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Early stem and form pruning effects on short-term tree growth and stem quality in hardwood plantations: differing results in *Nothofagus dombeyi* and *Nothofagus alpina* in south-central Chile

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Nothofagus species dominate the temperate forests of South America. Among them, *Nothofagus dombeyi* and *Nothofagus alpina* are long-lived, fast-growing pioneer trees with high-quality timber, which makes them attractive for plantation forestry. Unlike conifers, however, these species—particularly *N. dombeyi*—often lack strong apical dominance, leading to stem forking and the need for early form pruning to ensure straight, high-quality stems. Despite this, information about early form and stem pruning in *Nothofagus* plantations remains scarce. This study evaluated the effects of early pruning on growth and stem form dynamics in a young *N. dombeyi* (5-year-old) and a young *N. alpina* (8-year-old) plantation in south-central Chile. For each species, growth responses were evaluated over 4 years following pruning treatments (T1: unpruned control, T2: fork control, and T3: pruning to half of total height plus fork control). Pruning responses differed markedly between species. In *N. dombeyi*, pruning significantly reduced *d* and *v* growth ($p < 0.05$), with the strongest reductions under T3 (20–25% relative to T1), followed by rapid recovery within 4 years. Height growth was not affected ($p > 0.05$), although T3 tended to increase height increment in *N. dombeyi*. In contrast, *N. alpina* showed no differences among treatments ($p > 0.05$). Overall, *N. dombeyi* exhibited greater sensitivity to pruning, likely reflecting its higher light demand and greater biomass and leaf area removal compared to *N. alpina*. Despite short-term growth reductions, early pruning is recommended to improve stem form and produce high-quality, knot-free timber within the proposed 35-year rotations in good sites for both studied species.

KEYWORDS

apical control, hardwood silviculture, plantation diversification, timber quality, tree
tending treatments

1 Introduction

Early pruning of live branches is a key tending practice to improve plantation quality and produce high-value timber production, as it corrects crown structural defects and increases the proportion of clear, knot-free wood, thereby enhancing stand value at final rotation (Hubert and Courraud, 1989; Loewe and González, 2002; Oosterbaan et al., 2009; Carson et al., 2014; Leng et al., 2025). In broadleaved species, stem pruning reduces knot formation by removing lower branches with low photosynthetic contribution, while top or form pruning (also named formative pruning; Kerr and Morgan, 2006) may maintain apical dominance and prevent stem forking (Hubert and Courraud, 1989; Carson et al., 2014), although this varies by species and timing (Kerr and Morgan, 2006). However, pruning also reduces crown size and leaf area, potentially limiting photosynthetic capacity and affecting tree growth, productivity, and survival (Pinkard and Beadle, 1998; Pinkard et al., 2004; Alcorn et al., 2013; Forrester, 2013). Therefore, pruning may reduce light interception and the competitive ability of trees within a forest stand, but from a wood production perspective, it eliminates branches that are the primary source of knots and associated discoloration (stem pruning), or that would otherwise reduce the chances of growing straight trees (form pruning), which would substantially reduce future timber quality and market value (Pinkard et al., 2004; Zobel and Van Buijtenen, 2012).

In broadleaved species, appropriate early pruning can dramatically increase the value of the basal log by producing clear wood suitable for high-quality timber or veneer, which may reach prices two to ten times higher than those of high-grade sawlogs (Alderman et al., 2010). Knots disrupt normal fiber orientation and alter wood density, generating areas of structural weakness around branch insertion and reducing the mechanical performance of sawn timber (Zobel and Van Buijtenen, 2012; Hu et al., 2018). The main concern therefore is to prune trees to a degree that will improve quality while not significantly reducing growth (e.g., Leng et al., 2025). This can be achieved by implementing pruning and thinning at the same time, but pruning requirements may occur earlier than thinning requirements, and therefore in the case of only-pruning entries to a forest stand, the severity of pruning is a major consideration to improve quality without reducing growth.

In these cases, an appropriate pruning severity may increase the vigor of the trees and the resistance of a forest stand to disturbances such as those caused by climate change (i.e., increased temperatures and declining precipitations in south-central Chile; e.g. Salazar et al., 2024; Urrutia-Jalabert et al., 2015). In this sense, most literature indicates that pruning should not remove $\geq 40\text{--}50\%$ of green crown length (Bulfin and Radford, 1998; Pinkard et al., 1999), and that low-severity pruning seems convenient to improve form without reducing growth. Actually, in a recent study pruning poplar (*Populus deltoides*) at one-third of total height, trees increased their growth, which was attributed to a compensatory growth mechanism where water and nutrients that were originally directed to the pruned branches and leaves were relocated to the trunk after pruning (e.g., Leng et al., 2025). Therefore, pruning severity, derived from stem or stem + form pruning, is a key decision to achieve tree quality objectives while maintaining good growth rates, especially if it is not accompanied with thinning.

Nothofagus species dominate the temperate forests of the southern cone of South America (Perry et al., 2025). Several species of this genus produce high-quality timber (Díaz-Vaz et al., 2002; Donoso and

Navarro, 2025) and exhibit fast growth rates (Donoso, 1993; Donoso and Navarro, 2025). Despite these attributes, plantations with *Nothofagus* in the Chilean temperate region remain scarce (Bannister et al., 2018), representing a major opportunity to diversify the forest landscape of south-central Chile, which is currently dominated by exotic fast-growing tree species crops such as *Pinus radiata* and *Eucalyptus* spp. (Cubbage et al., 2007; Salas et al., 2016). Experimental plantations of *Nothofagus dombeyi*, *Nothofagus alpina*, and *Nothofagus obliqua* established under contrasting site conditions and silvicultural regimes have shown variable growth and survival (Donoso et al., 2009, 2011, 2015a,b; Navarro et al., 2024), but overall promising performance, with mean annual volume increments of $10\text{--}20\text{ m}^3\text{ ha}^{-1}\text{ yr}^{-1}$, survival rates of 60–90% (Navarro et al., 2024), and high plant diversity (Romero-Mieres et al., 2025). Similar growth rates have been also reported in plantations of the species in United Kingdom (Mason et al., 2018). This productive potential has encouraged the establishment of *Nothofagus* plantations in both open-field conditions and degraded forests in south-central Chile (Donoso et al., 2015a,b; Soto et al., 2015, 2020). However, as with many broadleaved species, these *Nothofagus* species exhibit a great architectural plasticity that may result in poor form and forking, and mid-term evaluations, particularly in *N. dombeyi*, confirm this pattern (Donoso et al., 2015a; Navarro et al., 2025). Self-pruning of branches is also poor in these species (Donoso et al., 2015a; Navarro et al., 2025). Such practices have proven effective in improving timber quality in several hardwoods (Hubert and Courraud, 1989; Kerr and Morgan, 2006; Leng et al., 2025) and are increasingly recognized as essential for *Nothofagus* plantations (Donoso et al., 2015a,b; Navarro et al., 2024). Consequently, the frequent early forking and development of thick stem branches in *Nothofagus* species highlight the need for early tending interventions to enhance the commercial value of these plantations.

Donoso et al. (2015a) recommended form pruning in *N. dombeyi* plantations between ages 4 and 7, depending on growth patterns, but did not propose this practice for *N. alpina* due to its generally straighter stem form. Despite these guidelines, empirical knowledge of pruning effects in *Nothofagus* species in Chile remains limited. Evaluating the effectiveness of early pruning is therefore essential to strengthen the technical basis for the silviculture of native-species plantations and to promote their adoption, particularly among small- and medium-size landowners willing to produce high-value timber (Navarro et al., 2025). Although pruning has been experimentally applied in both species (Donoso et al., 2015a), its mid- and long-term effects on growth dynamics and the persistence of improved stem form (i.e., maintenance of a single dominant stem) have rarely been assessed. Accordingly, the objective of this study was to evaluate the effects of early pruning on stem quality and growth performance in young *N. dombeyi* and *N. alpina* plantations prior to a first thinning (~8–10 years). Specifically, we assessed growth responses over 4 years following the application of two treatments: form pruning (fork control) and a combined treatment including both form and stem pruning (up to one-half of total tree height), applied without complementary thinning. We hypothesized that both pruning treatments would improve stem quality in both species and would at least temporarily reduce d and v growth. We further expected that form-pruned trees would maintain improved stem form, particularly under the combined treatment, where the leader branch concentrates a greater proportion of the crown's photosynthetic area. Finally, we hypothesized that (a) *N. dombeyi* would be more sensitive to pruning

than *N. alpina* due to its higher light demand and weaker apical control (Puntieri et al., 1998), and (b) that any initial growth reductions would be followed by rapid recovery, as both species exhibit high early growth rates that decline at later developmental stages (Donoso et al., 2015a,b).

