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Present and prospects for multi-aged silviculture in Chilean temperate forests: Targeting secondary forests in transition and partially harvested old-growth forests

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Valdivian Temperate Rainforests in Chile have a global conservation value, but nowadays many correspond to secondary forests following regeneration in agricultural and burned lands, and to high-graded old-growth due to mismanagement, especially at mid to low elevations. Perspectives for increasing old-growth attributes in these productive forests through silviculture are high considering the diverse demands of ecosystem services and the high timber value of tree species. In the Llancahue experimental forest (40°S Lat) we implemented three ecological silviculture approaches: variable-density thinning in a *Nothofagus dombeyi* secondary forest (NDS), irregular shelterwood in a mature *N. dombeyi* forest (NDM), and single-tree selection cutting in a partially harvested old-growth forest (OG). Based upon an old-growth index (OGI) that includes density, basal area (BA), BA of the trees >80 cm in diameter, ba of shade-tolerant species, and the Gini coefficient, and aims to estimate how close a given forest is to a typical old-growth forest, these forests had a 22, 22, and 62% OGI before management. The OGI remained similar or declined following management, but 7–10 years after management it increased in NDS and NDM and declined in the OG (significant changes only in NDM and OG). We discuss these results considering that managed forests should target for an OGI ≈70% rather than maximum values. These managed forests contribute to halt degradation, mitigate climate change (carbon stores in the forest and in timber), and may have greater adaptive capacity to disturbances. We discuss perspectives for the potential scale-up of implementing these approaches.

KEYWORDS

ecological silviculture, hardwood forests, Valdivian Temperate Rainforests, old-growth index, irregular forests, selection cutting, variable-density thinning

Introduction

The southern cone of South America is covered with temperate rainforests (Donoso et al., 2022), including rich mixed-species Valdivian Temperate Rainforests (37–43°S Lat.). These type of forests are highly productive (Barnes et al., 1998; Salas et al., 2018). In Chile, natural large-scale disturbances are common in the Andes (Veblen et al., 1996), while elsewhere natural small-scale disturbances (e.g., tree-fall gaps) are dominant (Veblen, 1985). However, human-caused disturbances have become common in populated landscapes, where past clearing and burning of forests to open lands for agriculture derived into large fires that expanded uncontrolled into the mountains (González et al., 2015). Many lands were regenerated and became secondary forests. In addition, illegal logging is leaving behind millions hectares of high-graded old-growth forests (Lara et al., 2018), and most of the harvest is firewood (Instituto Forestal [INFOR], 2020). Nowadays, secondary forests are dominant north of 41°S, and old-growth forests are dominant to the south (Lara et al., 2018). The scarcity of old-growth forests is especially critical in the lowlands of south-central Chile (Donoso et al., 2014, 2020a).

Nothofagus species played a key role in the process of regenerating lands after fires, especially *Nothofagus dombeyi*, *Nothofagus obliqua*, and *Nothofagus alpina* (Veblen et al., 1996; Donoso et al., 1999, 2022). Through succession, shade-tolerant species gradually replace *Nothofagus* species (Veblen et al., 1996). Chilean native tree species, mostly hardwoods, have valuable timber, and therefore their management is a great opportunity to provide a diversity of ecosystem goods and services, especially with silvicultural approaches that increase their contribution to climate change mitigation and their adaptive capacity to disturbances. The contradiction of having productive and valuable forests that are being mismanaged and degraded needs to be reversed, and that means both providing technical and governance solutions within a context of facing increased natural disturbances.

Secondary and old-growth forests in general have major differences in their attributes (Bauhus et al., 2009). Ponce et al. (2017) reported these differences in south-central Chile, providing a reference to direct, through silviculture, secondary forests to forests with a greater proportion of old-growth attributes. Most high-graded forests have also lost many attributes of well-conserved old-growth forests (Vásquez-Grandón et al., 2018). All these forests need to have solid silvicultural proposals to sustain or improve the ecosystem services they may provide (Donoso et al., 2018).

