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RESEARCH PAPER

Fire, logging and establishment patterns of second-growth forests in south-central Chile: implications for their management and restoration

Mauro E. González[1], Paul Szejner[2], Pablo J. Donoso[1], and Christian Salas[3]

[1]Facultad de Ciencias Forestales y Recursos Naturales, Universidad Austral de Chile, Casilla 567, Valdivia, Chile.
[2]University of Arizona, Laboratory of Tree-Ring Research, Box 210045, Tucson, AZ 85721, USA.
[3]Laboratorio de Biometría, Departamento de Ciencias Forestales, Universidad de La Frontera. Casilla 54-D, Temuco, Chile.

Abstract

M.E. González, P. Szejner, P.J. Donoso, and C. Salas. 2015. Fire, logging and establishment patterns of second-growth forests in south-central Chile: implications for their management and restoration. Cien. Inv. Agr. 42(3): 427-441. Second-growth forests represent the greatest potential resource for forest management and large-scale ecological restoration in many regions. In south-central Chile, second-growth forests include those dominated by *Nothofagus obliqua*, *N. dombeyi*, *Drimys winteri*, and a mixture of evergreen species, especially hardwoods. This article examines the influence of fire and logging on the establishment patterns and development of second-growth forests in south-central Chile. We characterize the size structure and composition of these four types of forests with sampling plots. The identification of the type of disturbance and its date of occurrence was determined from evidence such as fire scars and even-aged pulses of tree establishment. The size, structure and species composition of these forests indicate an intermediate state of development with an average density and basal area ranging from 1294 to 5038 trees ha^{-1} and from 59 to 85 m^2 ha^{-1}, respectively. Logging and/or devastating fires that occurred in the early decades of the 1900s promoted the relatively rapid establishment and growth of pioneer species (*Nothofagus obliqua, N. dombeyi, D. winteri*). In the Mixed Evergreen second-growth forests, mid-shade or shade tolerant species (e.g., *Gevuina avellana, Eucryphia cordifolia, Amomyrtus luma,* and *A. meli*) became established mostly through vegetative sprouting. Fires and logging have been pervasive factors in determining the structural and compositional uniformity of the native forests of south-central Chile. Ecological restoration at a landscape level, either by ecological processes (i.e., a reduction in fire frequency) and/or the structure and composition of second-growth forests, provide a relevant approach to accelerating the generation of attributes of old-growth forests, therefore meeting manifold societal demands for forest goods and services.

Key words*:* Disturbances, ecological restoration, *Nothofagus*, secondary succession.

Introduction

In many regions of the world, second-growth forests have become widespread as a result of the recolonization of abandoned agricultural lands, as well as after natural and anthropogenic destruction (logging, fire) of original old-growth forests (FAO, 2007). Currently, a major concern resulting from the present forest mosaic is how dense second-growth forests with little structural diversity can affect and determine the ecological

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Corresponding author: maurogonzalez@uach.cl

values and ecosystem services as compared with old-growth forests (Rapp *et al.,* 2002).

Old-growth forests provide an array of ecosystem benefits, including the storage of carbon and species biodiversity, and it sometimes consists of a unique or specific habitat for fauna (Barlow *et al.,* 2007). However, it has been suggested that if second-growth forests, which exhibit simple structures, developed some characteristics of old-growth forests, they could provide a wider range of ecological benefits (Carey *et al.,* 1999; Wilson and Puettmann, 2007).

Second-growth forests in south-central Chile (37°-42° S) are one of the main types of forests in the region. Currently, between the Bío-Bío and Los Lagos regions (37-42° S) there are approximately 2 million hectares of these forests (CONAF, 2011). These young forests have formed due to the abandonment of agricultural lands and livestock pastures or because of natural and anthropogenic disturbances that took the place of old growth *Nothofagus* forests (*N. dombeyi* (Mirb.) Blume*, N. nervosa* (Phil.) Dim. et Mil. *and N. obliqua* (Mirb.) Oerst), as well as other broadleaf evergreens (e.g., *Eucryphia cordifolia* Cav.*, Weinmannia trichosperma* Cav.*, Laureliopsis philippiana* Looser) (Donoso, 1993).