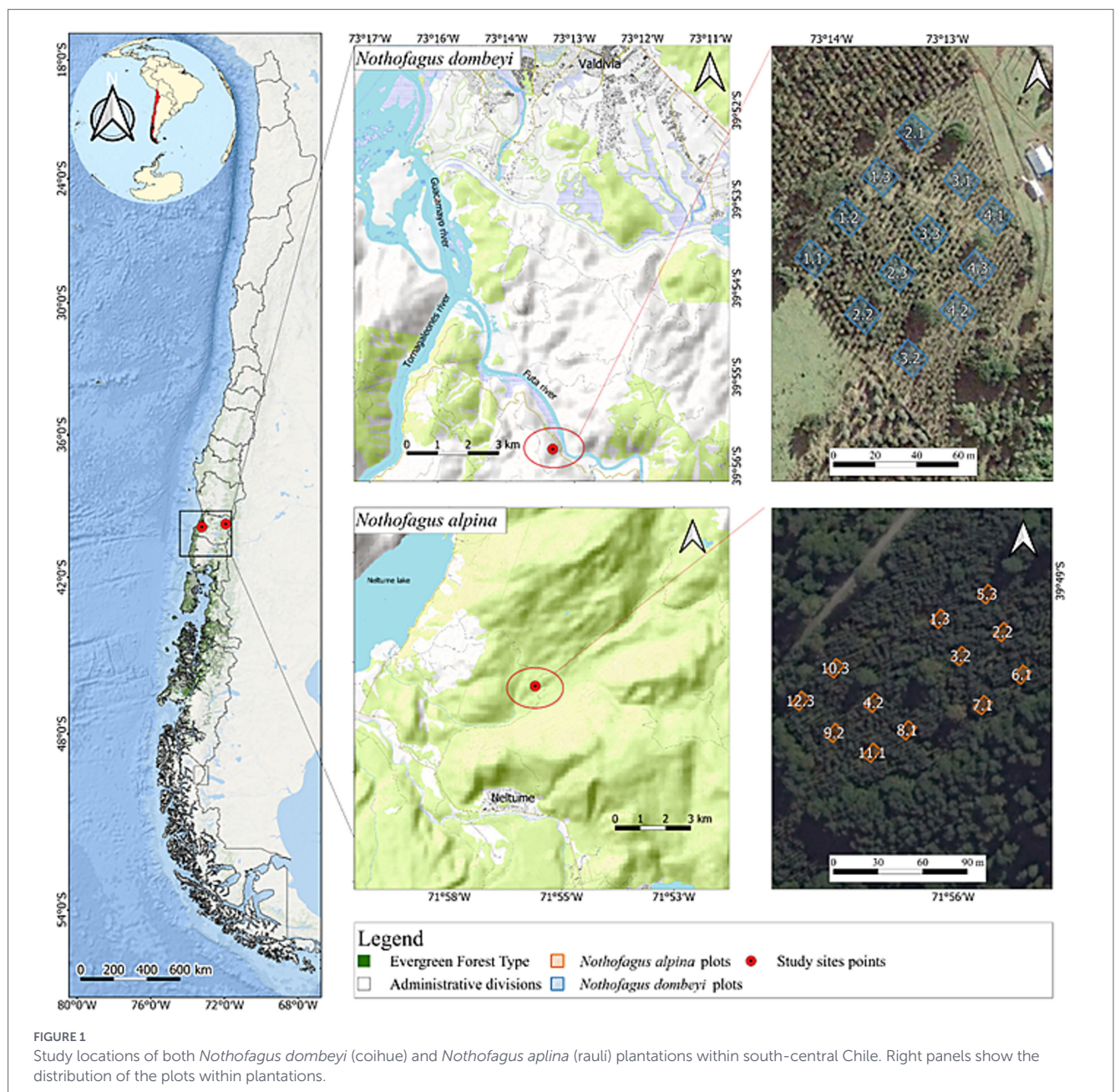
2 Materials and methods

2.1 Study area

The *N. dombeyi* plantation covers ~1.3 ha in the foothills of the Coastal Range (39°58'S, 73°20'W), at an elevation of 80–100 m a.s.l. (Figure 1). The site is situated on a northeast-facing slope with moderate gradients (5–30%) and a convex landform, within a small private

property. In contrast, the *N. alpina* plantation covers ~9 ha in the Andes Range (39°49'06"S, 71°55'58"W), at an elevation of 500–550 m a.s.l., on gentle to slightly sloping terrain (<15%), within the private Huilo Huilo Reserve (Figure 1). Both experimental plantations were established on former pastures that had remained fallow for several years prior to planting and within the natural distribution range for each.

The climate at the *N. dombeyi* plantation site is classified as temperate rainy with Mediterranean influence (di Castri and Hajek, 1976), with marked seasonal differences between the wettest and driest months (Fuenzalida, 1971). In the Köppen–Geiger classification, this coastal site broadly corresponds to a temperate oceanic climate (Cfb), consistent with the humid, year-round rainfall regime described for the Valdivian area. Mean annual temperature (1990–2020, CR2MET v2.5, <https://www.cr2.cl/datos-productos-grillados/>) is approximately 12.2 °C, with an



average minimum of 4.6 °C in the coldest month (August) and an average maximum of 23.3 °C in the warmest month (January). The proximity to large water bodies, including wetlands, rivers, and the sea, moderates frost occurrence, resulting in an average of 46 frost days per year. The frost-free period typically extends from November to March. Precipitation is distributed throughout the year, although approximately 80% occurs during autumn and winter, with a pronounced decline in summer (Frêne et al., 2019). Mean annual precipitation (CR2MET v2.5) is approximately 2,400 mm. The *N. alpina* plantation site has a humid temperate climate with slight Mediterranean influence, characterized by short and dry summers, and long and wet winters (di Castri and Hajek, 1976). Under the Köppen–Geiger classification, this interior Andean foothill site is also best described as temperate oceanic (Cfb), although with a stronger seasonal precipitation contrast than the coastal *N. dombeyi* site. Mean annual temperature (1990–2020, CR2MET v2.5) is approximately 11 °C, with average minimum and maximum temperatures of 5 °C in the coldest month (August) and 16 °C in the warmest month (February), respectively. Mean annual precipitation (1990–2020, CR2MET v2.5) is approximately 2,850 mm. Frosts are relatively frequent, with 30–50 events per year, and occur most frequently from August through September (Soto et al., 2009).

The *N. dombeyi* plantation is established on soils of the Los Ulmos series (Ultisols), which are clayey soils derived from ancient aeolian sediments deposited over metamorphic parent material of mica schist origin, typical of the Coastal Range. Soil depth ranges from moderately deep to deep, with well-developed structure and favorable physical properties (CIREN—Centro de Información de Recursos Naturales, 2001). The soil profile exhibits reddish-brown coloration throughout, and texture varies from clay loam to clay. Bulk density is moderate to high, and these soils have high water-holding and absorption capacity (CIREN—Centro de Información de Recursos Naturales, 2001). Chemically, they are acidic and rich in aluminum and iron, resulting in strong phosphorus fixation, although to a lesser extent than that observed in Andean volcanic (Trumao) soils (CIREN—Centro de Información de Recursos Naturales, 2001). The *N. alpina* plantation is located on soils derived from recent volcanic ash deposits (Andisol), which are well stratified and underlined by an andesitic–basaltic bedrock (CIREN—Centro de Información de Recursos Naturales, 2001). These soils are deep to moderately deep, rich in organic matter, and exhibit high water retention capacity with moderate internal drainage. Chemically, they are characterized by the presence of allophane, which confers a high potential for phosphorus fixation (Soto et al., 2009).

2.2 Plantations features and tree form assessment

The *N. dombeyi* plantation was established in mid-winter (early August) 2004 using two-year-old bare-root seedlings (1/1), prior to the onset of the growing season. Seedlings were grown in the nursery of the Universidad Austral de Chile and had an average of 60–80 cm in height and 6–8 mm in root-collar diameter. Site preparation was carried out using animal traction (oxen) to reduce soil compaction resulting from previous grazing. Furrows approximately 30 cm deep were opened along contour lines to improve water infiltration and reduce weed competition at the time of establishment. Planting was performed manually with a New Zealand–type planting spade at a spacing of 2.5 × 2.5 m, and no post-planting weed control was applied (Donoso et al., 2009).

The *N. alpina* plantation was established in late fall (May) 2001 also using two-year-old bare-root seedlings, prior to the first snowfall. Detailed morphological data for *N. alpina* seedlings at planting were unavailable; however, based on regional nursery standards (Bustos et al., 2008), they are expected to share similar baseline characteristics with *N. dombeyi*, albeit typically exhibiting a higher root-collar diameter for an equivalent height. Site preparation included the manual removal of shrubs and scattered trees to reduce early competition and facilitate planting.

Seedlings were planted at a spacing of 1.5 × 2.0 m by creating circular planting spots approximately 40 cm in diameter and 30 cm deep using a mattock, which allowed the removal of grasses and loosened the soil (Donoso et al., 2011).

At the time of treatment implementation, trees of both species exhibited comparable size across pruning treatments, despite the inherent variability typical of young plantations (Table 1). In the *N. dombeyi* plantation, mean diameter at breast height (d) ranged from 5.1 to 5.8 cm, mean total height (h) from 4.7 to 5.3 m, and mean stem volume index (v) from 450 to 678 cm³ tree⁻¹ across treatments. One-way ANOVA detected no significant differences among treatments for any of these variables (d : $F = 0.81$, $p = 0.474$; h : $F = 2.40$, $p = 0.146$; v : $F = 1.52$, $p = 0.270$), confirming homogeneous initial conditions prior to pruning experiment. Similarly, in the *N. alpina* plantation, mean d ranged between 4.6 and 4.9 cm, mean h between 5.4 and 5.9 m, and mean v between 440 and 587 cm³ tree⁻¹ among treatments. No significant treatment effects were detected for any growth variable (d : $F = 0.29$, $p = 0.754$; h : $F = 0.46$, $p = 0.648$; v : $F = 0.52$, $p = 0.610$). Overall, these results indicate adequate homogeneity among treatments at the onset of the experiments in each species, allowing subsequent differences in growth and stem form to be

TABLE 1 Mean and standard deviation for diameter (d , cm), height (h , m) and volume (v , cm³ tree⁻¹) per treatment prior to the establishment of the pruning experiment.