While implementation of silviculture in Chilean forests is in general scarce, it is an alternative to forest degradation due to mismanagement. Further, in the present context of increasing forest disturbances, the aim of silviculture should be at increasing their heterogeneity, complexity, and adaptive capacity to disturbances. Approaches of this kind are considered as ecological silviculture (Palik et al., 2021), and include variable-density thinning in secondary forests (Donoso et al., 2020a) and irregular shelterwood systems in forests that are ready to be harvested (Raymond and Bédard, 2017). For old-growth or uneven-aged forests, selection cuttings are recommended, especially if it retains some old-growth structures that are not considered when timber is the only objective (Bauhus et al., 2009; D'Amato et al., 2011; Nyland, 2016; Schnabel et al., 2017).

Here we report mid-term results (7–10 years) following the implementation of different ecological silviculture approaches in three forests located in different successional stages: a *N. dombeyi*-dominated secondary forest, a mature *N. dombeyi*-dominated forest, and a partially harvested old-growth forest dominated by late-successional species. We assess their changes in time through an old-growth index (OGI) developed for these mid to low elevation forests (Ponce et al., 2019), and discuss the perspectives of increasing the representation of managed native forests with old-growth attributes in Chile.

Methods

This work was developed in the Llancahue experimental forest (39°84′S, 73°14′ W; **Figure 1**), a public property in the Coastal range. Mean annual precipitation is 2,300 mm and mean annual temperature 12.2°C (Donoso et al., 2014). At the elevation of the study sites (300–350 m a.s.l.), soils correspond to silt deposits of volcanic origin of the Correltué soil series (Centro de Información de Recursos Naturales [CIREN], 1999). Forests correspond to the hardwood-dominated Evergreen forest type (Donoso, 1981), and include *N. dombeyi* (shade-intolerant), *Eucryphia cordifolia* (mid tolerant to shade), and *Laureliopsis philippiana* and *Aextoxicon punctatum* (shade-tolerant species), amongst many other species (Donoso et al., 2014, 2018).

All forests (**Figure 2**) were sampled with a similar intensity (approximately one 2,000 m^2 plot per 1–2 ha) in stands 4–12 ha in size (**Figure 1**), and were cut between 2009 and 2015. In a *N. dombeyi*-dominated secondary forest, we evaluated a variable-density thinning (Donoso et al., 2020a). In a mature *N. dombeyi*-dominated forest, we evaluated an irregular shelterwood cutting (*sensu* Raymond and Bédard, 2017). In a partially harvested old-growth forest, we evaluated a single-tree selection cut (Donoso et al., 2020b). Harvests in these forests provided mostly firewood that allowed profitable operations (personal observation Donoso et al., 2014).

We evaluated changes through the OGI (Ponce et al., 2019), which is based upon the OGI developed by Acker et al. (1998). This index considers reference values for

