameter (α) was the only one that varied with size class, being lowest in small trees. A possible cause of narrower tracheids in smaller, slower growing trees could be a shorter cell enlargement duration during xylem differentiation. Cuny et al. (2014) found that the duration of cell enlargement phase explained about 75% of the variation in tracheid diameter of silver fir, Norway spruce and Scots pine, confirming that the time a cell spends enlarging largely determines its final size. The smaller tracheid lumens observed in these trees contribute to higher density and may be linked to differences in cell enlargement and wall development (Cuny et al. 2014). Tracheid diameter reflects a fundamental trade-off between hydraulic efficiency and safety. Wider tracheids increase water transport capacity but are more vulnerable to embolism during drought or freeze events. Conversely, narrow tracheids resist both drought and freezing-induced embolism, maintaining hydraulic integrity under stress at the cost of reduced conductivity (Davis et al. 1999; Pittermann and Sperry 2006).

Beyond representing hydraulic efficiency-safety trade-offs, persistent differences in conduit dimensions may also reflect long-term physiological conditions. Studies linking wood anatomy to drought-induced decline have shown that trees experiencing prolonged stress developed narrower conduits for a long period before mortality and displayed reduced capacity to adjust conduit structure in response to climatic variations (Dow et al. 2026). In this context, the narrower tracheids and higher density observed in smaller trees may reflect not only slower growth and competition for resources, but also differences in long-term resource limitation influencing xylem development.

Management implications

Our results indicate that tree size and growth patterns influence redcedar wood quality properties associated with mechanical performance. Smaller trees displayed higher density and lower MFA, traits generally associated with greater wood stiffness and strength. In addition, thicker cell walls and smaller radial diameters may contribute to improved mechanical support and increased resistance to hydraulic failure under variable environmental conditions. These findings suggest that promoting rapid diameter growth may involve trade-offs, as larger trees tended to exhibit wood characteristics associated with lower mechanical performance (Davis et al. 1999; Pittermann and Sperry 2006; Donaldson 2008).

Although both sites were naturally regenerated following wildfire, the observed relationship between tree size and wood properties suggests that silvicultural practices influencing stand density and growth rates may also affect wood quality development. Slower-growing trees in this study produced denser wood with thicker cell walls, indicating that management interventions such as initial planting density and thinning regimes could influence the development of anatomical and mechanical wood traits (Rais et al. 2014; Isaac-Renton et al. 2025).

The strong site effects observed for all wood properties further highlight the importance of local growing conditions in shaping wood quality. Notably, MFA stabilized at different cambial ages between sites, occurring at approximately 20 years at Hushamu and 35 years at Malcolm Knapp. This substantial difference suggests that the transition from juvenile to mature wood can be site dependent. Consequently, decisions regarding rotation length should consider site-specific patterns of wood development, since shorter rotations may increase the proportion of juvenile wood and reduce stiffness, particularly on sites where wood maturation occurs more slowly (Auty et al. 2016).

Although species mixture did not significantly influence most of the wood properties analysed, further investigation of species interactions remains warranted. Mixtures of redcedar with species such as red alder are particularly promising because they can enhance soil nitrogen availability and improve tree growth (Harper et al. 2023), yet their effects on redcedar wood formation remain poorly understood. Expanding future studies to include a wider range of site conditions, stand compositions, soil characteristics, and microclimatic variables will improve our understanding of the factors influencing the wood quality in second-growth redcedar and support the development of management strategies that balance productivity, resilience, and wood performance.

Declarations

Conflicts of interest

The authors declare no competing interests.

Use of Generative AI

Generative AI (ChatGPT, OpenAI) was used for editorial assistance and code troubleshooting (e.g., improving readability, debugging errors). The authors reviewed and verified all outputs and take full responsibility for the content of the publication.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

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Author Contribution

Conceptualization: CF, IB, MN; Data curation: MN; Formal analysis: MN, CF; Funding acquisition: CF, IB; Investigation: CF, MN; Methodology: CF, IB, MN, JC; Project administration: CF, IB; Resources: CF, IB; Supervision: CF, IB; Visualization: MN; Writing – original draft: MN; Writing – review & editing: MN, CF, IB, JC.

Data Availability

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Code availability

The R code used for the statistical analyses is available from the corresponding author on reasonable request.