Treatments	n	d (cm)	<i>Nothofagus dombeyi</i>	v (cm ³ tree ⁻¹)	n	d (cm)	<i>Nothofagus alpina</i>	v (cm ³ tree ⁻¹)
			h (m)				h (m)	
T1	59	5.5 (1.6)	5.3 (0.7)	575.1 (353.1)	71	4.6 (1.4)	5.4 (1.0)	439.7 (319.2)
T2	31	5.1 (1.5)	4.7 (0.8)	449.9 (292.6)	26	4.9 (1.7)	5.9 (1.1)	587 (475.4)
T3	32	5.8 (1.7)	5.3 (0.9)	677.8 (427.8)	29	4.8 (1.4)	5.7 (1.0)	513.0 (379.8)
F -value		0.81 ns	2.40 ns	1.52 ns		0.29 ns	0.46 ns	0.52 ns

ns: $p > 0.05$.

F -value represents the results 249 obtained from ANOVA using the average sizes and volume per plot.

attributed primarily to treatment effects rather than pre-existing size differences (but see below).

2.3 Experimental design

In each plantation we established 12 plots with each containing approximately 20 trees, which meant different plot sizes for *N. dombeyi* and *N. alpina* due to the initial differences in establishment spacing (see above). Treatments were implemented in 2009—5 years after establishment in *N. dombeyi* and 8 years after establishment in *N. alpina*, but the diameter and height of the trees were similar (Table 1, see above). The three treatments—T1 = control (no pruning; Figure 2c), T2 = form pruning only (removal of forked or dissolved top branches; Figures 2b), and T3 = form plus stem pruning (removal of lower dead and green branches up to one-half of total height plus removal of forked branches above this point; Figure 2c)—were replicated four times within contrasting microsites in each plantation (e.g., upper, middle, and lower slope positions and flat terrain). In the plots assigned for the implementation of T2 or T3 only trees that had high potential quality once pruned were treated, which meant that close to one half of the trees were treated (Table 1). All trees subjected to form pruning in T2 were included. In the case of T3, only trees that received both pruning interventions were considered. Trees classified as form 1 in T2 and T3, as well as those in T3 that received only stem pruning, were excluded from the analysis. Conversely, all trees in the control plots were included in the assessment of periodic annual increment (PAI). Therefore, number of trees (n) used at each treatment per species were different (Table 1). Prior to treatment implementation, an initial inventory was conducted to determine baseline tree dimensions (i.e., d and h) and to classify each tree into form categories (Figure 2b). Thus, pruning treatments were selectively applied based on initial stem form, with trees of poorer form preferentially assigned to more intensive interventions. Last, to clarify the treatments pictorial details of the treatments are shown in Figure 2.

While the same treatments were implemented for each species in an equal number of plots with similar number of trees, the severity of the treatments in each species differed in terms of biomass removal, which was greater in *N. dombeyi*. While we acknowledge this as a major limitation, Figure 3 illustrates the common differences in two young plantations of *N. dombeyi* and *N. alpina*, with the former having thicker lower branches and a higher proportion of forked trees.

What explains this is that in *N. dombeyi* there is a great tendency for the apical bud to abort and be replaced by one or more distal axillary buds, generating forked trees, a tendency that seems more common in open conditions in good sites (Puntieri et al., 1998, 2000), like the one in this study. In addition, *N. dombeyi* develops these characteristics as part of its architecture in response to its pioneer character (Navarro et al., 2025), a great difference with *N. alpina* that is a mid-tolerant species that tends to grow straight, with relatively thin branches (Mason et al., 2018).

2.4 Data management

All measurements were conducted during the dormant season (i.e., May–August) to ensure full-year growth assessment and to minimize seasonal variability. For each year, individual tree volume (v) was estimated using the geometric formula of a cone as an indicator of productivity Equation 1 (Donoso et al., 2009). The equation used was:

$$v(\text{cm}^3 / \text{tree}) = \left\{ \pi * d^2 * h \right\} / 12 \quad (1)$$

The PAI Equation 2 was used as the response variable to evaluate the effects of the silvicultural treatments for d , h and v .

$$\text{PAI}(\text{cm}^3 / \text{tree}) = \left\{ (g_{1+i} - g_0) / (t_{1+i} - t_0) \right\} \quad (2)$$

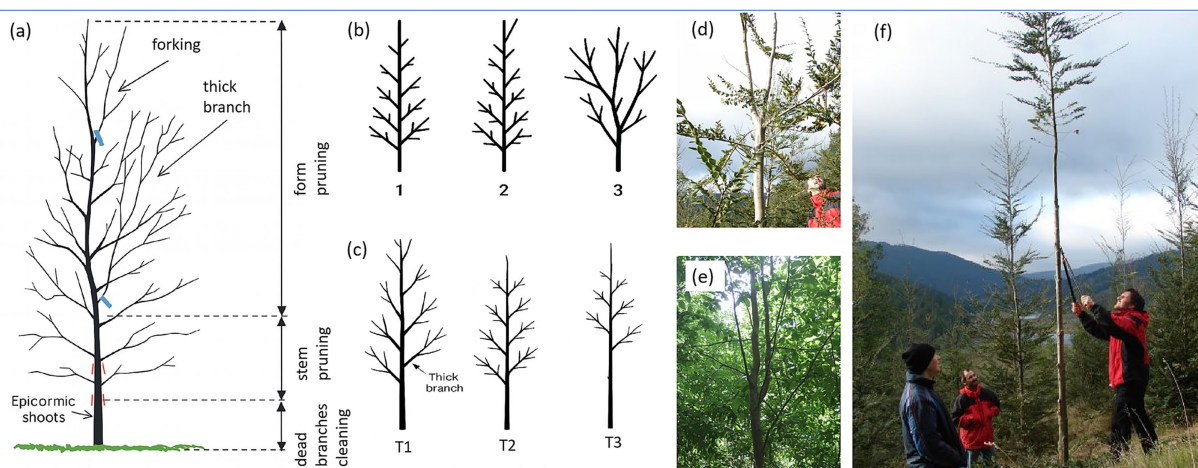


FIGURE 2

(a) General schematic representation of tree architecture of *Nothofagus* (without leaves) illustrating the effects of forking (i.e., loss of epinastic control), thick branches on stem, and crown form. (b) Crown form classification used in this study: (1) straight form without loss of apical control, (2) forked trees (see d, e for each studied species), and (3) trees with dissolved crowns and multiple shoot leaders affecting overall tree quality. (c) Pruning treatments applied in this study: (T1) control (no pruning), (T2) form pruning (removal of upper forked and/or thick branches when present), and (T3) form and stem pruning (removal of forked and/or thick branches plus stem pruning up to one-half of total height; see panel f). (d, e) show examples of the forked trees of *Nothofagus dombeyi* and *Nothofagus alpina*, respectively. (f) Shows the top- and stem-pruning treatment applied in a *N. dombeyi* plantation (photographs by Daniel P. Soto). Photo in f comes from Donoso et al. 2015a.



FIGURE 3

Young plantations that illustrate the greater tendency of *Nothofagus dombeyi* (left) over *Nothofagus alpina* (right) to forking and thicker lower branches, in addition to poorer self pruning (photographs by Pablo J. Donoso).

Where g_{1+i} is the size of a given year $1+i$ respects the size prior to applied the treatments g_0 .

Thus, the growth for year 1 is $(g_1 - g_0)$, for year 2 $(g_2 - g_0)/2$, for year 3 $(g_3 - g_0)/3$, and for year 4 $(g_4 - g_0)/4$. This simple equation was used to isolate the effects of initial size, i.e., prior to the application of the pruning treatments, and to obtain the unbiased growth increment per year (MacFarlane and Kobe, 2006; Soto et al., 2015). The periodic annual increment (PAI) used in this study represents a cumulative measure over time, integrating growth since treatment application. Consequently, PAI values across years are not statistically independent, as later measurements include information from previous periods.

The relative response of each silvicultural treatment (T2 and T3) in relation to the unpruned control (T1) was evaluated using the following formula Equation 3, which expresses the percentage difference in growth performance between treatments:

$$RR(\%) = \left\{ \left(\frac{X_t - X_c}{X_c} \right) \times 100 \right\} \quad (3)$$

Where RR is the relative response (%), X_t is the mean value of the growth variable (d , h , or v) for each silvicultural treatment, and X_c is the corresponding mean value for the control treatment at the specific year. Positive values indicate a relative increase in growth compared with the control, while negative values denote a relative reduction associated with the treatment through time of the study.

2.5 Data analysis

All statistical analyses were performed using plot-level means as the unit of replication. Individual tree measurements were averaged within each plot prior to analysis, resulting in four independent replicates per treatment to avoid pseudoreplication and ensure consistency with the experimental design. Prior to this, the data for PAI in d , h , and v per plot were tested for normality using the Shapiro–Wilk test and for homogeneity of variances using Levene's test (Sokal and Rohlf, 2012). A one-way analysis of variance (ANOVA) was then performed to evaluate treatment effects per each year of evaluation. When significant differences were detected in ANOVA, a *post-hoc* comparison was conducted using the Least Significant Difference (LSD) test

(Sokal and Rohlf, 2012). A significant level of 0.05 (95% confidence) was applied to all statistical analyses.