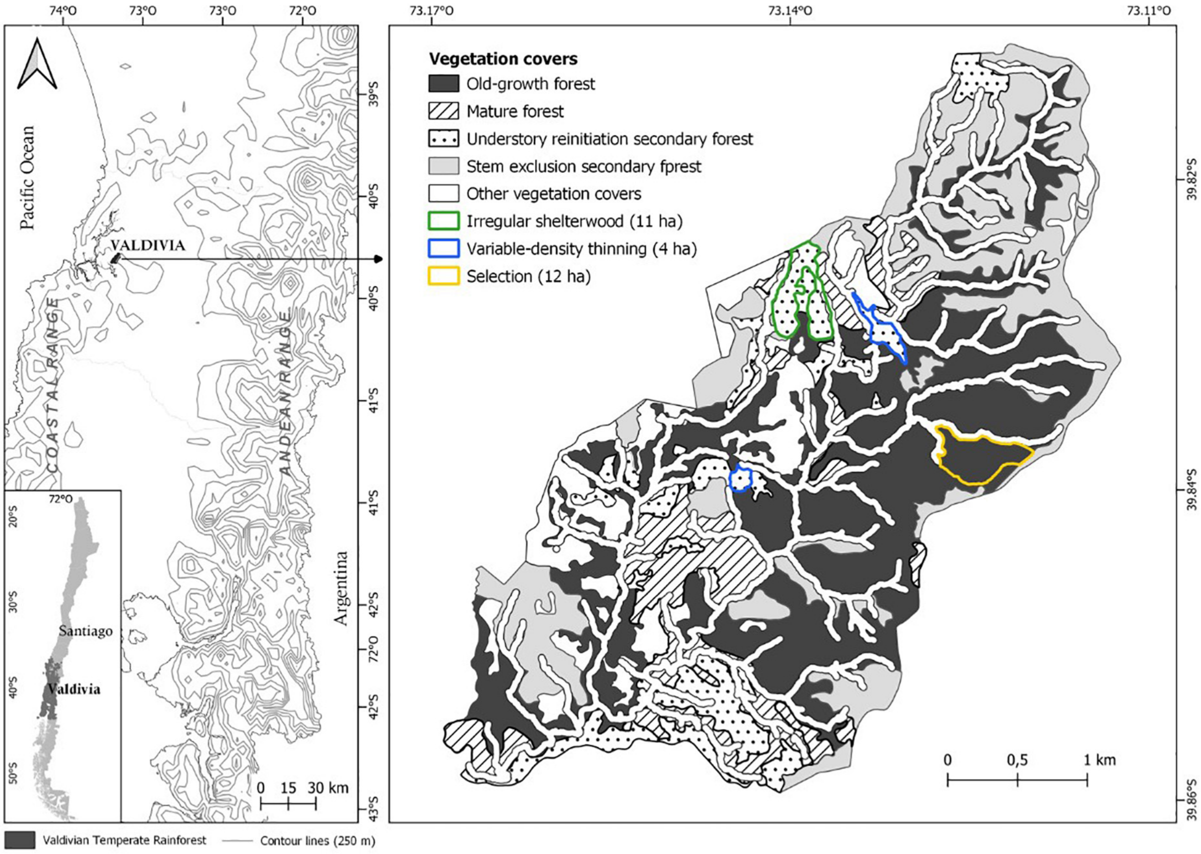

FIGURE 1
Location of the Llancahue experimental forest and the studied stands within it.

old-growth and secondary forests for tree density (trees ≥5 cm), basal area (BA) (m^2 ha^{-1}), BA of trees ≥80 cm in dbh, BA of shade-tolerant species, and the Gini size heterogeneity coefficient (Lexerød and Aid, 2006). The OGI varies from 0 (for a typical young stand) to 100 (for a typical old-growth stand) (Acker et al., 1998; Ponce et al., 2019). We evaluated Changes in the OGI and in each of its variables in an independent manner for each silvicultural treatment through analysis of variance (ANOVA). The analyses considered the evaluation of each treatment (pre-harvest, immediately post-harvest, and 7–10 years post-harvest) as a categorical predictor variable. We checked that the residuals of the linear statistical model followed a Gauss distribution through Shapiro–Wilk test and checked for homoscedasticity of variance through the Levene test. To identify significant statistical differences among time of evaluation of the OGI as well as the variables that compose this index we used the *T*-test and the Scheffé test in the "agricolae" statistical package (De Mendiburu, 2010). In both tests we used $\alpha = 0.05$ as a significant level. Analyses were conducted with the R statistical software (R Core Team, 2020).

Results

For both variable-density thinning and irregular shelterwood cut the OGI increased, but only significantly for the latter (**Table 1**). For the selection cut, the OGI decreased and has remained with nearly the same value since the cut. This is the result of changes in all five OGI variables used.

Silvicultural treatments that include tree cuttings will generate a decline in tree density and BA, and these were significant in the three stands, except for tree density in the selection cut, in which harvest occurred mostly in a low number of trees of relatively high individual BA. For the same reason, also BA of trees >80 cm significantly declined in the selection cut (55% was cut). BA of shade-tolerant species did not have any significant change in any situation, although it is increasing in all of them 7–10 years following the cut. Finally, the Gini coefficient has been increasing in the variable-density thinning cut and in the irregular shelterwood cut compared to the pre-cut condition, but this change has been significant only in the irregular shelterwood cut. In the selection cut, the Gini coefficient diminished following the cut, and was significantly lower than the pre-harvest value 7 years after the cut.