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Figures

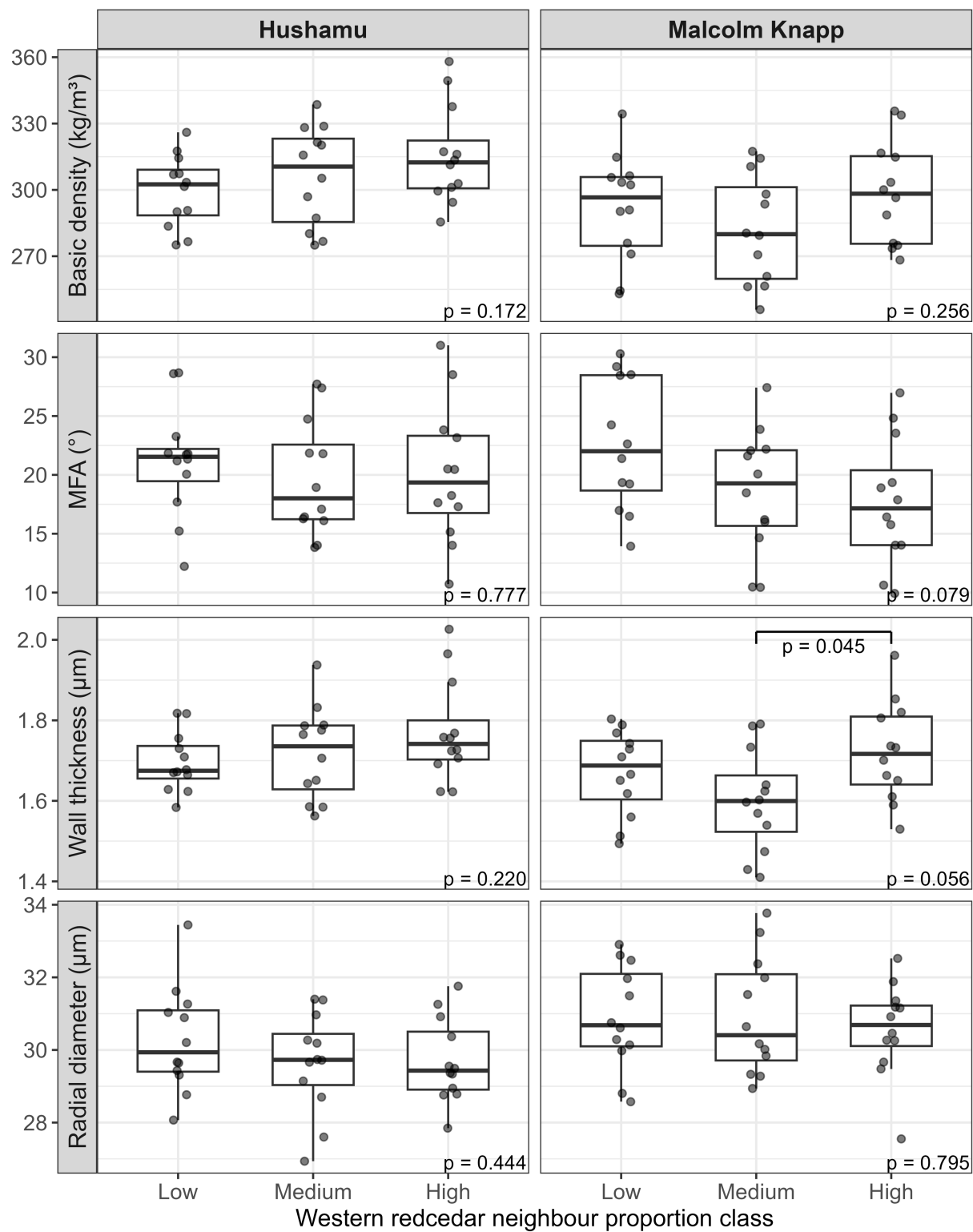


Figure 1

Variation in basic density, microfibril angle (MFA), wall thickness, and radial diameter across western redcedar neighbour proportion classes at Hushamu and Malcolm Knapp. Low = higher mixture with other species, and High = predominantly western redcedar. P-values from one-way ANOVA are shown in each panel, and the p-value of post-hoc Tukey test is shown in the bracket between Medium and High class for wall thickness at Malcolm Knapp