To summarize the structural responses to pruning, we calculated the mean proportion of trees in each stem form class (Form 1–3) for each treatment and species. Stem form classes were evaluated at the end of the monitoring period (year 4) based on visual assessments of stem straightness and apical dominance (Figure 2b). A bar plot was produced to display the mean percentage of trees per form class across four replicated plots per treatment, providing an estimate of central tendency. Given the exploratory nature of stem form transitions and the limited number of replicates ($n = 4$), no formal statistical tests were applied to proportional differences among treatments. Instead, variability among plots was represented using standard error.

To visualize changes in stem form classes over time and among pruning treatments, we used Sankey flow diagrams, which depict transitions among discrete categorical states while preserving their relative frequencies. For each species, transition matrices were constructed between the initial (Form 0) and final (Form 4) stem form classes, separately for each treatment (T1: control, T2: form pruning, T3: top plus stem pruning). The width of each flow was scaled according to the number of trees transitioning between form classes, providing a proportional representation of improvement (Form4 < Form0), deterioration (Form4 > Form0), or stability (Form4 = Form0). This graphical approach offers an intuitive means of visualizing categorical dynamics through time and has been increasingly applied in ecological and forestry studies to represent state transitions, management effects, or disturbance responses (Riehmman et al., 2005; Lupton and Allwood, 2017; Petrokofsky et al., 2025). This analysis was performed in Python using the `plotly.graph_objects` library.¹

3 Results

3.1 Effects of pruning treatments on growth

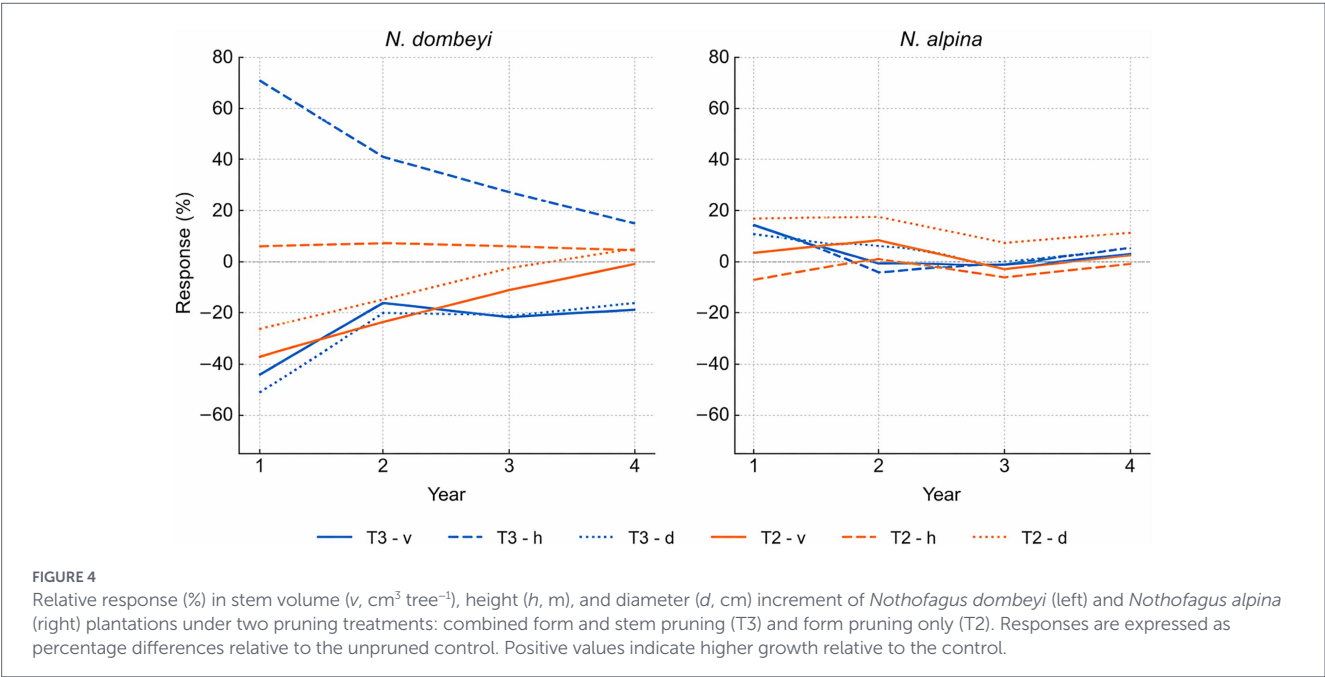
The effect of pruning treatments on tree growth varied according to species and time since intervention (Table 2). In *N. dombeyi*, the first year after treatments had a significant lower growth in d (nearly 50%) in T3 compared to T1. While the magnitude of these differences declined with time, T3 had significant lower growth in d compared to both T1 and T2 (which did not differ) in years 3 and 4. Growth in h did not significantly differ between treatments for any year, but every year growth behaved with $T3 > T2 > T1$, i.e., as opposed to growth in d . Consequently, growth in v was significantly different among treatments only in year four, with T1 and T2 greater than T3. This pattern was consistent with the relative growth response (Figure 4), where *N. dombeyi* exhibited a sustained reduction in growth, especially in T3 plots relative to control plots, which showed decreases of up to 20–25% during the first years after pruning, whereas T2 exhibited a smaller reduction and a gradual recovery by the fourth year. Growth in d followed similar patterns. In both the initial and final measurement years, trees subjected to T3 showed the lowest mean values in d (1.68 cm at year 4), whereas trees under T2 and the control reached the highest values in d (2.11–2.01 cm), with

¹ <https://plotly.com/python/>

TABLE 2 Summary of mean annual increment ($\pm$ SE) for stand structural variables (d , h , v) during 4 years of evaluation in *Nothofagus dombeyi* and *Nothofagus alpina* plantations, respectively.

Species	Variable	Treatments	Year 1	Year 2	Year 3	Year 4
<i>Nothofagus dombeyi</i>	d (cm)	T1	3.87a (0.79)	2.73a (0.10)	2.29a (0.07)	2.01a (0.06)
		T2	2.86ab (0.21)	2.32ab (0.22)	2.24a (0.07)	2.11a (0.07)
		T3	1.89b (0.79)	2.17b (0.07)	1.80b (0.06)	1.68b (0.08)
		F-value	4.32*	4.07*	16.76***	8.53**
	h (m)	T1	1.38 (0.12)	1.17 (0.07)	1.06 (0.03)	1.14 (0.02)
		T2	1.46 (0.06)	1.25 (0.03)	1.12 (0.03)	1.19 (0.03)
		T3	2.34 (0.83)	1.65 (0.44)	1.34 (0.31)	1.31 (0.2)
		F-value	1.19 ns	0.98 ns	0.65 ns	0.54 ns
	v (cm ³)	T1	112.19 (23.45)	98.32 (7.19)	98.40 (4.15)	107.23a (3.99)
		T2	70.58 (6.96)	75.22 (12.72)	87.45 (3.68)	105.98a (5.22)
		T3	62.86 (10.22)	82.22 (10.43)	76.95 (7.66)	86.91b (6.17)
		F-value	3.00 ns	1.30 ns	3.85 ns	4.78*
<i>Nothofagus alpina</i>	d (cm)	T1	0.98 (0.04)	0.95 (0.06)	0.91 (0.04)	0.79 (0.03)
		T2	1.15 (0.07)	1.12 (0.05)	0.98 (0.02)	0.88 (0.00)
		T3	1.08 (0.05)	1.01 (0.07)	0.92 (0.03)	0.82 (0.04)
		F-value	2.14 ns	1.75 ns	1.49 ns	2.13 ns
	h (m)	T1	1.14 (0.22)	1.16 (0.07)	1.29 (0.03)	1.06 (0.02)
		T2	1.06 (0.09)	1.17 (0.09)	1.21 (0.03)	1.05 (0.02)
		T3	1.31 (0.22)	1.11 (0.13)	1.28 (0.08)	1.12 (0.06)
		F-value	0.78 ns	0.11 ns	0.79 ns	0.87 ns
	v (cm ³)	T1	26.04 (2.73)	31.01 (3.55)	36.73 (4.06)	33.59 (3.47)
		T2	26.86 (3.23)	33.64 (4.55)	35.55 (2.67)	34.42 (2.09)
		T3	29.61 (5.62)	30.72 (2.99)	36.19 (4.50)	34.59 (3.55)
		F-value	0.21 ns	0.18 ns	0.02 ns	0.03 ns

ns: $p > 0.05$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Bold values indicate that they are statistically significant.



statistically significant differences ($p < 0.05$). No pruning effects were detected on h ($p > 0.05$), suggesting that growth reductions were mainly concentrated in diameter and biomass-related variables, which are more sensitive to foliage loss.

In *N. alpina*, pruning treatments produced no significant differences in growth in any of the tested variables (d , h and v) in any evaluation year ($p > 0.05$ in all cases; Table 2). d (0.79–1.15 cm), h (1.06–1.31) and v (26–37 cm³) mean annual growth values remained relatively stable across treatments and years. The relative growth response (Figure 4) confirmed this trend: both T2 and T3 curves remained close to 0% relative to the control, showing no evident reductions throughout the study period. Because of these results there were no significant species-treatment interactions (not shown).