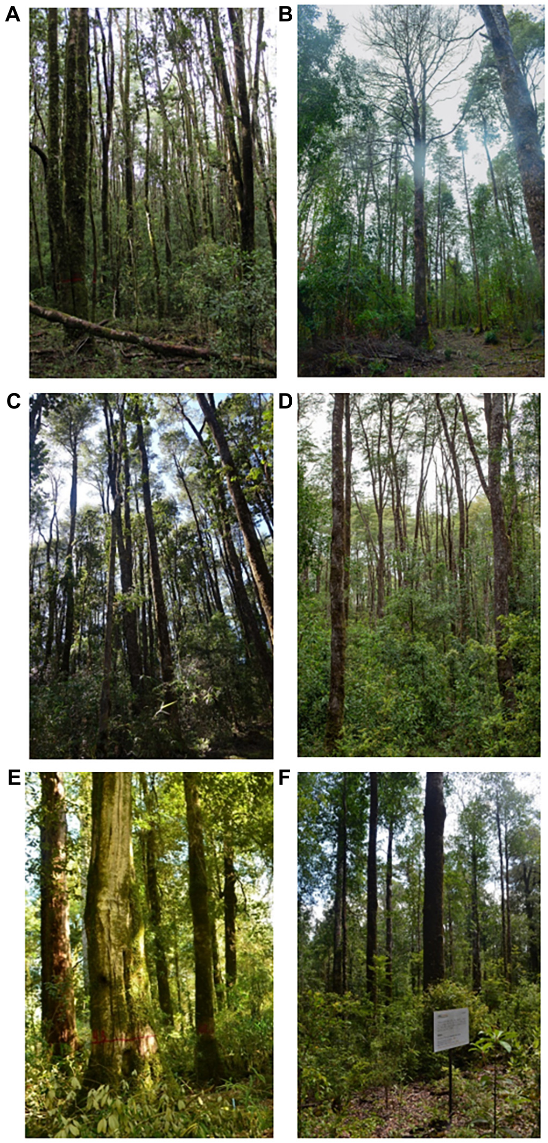

FIGURE 2
Studied forests before (left) and 7–10 years after management (right) for variable-density thinning, irregular shelterwood and single-tree selection cuts. The forest with variable-density thinning **(A,B)** included girdling trees to become dead standing trees like the one in front within the thinned matrix. The forest with irregular shelterwood **(C,D)** has had a vigorous growth of the advanced and new regeneration. The forest with selection cut **(E,F)** resulted in a balance between trees of different sizes and abundant regeneration.

Discussion and perspectives

Recent experiences in ecological silviculture in Chile reported here start to provide some promising results and ideas in terms of future directions for their implementation. Ecological silviculture consists in developing managed forests that will have greater adaptive capacity to cope with disturbances while providing timber and enhanced ecosystem services, especially carbon sequestration (D'Amato et al., 2011; Palik et al., 2021). This implies managing forests to enhance diversity and structural complexity (Ehbrecht et al., 2017; Schnabel et al., 2017). Multi-aged silviculture is proposed to achieve these purposes, where the selection and the irregular shelterwood systems are recommended (D'Amato et al., 2011). We report here the 7–10 years preliminary results with these silvicultural systems in Chile, in addition to variable-density thinning in secondary forests, which aims to increase old-growth forest attributes in secondary forests. We chose to assess changes through the OGI and found that it increased in the secondary and mature forests subjected to variable-density thinning and irregular shelterwood, respectively, but declined in the older forest subjected to single-tree selection cutting. While this might be expected, especially since the selection cut defined a maximum residual diameter (Donoso et al., 2020b), these results illustrate that restoring old-growth attributes through ecological silviculture should aim to attain a percentage of the OGI (e.g., ≈70%; Ponce et al., 2019). It also might reconsider the variables included to calculate this index, such as coarse woody debris (see also Acker et al., 1998). Still, while an OGI decline occurred in the forest with selection cut, Schnabel et al. (2017) reported for the same forest that there were no significant changes in tree species richness and diversity compared to the old-growth forest.