In the last 150 years, anthropogenic disturbances have greatly shaped the landscape in south-central Chile. The arrival of Euro-Chilean settlers, in association with the colonization of the region Osorno-Llanquihue (41-42° S), beginning in 1850, and La Frontera (38-39° S) beginning in 1882) had a significant impact on the structure, composition, and cover of forests in these regions (Donoso and Lara, 1996). During the first years of colonization, fire was the principal tool used to clear land for agriculture and livestock. Later, beginning in 1920, fires and logging for timber production continued to degrade and destroy native forests, in many cases (especially in regions with less agricultural potential) generating extensive areas of second-growth forests. As a result, the regrowth of the forest promoted significant changes – at the stand and landscape scale – in the structure and composition of the forest.

The dynamics of temperate forests in south-central Chile are primarily shaped by large scale allogenic disturbances. Fires, landslides, mudslides, blowdowns, and volcanic eruptions, among others, are the main type of natural disturbances that destroy old growth forests and initiate ecological succession (Donoso, 1993; Veblen *et al.,* 1996). After a large scale disturbance – depending on their geographic location – different pioneer and shade- or mid-shade intolerant species (e.g., *Nothofagus*, *Drimys winteri* J.R. *et* G. Forster) rapidly and densely colonize the affected areas, following a catastrophic regeneration mode (Veblen, 1992; Veblen *et al.,* 1996).

Different studies on the dynamics of temperate forests in south-central Chile show stand development patterns similar to the model proposed by Oliver (1981). After severe disturbances that destroy the stand, pioneer species colonize and dominate the area, modifying the environment and allowing the arrival of successional species that will eventually become predominant (Veblen *et al.,* 1996). These patterns and changes in the physiognomy of the stand are largely the result of autecological characteristics of each species, expressed as their competitive advantages after disturbances. The changes in the structure of the forest patch and the dominant species have been adequately described by the model proposed by Oliver (1981), who recognized four developmental stages: stand initiation, stem exclusion, re-initiation of the undergrowth, and old-growth forests. Second-growth forests typically correspond to forests in the first two stages described by Oliver (1981) because in more advanced stages, they may begin to have new cohorts and an increasingly stratified structure.

The design of silvicultural systems that integrate economic and ecological objectives requires a comprehensive scientific understanding of natural stand development patterns, including the roles of disturbances, biological legacies and their influence on the ecological response of species. Therefore, an important area of study centers on understanding how natural and human disturbances affect the forest structure and the composition of species at distinct spatial and temporal scales (Oliver, 1981; Spies and Turner, 1999). While many studies have been conducted on second-growth forests (especially on *Nothofagus*) from the perspective of their distribution, characterization, silviculture, and growth (Donoso *et al.,* 1993; Navarro *et al.,* 1999; Grosse and Quiroz, 1999; Lara *et al.,* 1999), research that inquires and describes the type, frequency, and severity of disturbances and their influence on the origin and development of second-growth forests, has, paradoxically, only been briefly addressed.

This study examines the effect of allogenic disturbances on the structure, composition, and development of second-growth forests. The principal objective of this study is to determine the major disturbance events that promoted the different forest patches and analyze the species establishment patterns and growth development after disturbance. This study was carried out in four types of second-growth forests that correspond to the forests with the greatest coverage and ubiquity in the coastal mountain range, Andean foothills, and central valley (at altitudes lower than 600 m.a.s.l.) in south-central Chile: a) second-growth forests of *Nothofagus obliqua*, b) second-growth forests of *N. dombeyi*, c) second-growth forests of *D. winteri*, and d) mixed evergreen second-growth, primarily composed of *Gevuina avellana Mol.*, *Eucryphia cordifolia*, *Dasyphyllum diacanthoides* (Less) Cabrera, *Amomyrtus luma* (Mol.) Legr. *et* Kausel, and *A. meli* (Phil) Legr. *et* Kausel.

Materials and methods

Second-growth *N. obliqua* were studied in the Rucamanque experimental forest (38° 39' S y 72° 35'), located 12 km northeast of Temuco. Of the total area (435 ha), 230 ha (53%) correspond to remnant and very well conserved old-growth forests of the Roble-Raulí-Coihue forest type (Donoso, 1993). Second-growth forests of *N. obliqua* cover 70 ha (16%). The topography consists of rolling hills located in the central valley, with altitudes that do not exceed 400 m. Rucamanque's soil is of volcanic origin, very deep, and fertile. The climate in the region is temperate and humid, with Mediterranean characteristics. The annual average rainfall is 1311 mm, concentrated between March and September of each year. The average annual temperate is 11.6 °C.