3.2 Short-term effects of pruning treatments on stem form

At the end of the monitoring period, 4 years after pruning, the distribution of stem form classes showed clear species- and treatment-specific responses (Figure 5). In *N. dombeyi*, the proportion of Form 1 trees increased markedly from 15% in the control (T1) to 48% under form pruning (T2) and 63% under the combined form + stem pruning (T3), while Form 3 trees decreased from 20 to 0% (Figure 5). In *N. alpina*, the improvement was even more pronounced, with Form 1 trees rising from 39% in the control plots to 59 and 89% under T2 and T3 plots, respectively, and the proportion of Form 3 trees falling below 2% in both pruning treatments (Figure 5).

Sankey diagrams revealed distinct pathways of stem form development in *N. dombeyi* and *N. alpina* across pruning treatments (Figure 6). In *N. dombeyi*, control plots (T1) showed structural changes, with most trees retaining their original form class and few changing from Form 1 to Form 2, or from Form 2 to Form 3 (Figure 6). Form pruning (T2) induced partial enhancement, as approximately half of the trees initially classified as Form 2 improved to Form 1, while a small fraction of Form 3 individuals improved to Form 2 (Figure 6). The combined top and stem pruning treatment (T3) produced the greatest effect, with a dominant upward transition from Form 2 to Form 1 and the near disappearance of Form 3 trees. Downward transitions (Form 1 → 2 or 3) were negligible, indicating

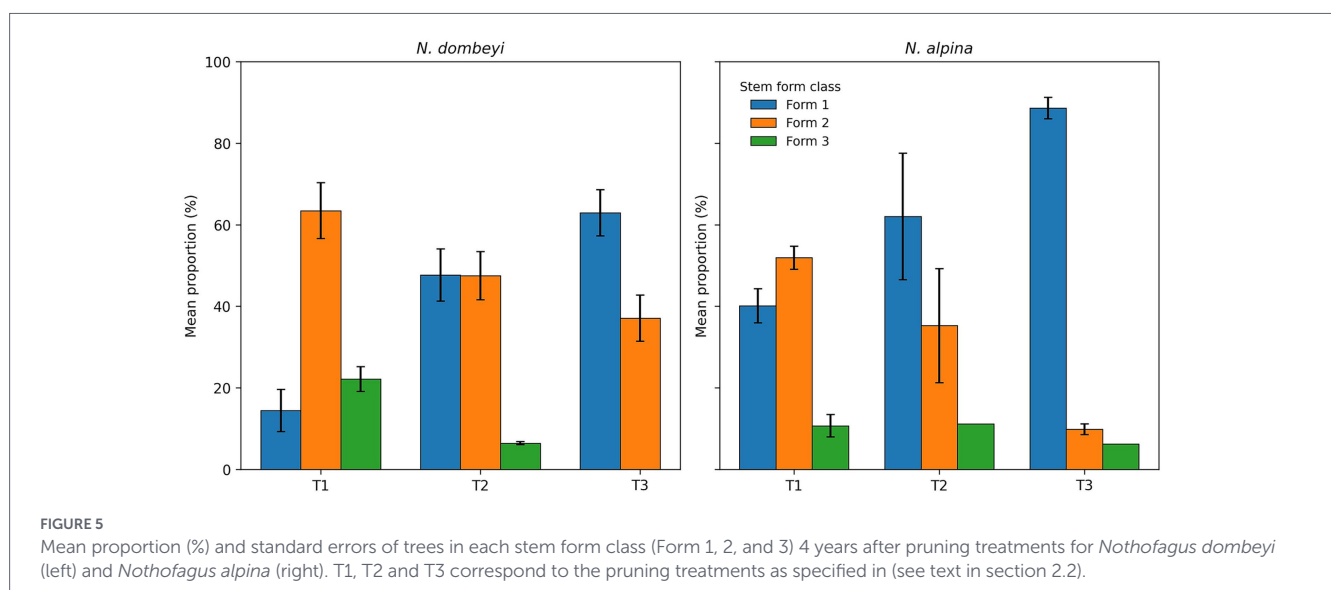
a consistent improvement in stem quality during the 4 years after the implementation of the pruning treatments.

In *N. alpina*, there were also some structural changes, with most trees retaining their original form class 4 years after the implementation of the treatments, and only a few trees changing from Form 1 to Form 2 or from Form 2 to Form 3 (Figure 6). Form pruning (T2) substantially enhanced stem quality, with a large proportion of trees improving from Form 2 to Form 1, but also with a similar proportion of trees degrading from Form 1 to Form 2 (Figure 6). The combined pruning treatment (T3) generated the most pronounced upward flow, with nearly all trees attaining Form 1 4 years after pruning and only a minimal proportion remaining in lower-quality classes (Figure 6). A small fraction of downward transitions was detected under T3.

4 Discussion

4.1 Differential responses of *N. alpina* and *N. dombeyi* to pruning

Our findings demonstrate that artificial pruning exerts contrasting effects on growth performance in the evergreen *N. dombeyi* and the deciduous *N. alpina*, suggesting species specific growth and morphological responses to canopy reduction. Although both plantations had similar initial tree sizes at the onset of the experiment [but different ages since *N. dombeyi* grows faster (e.g., Donoso et al., 2011, 2015a)] and had the same pruning treatments implemented, the combined form and stem pruning treatment (T3) significantly reduced radial and stem volume growth in *N. dombeyi*, whereas no such effects were detected in *N. alpina*, which exhibited quite stable growth for all the evaluated variables through all years of evaluation. These results suggest that the trade-off between photosynthetic capacity loss associated with leaf area removal and improvements in stem quality and structure may be species dependent, likely driven by differences in light requirements, crown plasticity, and apical dominance control (Niinemets, 2010; Alcorn et al., 2013). However, this interpretation has to be considered cautiously in this case due especially to differences in plantation densities. The fact that the *N. dombeyi* plantation was more sensitive to pruning although



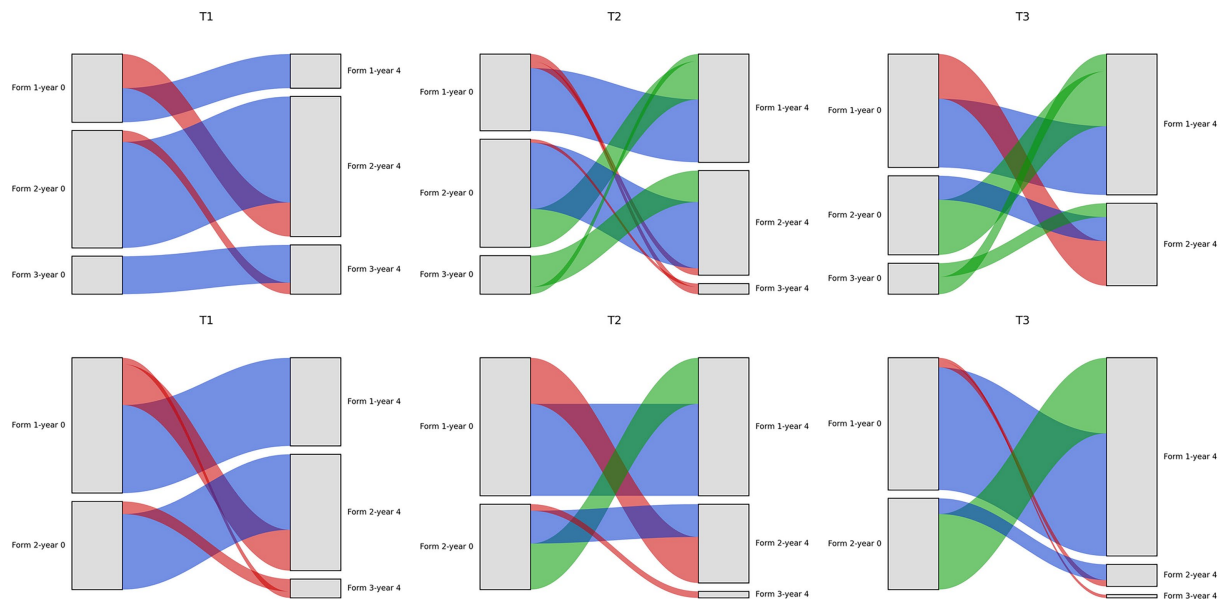


FIGURE 6

Sankey diagrams of stem form transitions (year 0 or pre-treatment to year 4 posttreatment) for *Nothofagus dombeyi* and *Nothofagus alpina*. Upper row: *N. dombeyi*; lower row: *N. alpina*. From left to right: T1 (Control), T2 (Form pruning), and T3 (Form + Stem pruning). Each diagram depicts transitions in individual stem form classes between 2009 and 2012 (Form 1 → Form 3). Flow width is proportional to the number of trees in each transition. Green indicates improvement, blue indicates no change, and red indicates deterioration.

it had lower higher density reflects that differences in tree densities may alter this preliminary inference, although it is well reported that natural secondary forests of *N. dombeyi* have higher trees densities for equivalent mean diameters in full-density stands compared to *N. alpina* (Lusk and Ortega, 2003; Gezan et al., 2007). Therefore, different tree densities in both plantations may have reflected similar competition status between trees in each case. If this was the case, the contrasting responses reported in this study would reflect the need to adjust pruning severity and timing according to species-specific ecological strategies—especially growth and competition dynamics and tree architecture—rather than applying uniform silvicultural prescriptions across species (Carson et al., 2014; Navarro et al., 2025). In fact, tree architecture and allometry is very different, although poorly reported, in these two *Nothofagus* species. Donoso et al. (2015a), Puntieri et al. (1998, 2000), Navarro et al. (2024) report that *N. dombeyi* has a great tendency to developing thick branches and forking, while Mason et al. (2018) mention that *N. alpina* has excellent stem form with good self-pruning, although the latter statement is arguable (Donoso et al., 2015a). These differences illustrate that pruning opportunity and severity require further experimentation in each species and even more when jointly comparing their responses.