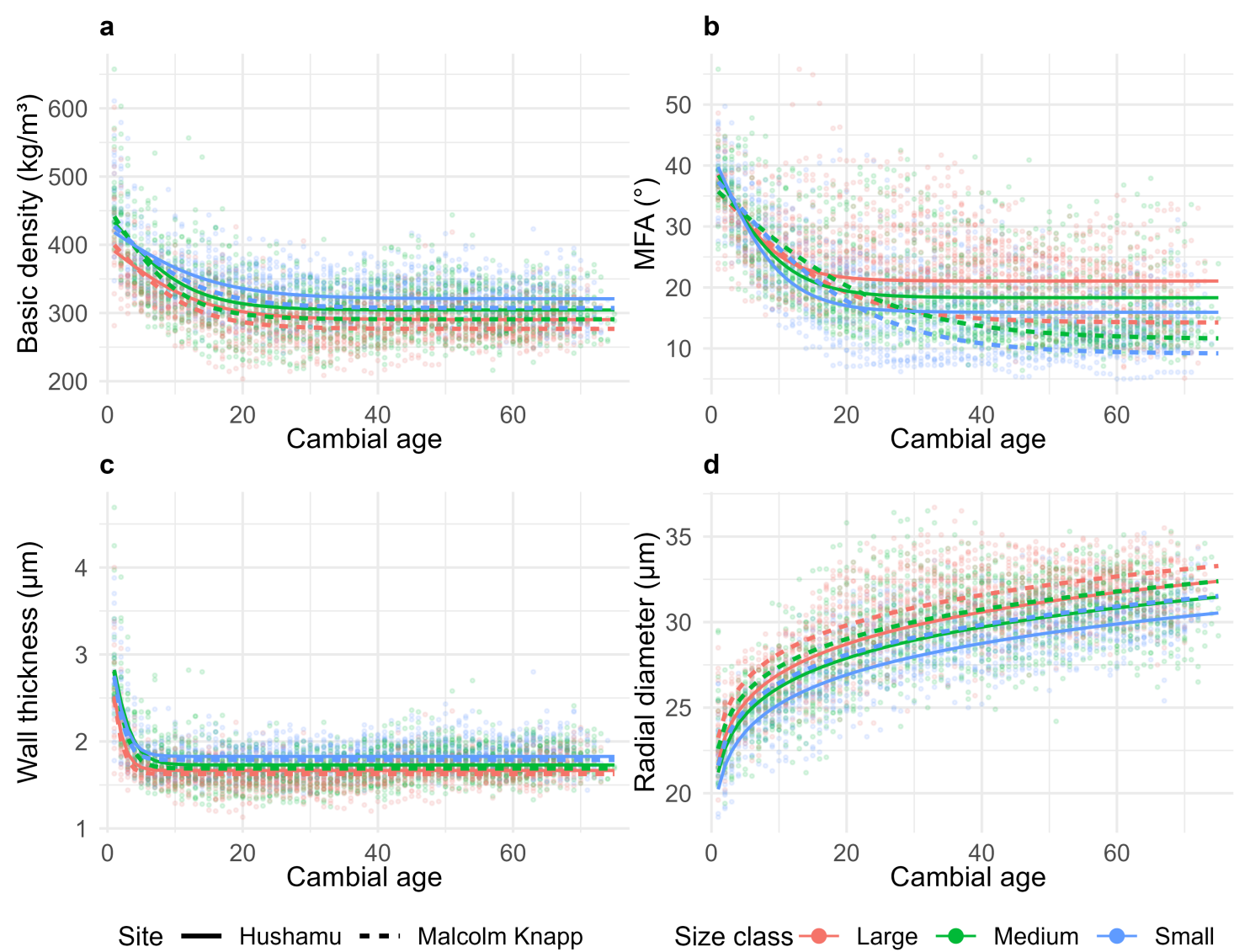


Figure 2

Radial trends in basic density (a), microfibril angle (MFA) (b), wall thickness (c), and radial diameter (d) at Hushamu and Malcolm Knapp for the three size classes. Data points are raw ring measurements and curves are fitted values from the corresponding nonlinear mixed-effects models