Managing forests to increase their old-growth attributes seems a reasonable approach for regions with abundant secondary forests or partially degraded forests and high demand for timber or firewood, as in Chile. Those regions where many lands were cleared for agriculture (e.g., Foster et al., 1998; Otero, 2006), and fires eliminated forests and created the conditions for the regeneration of new forests, are now in the juncture of deciding whether to continue with a forestry focused in even- or multi-aged silviculture. Most likely, meeting a balance between both options might be needed. In existing Chilean private old-growth forests, where some landowners may harvest timber or firewood, it is urgent to promote silviculture to avoid high-grading (Soto and Puettmann, 2018; Vásquez-Grandón et al., 2018). Overall, ecological silviculture may be a great ally in preventing high-grading of old-growth forests and in promoting old-growth forest attributes in managed forests, reconciling the provision of goods and services and old-growth conservation (Donoso et al., 2014; Soto and Puettmann, 2020).

We have aimed to show that perspectives for ecological silviculture are promising for Chilean forests, but there is a need for more research as well as a stronger governance of native forests. A new deal for the conservation of native forests needs to consider managed forests in the landscape, through silviculture for adaptation, with a clear vision about conservation of native forests. This vision needs to include forests with great carbon stores and adaptive capacity, with increased old-growth forest

TABLE 1 Pre-harvest, immediate post-harvest and 7–10 years post-harvest stand variables and OGI in the three silvicultural approaches tested.

	Silvicultural approach													
	Reference		Variable-density thinning				Irregular shelterwood				Selection			
Condition variable	OG	Sec	PreH	PostH	7 years post H	*F*-value	PreH	PostH	10 years post H	*F*-value	PreH	PostH	7 years post H	*F*-value
Density (trees ha^{-1})	1014	2052	2292a	1340b	1427b	6.03*	1315a	815b	1176a	25.01***	1532	1408	1533	0.66ns
Total BA (m^2 ha^{-1})	85.8	66.0	71.9a	53.5c	62.9b	114.8***	73.6a	48.1c	57.4b	47.29***	71.9a	50.3b	57.3b	8.02**
BA > 80 cm (m^2 ha^{-1})	37.7	0	10.3	8.9	9.2	1.22ns	1.48	1.48	2.92	0.69ns	29.4a	13.2b	15.7b	4.54*
BA shade tolerant (m^2 ha^{-1})	48.8	6.2	11.4	5.6	10.5	1.22ns	2.51	2.51	3.53	0.48ns	30.8	26.6	31.4	2.18ns
Gini coefficient	0.8	0.63	0.7	0.71	0.73	1.37ns	0.61b	0.65ab	0.72a	11.31**	0.82a	0.79ab	0.78b	4.27*
OGI	100	0	22.4	20.8	25.9	0.29ns	22.4b	23.2ab	29.0a	3.78*	62.4a	48.8ab	49.2b	4.29*

BA, Basal Area; OG, Old-growth; Sec, Secondary; PreH, Pre harvest; PostH, Post harvest; Sign, codes: *** = 0.001; ** = 0,01; * = 0,05; ns = non sign.
Reference old-growth and secondary forests are represented by typical values expected for these following the sampling units used by Ponce et al. (2019). Different letters within each line for each silvicultural approach represent significant differences between time of evaluation for the OGI or for its variables.

attributes, and capable of providing timber that will contribute to climate change mitigation. Climate-smart forestry has great opportunities in Chile, but the starting point is adequately conserving the forests to sustain the ecosystem goods and services that they can provide. Here we have given some perspectives to move in that direction.

Data availability statement

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

Author contributions

PD led all the installation, monitoring and data collection of the three experiments reported, and wrote and edited the manuscript. CS-E was a co researcher in the projects that were linked to the experiments and the supervisor of experimental designs and statistical analyses, reviewed all the manuscript, and made corrections and editing. DS edited and commented the manuscript and had an active participation in the implementation of two of the experiments reported here. TR conducted the last field data collection of all the experiments and conducted the statistical analyses. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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