In *N. dombeyi*, the reductions in diameter and stem volume growth observed with T3 reflect a high sensitivity to canopy reduction and a limited short-term capacity to compensate for the loss of photosynthetic biomass. This is an important warning for the pruning practice in this species. In favorable sites or environments in south-central Chile, such as the one in this study, young *N. dombeyi* plantations already have a great proportion of poorly formed trees (Donoso et al., 2009), and if there is no pruning of these plantations at ages 30–40 year just few trees have Form 1 trees (see Navarro et al., 2025). Under this context, combined pruning represents a justified early tending intervention to prevent stem forking and promote long-term stem quality, accepting temporary growth reductions in exchange for

improved timber value (Pinkard and Beadle, 2000; Carson et al., 2014). Similar trade-offs between stem form improvement and short-term growth decline have been widely reported in shade-intolerant broadleaved species, such as *Fraxinus excelsior* and *Juglans regia*, particularly when pruning removes ≥ 40 –50% of green crown length (Bulfin and Radford, 1998; Pinkard et al., 1999). *Fraxinus excelsior* is a strong resprouting species (as *N. alpina*) while *Juglans regia* is a weak resprouting species (as *N. dombeyi*, which does not resprout), and the former has a better response to pruning, also like *N. alpina* in this study. According to these and other studies (e.g., Leng et al., 2025) low severity pruning seems convenient to improve form without reducing growth. Our results therefore reinforce the need to carefully regulate pruning intensity in *N. dombeyi*, preferably limiting green-crown removal to approximately one-third of total tree height during the early stage of the plantation, to minimize physiological stress and preserve sufficient crown area for post-pruning recovery (Pinkard and Beadle, 1998; Nyland, 2002; Forrester, 2013; Carson et al., 2014). In addition, form pruning should be applied selectively to a limited proportion of trees—ideally those expected to remain after the first thinning—to maximize economic returns while avoiding unnecessary growth reductions at the stand level and reducing the high cost of this tending practice (Donoso et al., 2015a).

Anyhow, stem or form pruning in species with a high tendency to forking, such as *N. dombeyi*, is recommended once canopy closure has occurred (Kerr and Morgan, 2006).

Despite the initial reductions in diameter and volume growth observed in *N. dombeyi*, both species exhibited growth stabilization or partial recovery within 4 years after pruning, highlighting the high plasticity and compensatory capacity of young trees. Following leaf area removal, trees can increase photosynthetic rates and nitrogen concentration in remaining leaves, mobilize non-structural carbohydrate reserves, and adjust carbon allocation

to restore crown function, prioritizing shoot elongation and new foliage production (Pinkard et al., 1999; Maurin and Desrochers, 2013; Zhang and Liu, 2021). Hormonal regulation associated with apical dominance—particularly auxin–cytokinin–strigolactone interactions—also plays a central role in re-establishing a dominant leader and suppressing competing shoots after pruning (Ferguson and Beveridge, 2009; Beveridge et al., 2023). Moreover, because foliage located in the lower crown typically exhibits lower carbon-use efficiency due to higher respiration costs, so that its removal may partially offset the negative effects of reduced leaf area, particularly under high stand density and limited light availability (Pinkard and Beadle, 2000), which was the case for both species in this study.

The transient increase in height growth observed in *N. dombeyi* during the first year after severe pruning (T3) likely reflects a short-term allocation shift toward vertical growth aimed at restoring crown position and light interception. This response is consistent with the architectural plasticity of the species, which exhibits sympodial axis construction, short persistence of the apical meristem, and frequent development of shoots in the upper crown (Puntieri et al., 1998, 2002). After pruning, the remaining leader may exhibit enhanced elongation and branching in the upper crown, facilitating rapid reconstruction of lost foliage and contributing to subsequent growth recovery. Similar transient “height-first” recovery patterns have been reported in other fast-growing and shade-intolerant species, including *Pinus radiata*, where pruning induces temporary changes in shoot structure until foliage mass and growth trajectories are restored (Fernández et al., 2017). Together, these mechanisms explain why early pruning in *N. dombeyi* leads to short-term growth reductions but does not compromise medium-term growth potential when applied with appropriate severity (ideally no more than one-third of the crown) and developmental stage (early, when the trees are vigorous and have rapid growth rates).

The absence of significant growth differences among treatments in *N. alpina* indicates that moderate pruning can be safely applied in this species without compromising growth, further supporting its suitability for high-quality timber plantations (Donoso et al., 2015a). From a management perspective, these results suggest that early pruning—when trees are below approximately 8–10 cm in diameter at breast height or 5–8 years of age—represents a strategic window to improve stem form while maintaining overall stand growth potential. This approach enhances the long-term production of clear, knot-free logs and supports the development of profitable silvicultural systems for high-value timber in southcentral Chile (Navarro et al., 2025). Considering the high stand density at the time of pruning (3,333 trees ha⁻¹) and the young developmental stage of the plantation, the lack of growth response in *N. alpina* may also reflect the low light exposure and limited photosynthetic contribution of the removed branches. Under dense, unthinned conditions, foliage distribution tends to be concentrated in the upper, more light-exposed portions of the crown, whereas lower branches contribute relatively little to carbon gain (Pinkard and Beadle, 2000). Consequently, the removal of shaded lower foliage in *N. alpina* likely had a negligible effect on whole-tree carbon balance, allowing growth rates to remain stable despite pruning.

4.2 Study limitations

We acknowledge that these results have to be interpreted cautiously for two reasons: (a) we did not report biomass removal in

each species, although it was greater for *N. dombeyi* as a response to the different growth and branching patterns of the two species (Puntieri et al., 1998, 2000; Donoso et al., 2006a,b), and (b) the planting distance on the two experiments were different (1.5 × 2 m in *N. alpina* and 2.5 × 2.5 m in *N. dombeyi*). The first reason may be part of the explanation why *N. dombeyi* had a significant loss in growth when subjected to combined pruning, which did not occur for *N. alpina*. The second reason may explain why the recovery in *d* and *v* growth of *N. dombeyi* was relatively more rapid than *N. alpina*, although also the relatively lower biomass removal in *N. alpina* trees may explain the low growth recovery rates of this species following the implementation of the treatments. On the other hand, a couple of concerns might be acknowledge: first is in regards to analysis the PAI was calculated as cumulative metric, and temporal dependence among years may lead to conservative interpretations of year-specific differences, and the second concern is that usually pruning must be accompanied by thinning (Hubert and Courraud, 1989), since thinning allows the lower crown of the pruned trees to receive more light and fix more carbon (Forrester, 2013). That was not the case in the present study. Had thinning being conducted, most likely responses would have been different in both species. That is a pending experiment in plantations with these species. However, managers have to consider that in hardwood species with a high tendency to forking and the development of thick low branches, such as *N. dombeyi*, early pruning without thinning may be necessary.

4.3 Implications for forest management

Several challenges remain for the large-scale implementation of pruning regimes in plantations of *Nothofagus* tree species in Chile. Investment in plantations—particularly those based on native species—entails relatively high uncertainty due to the limited availability of mid- and long-term empirical evidence supporting their growth performance and responses to silvicultural treatments (Donoso et al., 2015a; Navarro et al., 2025), and economic returns (Cubbage et al., 2007; Navarro et al., 2025), although some important progress has occurred during the last years. One key premise to reduce this uncertainty is that plantations should be preferentially established on high-quality sites for each species, where physiological recovery following pruning and effective wound occlusion are more likely to occur (Forrester, 2013; Mäkinen et al., 2020). In that way, management decisions must also consider the need, timing, and severity of complementary silvicultural treatments, as well as the expected proportions and economic value of different wood products obtained through thinning operations and final harvest under even-aged management systems (Navarro et al., 2025). Long-term studies remain essential to assess the cumulative effects of pruning on wood properties, decay risk, and interactions with thinning regimes in these *Nothofagus* species, particularly as these factors ultimately determine product quality and stand profitability (Auty et al., 2012; Forrester, 2013).

Beyond biophysical considerations, socio-economic factors—including labor costs, timber market dynamics, and landowners' perceptions, expectations, and risk tolerance—will strongly influence the adoption of native-species plantations. These factors are further shaped by public policies aimed at promoting the

establishment and management of native forests (Donoso and Navarro, 2025). At the same time, increasing international commitments and local demands related to landscape diversification and climate change mitigation and adaptation are generating renewed interest among a broad range of stakeholders in native tree plantations. Accelerating this transition will require sustained applied research, adequate incentives or subsidy schemes, and improved availability of high-quality planting material (Bannister et al., 2018; Donoso and Navarro, 2025). In this context, the high growth potential and timber value of *Nothofagus* species, combined with appropriate governance and market frameworks, provide a strong foundation for the development of productive and high-value native-species plantations in south-central Chile. These may be managed through traditional even-aged systems or alternative ones that conduct these initially even-aged plantations towards more structurally (Donoso et al., 2024) and compositionally (Romero-Mieres et al., 2025) complex productive forests. In any case, whichever the objective of these plantations may be, landowners will likely expect to have positive financial returns from harvested trees, and those returns will be significantly greater if planned silvicultural systems that include pruning are considered. If there will ever be a state subsidy for native plantations in Chile, such as the one that triggered plantations of exotic tree species (Salas et al., 2016), it must consider pruning among other silvicultural treatments. This instrument will enable profitable plantations of hardwood native species which would also benefit landscape diversification, but meanwhile more experiments should provide guidelines on the effects of pruning regimes depending on species, sites and timing, among other variables.

5 Conclusion

Artificial pruning produced contrasting growth responses in *N. dombeyi* and *N. alpina*. In *N. dombeyi*, more severe pruning significantly reduced diameter and stem volume growth, whereas *N. alpina* maintained stable growth across pruning treatments. These differences between these species may have several despite these short-term growth reductions, pruning markedly improved stem form in both species, supporting its use as an effective early treatment to enhance future timber quality. To minimize physiological stress and growth reductions, pruning should be applied at early developmental stages and should limit green-crown removal to no more than one-third to one-half of total tree height. Overall, these findings emphasize the need for species-specific pruning regimes when managing native *Nothofagus* plantations, balancing short-term growth responses with long-term improvements in stem quality and timber value. However, since this is the first report on pruning effects in these or other native hardwood plantations in Chile, with a relatively modest experiment that lacked a more robust potential experimental design, there is a great challenge to increase the evaluation of pruning regimes in hardwood native plantations with rapid growth rates and high timber value. These plantations are strategic for environmental and economic reasons in south-central Chile.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

DS: Writing – review & editing, Data curation, Writing – original draft, Investigation, Formal analysis, Conceptualization. PD: Investigation, Funding acquisition, Conceptualization, Project administration, Writing – review & editing, Methodology, Supervision. CN: Conceptualization, Funding acquisition, Project administration, Writing – review & editing. MF: Conceptualization, Writing – review & editing.

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Conflict of interest

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References

- Alcorn, P. J., Forrester, D. I., Thomas, D. S., James, R., Smith, R. G. B., Nicotra, A. B., et al. (2013). Changes in whole-tree water use following live-crown pruning in young plantation-grown *Eucalyptus pilularis* and *Eucalyptus cloeziana*. *Forests* 4, 106–121. doi: 10.3390/f4010106
- Alderman, D. R., Brinberg, D., and Wiedenbeck, J. (2010). Forestry practices and veneer log value—manufacturer's assessments of veneer log attributes. *For. Sci.* 56, 193–200. doi: 10.1093/forestscience/56.2.193
- Auty, D., Weiskittel, A. R., Achim, A., Moore, J. R., and Gardiner, B. A. (2012). Influence of early re-spacing on Sitka spruce branch structure. *Ann. For. Sci.* 69, 93–104. doi: 10.1007/s13595-011-0141-8
- Bannister, J. R., Vargas-Gaete, R., Ovalle, J. F., Acevedo, M., Fuentes-Ramirez, A., Donoso, P. J., et al. (2018). Major bottlenecks for the restoration of natural forests in Chile. *Restor. Ecol.* 26, 1039–1044. doi: 10.1111/rec.12880
- Beveridge, C. A., Rameau, C., and Wijerathna-Yapa, A. (2023). Lessons from a century of apical dominance research. *J. Exp. Bot.* 74, 3903–3922. doi: 10.1093/jxb/erad137
- Bulfin, M., and Radford, T. (1998). Effect of early formative shaping on newly planted broadleaves—part 2: height and diameter growth. *Irish For.* 55, 52–61. Available online at: <https://www.cabidigitallibrary.org/doi/full/10.5555/20000605940>
- Bustos, F., González, M. E., Donoso, P. J., Gerding, V., Donoso, C., and Escobar, B. (2008). Efectos de distintas dosis de fertilizante de liberación controlada (Osmocote®) en el desarrollo de plantas de coigüe, raulí y ulmo. *Bosque* 29, 155–161. doi: 10.4067/S0717-92002008000200008
- Carson, S. D., Cown, D. J., McKinley, R. B., and Moore, J. R. (2014). Effects of site, silviculture and seedlot on wood density and estimated wood stiffness in radiata pine at midrotation. *New Zeal. J. For. Sci.* 44:26. doi: 10.1186/s40490-014-0026-3
- CIREN—Centro de Información de Recursos Naturales (2001) in *Estudio Agrológico X Región: Descripción de suelos, materiales y símbolos*, ed. Ministerio de Agricultura (Santiago). (Reporte Técnico N°123)
- Cubbage, F., MacDonagh, P., José, S. J., Rubilar, R., Donoso, P., Ferreira, A., et al. (2007). Timber investment returns for selected plantations and native forests in South America and the southern United States. *New For.* 33, 237–255. doi: 10.1007/s11056-006-9025-4
- di Castri, F., and Hajek, E. R. (1976). *Bioclimatología de Chile*. Santiago: Vicerrectoría Académica Pontificia Universidad Católica de Chile, 128.
- Díaz-Vaz, J. E., Poblete, H., Juacida, R., and Devlieger, F. (2002). *Maderas comerciales de Chile*. 3ª Edn Valdivia: Marisa Cuneo Ediciones.
- Donoso, C. (1993). *Bosques templados de Chile y Argentina: variación, estructura y dinámica*. Santiago: Editorial Universitaria.
- Donoso, P. J., Donoso, C., Baldini, A., Escobar, B., and Gallo, L. (2006a). Especies arbóreas de los bosques templados de Chile y Argentina. *Autoecología*. Capítulo Nothofagus obliqua. Marisa Cuneo Ediciones, 471–485.
- Donoso, P. J., Donoso, C., Escobar, B., Navarro, C., and Gallo, L. (2006b). Especies arbóreas de los bosques templados de Chile y Argentina. *Autoecología*. Capítulo Nothofagus dombeii. Marisa Cuneo Ediciones, 423–432.
- Donoso, P. J., Muñoz, A. A., Thiers, O., Soto, D. P., and Donoso, C. (2011). Effects of aspect and type of competition on the early performance of *Nothofagus dombeii* and *Nothofagus nervosa* in a mixed plantation. *Can. J. For. Res.* 41, 1075–1081. doi: 10.1139/x11-019
- Donoso, P. J., and Navarro, C. (2025). *Silvicultura y Manejo de Bosques Nativos. Ecología aplicada para la conservación de ecosistemas forestales*. Santiago: Editorial Universitaria.
- Donoso, P. J., Navarro, C., Soto, D. P., Gerding, V., Thiers, O., Pinares, J., et al. (2015a). *Manual de plantaciones de raulí (Nothofagus alpina) y coihue (Nothofagus dombeii) en Chile*. Temuco: Universidad Católica de Temuco.
- Donoso, P. J., Navarro, C., Vásquez-Grandón, A., Larraín, O., González-Chang, M., Romero, M., et al. (2024). La silvicultura ecológica: un modelo para plantaciones de especies del género *Nothofagus* en Chile. *Bosque* 45, 385–391. doi: 10.4067/s0717-92002024000300385
- Donoso, P. J., Soto, D. P., and Fuentes, C. (2015b). Differential growth rates through the seedling and sapling stages of two *Nothofagus* species underplanted at low-light environments in an Andean high-graded forest. *New For.* 46, 885–895. doi: 10.1007/s11056-015-9480-x
- Donoso, P. J., Soto, D. P., Schlatter, J. E., and Büchner, C. A. (2009). Effects of early fertilization on the performance of *Nothofagus dombeii* planted in the coastal range of south-central Chile. *Cienc. Investig. Agrar.* 36, 475–486. doi: 10.4067/S0718-16202009000300014
- Ferguson, B. J., and Beveridge, C. A. (2009). Roles for auxin, cytokinin, and strigolactone in regulating shoot branching. *Plant Physiol.* 149, 1929–1944. doi: 10.1104/pp.109.135475
- Fernández, M. P., Basauri, J., Madariaga, C., Menéndez, M., Olea, R., and Zubizarreta, A. (2017). Effects of thinning and pruning on stem and crown characteristics of radiata pine (*Pinus radiata* D. Don). *iForest* 10:383. doi: 10.3832/for2017-009
- Forrester, D. I. (2013). Growth responses to thinning, pruning and fertiliser application in *Eucalyptus* plantations: a review of their production ecology and interactions. *For. Ecol. Manag.* 310, 336–347. doi: 10.1016/j.foreco.2013.08.047
- Frêne, C., Dörner, J., Zúñiga, F., Cuevas, J. G., Alfaro, F. D., and Armesto, J. J. (2019). Ecohydrological functions in forested catchments of southern Chile. *Ecosystems* 23, 307–323. doi: 10.1007/s10021-019-00404-7
- Fuenzalida, P. (1971). *Climatología de Chile*. Santiago: Editorial Universitaria.
- Gezan, S., Ortega, A., and Andenmatten, E. (2007). Diagramas de manejo de la densidad para bosque secundarios de Roble, Raulí y Coigüe en Chile. *Bosque* 28, 97–105.
- Hu, M., Briggert, A., Olsson, A., Johansson, M., Oscarsson, J., and Säll, H. (2018). Growth layer and fibre orientation around knots in Norway spruce: a laboratory investigation. *Wood Sci. Technol.* 52, 7–27. doi: 10.1007/s00226-017-0952-3
- Hubert, M., and Courraud, R. (1989). Poda y formación de árboles forestales. Madrid: mundi-Prensa. Kerr G., and Morgan G. 2006. Does formative pruning improve the form of broadleaved trees? *Can. J. For. Res.* 36, 132–141.
- Kerr, G., and Morgan, G. (2006). Does formative pruning improve the form of broad-leaved trees? *Can. J. For. Res.* 36, 132–141.
- Leng, W., Cao, P., Chen, C., and Tang, L. (2025). The influence of pruning on the growth and wood properties of *Populus deltoides* “Nanlin 3804”. *Forests* 16:848. doi: 10.3390/f16050848
- Loewe, V., and González, M. (2002). *Técnicas de poda para producir maderas duras de alta calidad y valor*. Santiago: INFOR.
- Lupton, R. C., and Allwood, J. M. (2017). Hybrid Sankey diagrams: visual analysis of multidimensional data for understanding resource use. *Resour. Conserv. Recycl.* 124, 141–151. doi: 10.1016/j.resconrec.2017.05.002
- Lusk, C. H., and Ortega, A. (2003). Vertical structure and basal area development in second-growth *Nothofagus* stands in Chile. *J. Appl. Ecol.* 40, 639–645.
- MacFarlane, D. W., and Kobe, R. K. (2006). Selecting models for capturing tree-size effects on growth resource relationships. *Can. J. For. Res.* 36, 1695–1704.
- Mäkinen, H., Korppinen, H., Raatevaara, A., Heikkinen, J., Alatalo, J., and Uusitalo, J. (2020). Predicting knottiness of scots pine stems for quality bucking. *Eur. J. Wood Wood Prod.* 78, 143–150. doi: 10.1007/s00107-019-01476-x
- Mason, B., Jinks, R., Savill, P., and McG, W. S. (2018). Southern beeches (*Nothofagus* species) Rauli (*Nothofagus alpina* syn. *N. procera*), roble (*Nothofagus obliqua*) and related species. *Q. J. For.* 112, 30–43. Available online at: <https://www.cabidigitallibrary.org/doi/full/10.5555/20183042456>
- Maurin, V., and Desrochers, A. (2013). Physiological and growth responses to pruning season and intensity of hybrid poplar. *For. Ecol. Manag.* 304, 399–406. doi: 10.1016/j.foreco.2013.05.039
- Navarro, C., Donoso, P. J., Soto, D. P., and Esse, C. (2025). Silvicultural systems and estimated profitability of *Nothofagus dombeii* plantations: an option for forestry diversification in Chile. *New For.* 56:4. doi: 10.1007/s11056-024-10073-7
- Navarro, C., Donoso, P. J., Vásquez-Grandón, A., Larraín, O., González-Chang, M., Romero-Mieres, M., et al. (2024). *Manual de Sistemas Silviculturales Ecológicos (SSE) en plantaciones de Coihue y Raulí para la mitigación y adaptación al cambio climático en Chile*. Temuco: Universidad Católica de Temuco.
- Niinemets, Ü. (2010). Responses of forest trees to single and multiple environmental stresses from seedlings to mature plants: past stress history, stress interactions, tolerance and acclimation. *For. Ecol. Manag.* 260, 1623–1639. doi: 10.1016/j.foreco.2010.07.054
- Nyland, R. D. (2002). *Silviculture: Concepts and Applications*. New York: McGraw-Hill.
- Oosterbaan, A., Hochbichler, E., Nicolescu, V. N., and Spiecker, H. (2009). Silvicultural principles, goals and measures in growing valuable broadleaved tree species. *Die Bodenkultur* 60, 45–51.
- Perry, G. L. W., Brock, J. M. R., and Veblen, T. T. (2025). A systematic review of 65 years of research on *Nothofagus*: an iconic southern hemisphere genus. *Austral Ecol.* 10:e70130. doi: 10.1111/aec.70130
- Petrokofsky, G., Dunn, M., Edwards, D., Harvey, W., Hemery, G. E., Marshall, H., et al. (2025). Development of a tool for navigating the evidence concerning land managers and woodland creation in the United Kingdom. *Forests* 15, 1–12. doi: 10.3390/f15020299
- Pinkard, E. A., Battaglia, M., Beadle, C. L., and Sands, P. J. (1999). Modeling the effect of physiological responses to green pruning on net biomass production of *Eucalyptus nitens*. *Tree Physiol.* 19, 1–12. doi: 10.1093/treephys/19.1.1
- Pinkard, E. A., and Beadle, C. L. (1998). Regulation of photosynthesis in *Eucalyptus nitens* (Deane and Maiden) Maiden following green pruning. *Trees* 12, 366–376. doi: 10.1007/PL00009722
- Pinkard, E. A., and Beadle, C. L. (2000). A physiological approach to pruning. *Int. For. Rev.* 2, 295–305. Available online at: <https://www.jstor.org/stable/42609327?seq=1>
- Pinkard, E. A., Mohammed, C., Beadle, C. L., Hall, M. F., Worledge, D., and Mollon, A. (2004). Growth responses, physiology and decay associated with pruning plantation-grown *Eucalyptus globulus* Labill. And *E. nitens* (Deane and Maiden) Maiden. *For. Ecol. Manag.* 200, 263–277. doi: 10.1016/j.foreco.2004.07.004
- Puntieri, J., Barthélémy, D., Martinez, P., Raffaele, E., and Brion, C. (1998). Annual-shoot growth and branching patterns in *Nothofagus dombeii* (Fagaceae). *Can. J. Bot.* 76, 673–685. doi: 10.1139/b98-041
- Puntieri, J. G., Barthélémy, D., Mazzini, C., and Brion, C. (2002). Periods of organogenesis in shoots of *Nothofagus dombeii* (Mirb.) Oersted (Nothofagaceae). *Ann. Bot.* 89, 115–124. doi: 10.1093/aob/mcf012

- Puntieri, J., Souza, M., Barthélémy, D., Raffaele, E., and Brion, C. (2000). Preformation, neoformation, and shoot structure in *Nothofagus dombeyi* (Nothofagaceae). *Can. J. Bot.* 78, 1044–1054. doi: 10.1139/b00-069
- Riehmann, P., Hanfler, M., and Froehlich, B. (2005). Interactive Sankey diagrams. *IEEE symposium on information visualization, 2005. INFOVIS 2005. IEEE*. doi: 10.1109/INFVIS.2005.1532152
- Romero-Mieres, M., Navarro, C., Donoso, P., Dumont, P., Larrain, O., and Vásquez, A. (2025). Flora vascular en plantaciones dominadas por Coihue (*Nothofagus dombeyi*) y Raulí (*Nothofagus alpina*). *Gayana Bot.* 82, 38–61. doi: 10.4067/s0717-66432025000100038
- Salas, C., Donoso, P. J., Vargas, R., Arriagada, C. A., Pedraza, R., and Soto, D. (2016). The forest sector in Chile: an overview and current challenges. *J. For.* 114, 562–571. doi: 10.5849/jof.14-062
- Salazar, A., Thatcher, M., Goubanova, K., Bernal, P., Gutiérrez, J., and Squeo, F. (2024). CMIP6 precipitation and temperature projections for Chile. *Clim. Dyn.* 62, 2475–2498. doi: 10.1007/s00382-023-07034-9
- Sokal, R. R., and Rohlf, F. J. (2012). *Biometry. The Principles and Practice of Statistics in Biological Research*. Fourth Edn New York: W.H. Freeman and Company.
- Soto, D. P., Donoso, P. J., Salas, C., and Puettmann, K. J. (2015). Light availability and soil compaction influence the growth of underplanted *Nothofagus* following partial shelterwood harvest and soil scarification. *Can. J. For. Res.* 45, 998–1005. doi: 10.1139/cjfr-2014-0353
- Soto, D. P., Donoso, P. J., Uteau, D., and Zúñiga-Feest, A. (2009). Environmental factors affect the spatial arrangement of survival and damage of outplanted *Nothofagus dombeyi* seedlings in the Chilean Andes. *Interciencia* 34, 100–105. Available online at: <https://www.cabidigitallibrary.org/doi/full/10.5555/20093073925>
- Soto, D. P., Donoso, P. J., Vásquez-Grandón, A., González, M., and Salas-Eljatib, C. (2020). Differential early performance of two underplanted hardwood tree species following restoration treatments in high-graded temperate rainforests. *Forests* 11:401. doi: 10.3390/f11040401
- Urrutia-Jalabert, R., Barichivich, J., Szejner, P., Rosas, V., and Lara, A. (2015). Ecophysiological responses of *Nothofagus obliqua* forests to recent climate drying across the Mediterranean-temperate biome transition in south-central Chile. *J. Geophys. Res. Biogeosci.* 128:e2022JG007293. doi: 10.1029/2022JG007293
- Zhang, J., and Liu, L. (2021). Effects of pruning intensity on nonstructural carbohydrates of *Populus alba* × *P. Talassica* in the arid desert region of Northwest China. *J. For. Res.* 32, 823–830. doi: 10.1007/s11676-020-01098-7
- Zobel, B. J., and Van Buijtenen, J. P. (2012). *Wood Variation: its Causes and Control*. Springer Berlin, Heidelberg: Springer Science & Business Media.