The second-growth forests of *N. dombeyi* (Coihue), *D. winteri* (Canelo), and mixed evergreens were studied in an experimental forest in Llancahue (39° 50' S and 73° 07' W), which corresponds to a protected area of 1300 hectares that provides drinking water for Valdivia. This basin is principally covered by forests in different stages of development that belong to the evergreen forest type (Donoso, 1993). The original old-growth forests cover the majority of the area (723 ha), while second-growth forests cover 408 ha. The topography consists of mountains that cross the central depression, with altitudes that reach 400 m. The main type of soil is red clay; ancient volcanic ash deposited on a substrate of metamorphic origin. The climate is temperate/humid, with annual precipitation that reaches 2100 mm, 70% of which falls between April and October. The average annual temperature, according to the meteorological station located in Valdivia is 12 °C, with a minimum of 7.6 °C in July and a maximum of 17 °C in January.

Field sampling and data analysis

Structure and composition of the second-growth forests. We sampled each forest with four to six plots of 900 m^2 (30 × 30 m). For each sample plot, the species and dbh of all live and dead standing trees with a diameter at breast-height (dbh – 1.3 m) ≥ 5 cm were recorded. For the living trees, their sociological position was determined according to the modified Kraft classification (emergent, dominant, co-dominant, intermediate, suppressed, or submerged) (Donoso, 1993). To determine the ages and dates of establishment, we randomly selected 20-30 trees from one-half of the plot and extracted increment cores at a height of 30 cm.

Identification and recording of disturbances. The identification of the type and attributes of the disturbances that generated the forest patches and their date of occurrence was based on different types of evidence. The second-growth forests with remnant trees from previous disturbances were revised to verify the presence of fire scars and/or wood showing evidence of carbon residues. When a tree exhibited a fire scar, a wedge was extracted following the established protocol (McBride, 1983). For each wedge, the species, DBH and number of fire scars were registered. The presence of stumps of adult trees was registered as evidence of logging. Likewise, the dense re-establishment of tree species through vegetative reproduction (from the root or stump) was considered as clear evidence of logging or fire. Furthermore, these observations and field evidence were complemented with verified oral sources and documentation from each location.

Dating age, fire scars and growth rates. The processing of the tree cores and fire scar wedges was done according to standard procedures (McBride, 1983). For each wedge, the fire's date was determined by counting the rings from the bark (outer ring) to the location of the scar. The age of the tree cores was determined by counting the growth rings from the bark to the pith (center) or to the ring closest to the pith. For cores without piths, but with visible arcs, the total age was estimated using standard procedures (Duncan, 1989). For the tree cores without a center and visible arcs, or when the estimate of the rings was greater than 15 years, they were considered to be a minimum age. To analyze the radial growth pattern of the principal species that became established after a disturbance, the widths of their rings were measured by 10-15 cores per species. The dates of the disturbances (i.e., fire), the age structure of the second-growth forests, and the initial growth patterns of the dominant species were used as evidence to reconstruct and analyze the history and origin of each patch.

Results

Nothofagus obliqua second-growth forests

Trees species richness in the second-growth *N. obliqua* forests was 13 species belonging to 11 families (Table 1). The main species that dominates the upper canopy is *N. obliqua*, including remnant trees of the same species of a previous cohort that survived the disturbance. *Eucryphia cordifolia* is also present in the upper canopy, although its density is lower (Table 2). In the intermediate and lower canopy, there is an abundance of mid-shade and shade-tolerant species, such as *E. cordifolia*, *Aextoxicon punctatum* R. *et.* Pav., *Persea lingue* Ness., and *Dasyphyllum diacanthoides*.

The size structure (similar to that described by a Gaussian probability function) and density observed in *N. obliqua*, as well as the similar height of the upper canopy trees, indicate a cohort that was established after a severe disturbance (Figure 1a). Therefore, it is possible to observe large living trees (>100 cm dbh) and snags of *N. obliqua*, which correspond to trees that survive from the original forest. The aforementioned species that are tolerant and mid-tolerant to shade participate abundantly in the diameter classes below 40 cm, together with other species such as *Laurelia sempervirens* and *Gevuina avellana* Mol., which became less densely established after the disturbance.

Table 1. Tree species participation in the second-growth forests of *Nothofagus obliqua* (Roble), *Nothofagus dombeyi* (Coihue), *Drimys winteri* (Canelo) and the Mixed Evergreen (SV) forest.

Family/Species	Second-growth forests			
	Roble	Coihue	Canelo	SV
Aextoxicaceae				
Aextoxicon punctatum	X	X	X	X
Asteraceae				
Dasyphyllum diacanthoides	X		X	
Cunoniaceae				
Weinmannia trichosperma	X	X		X
Elaeocarpaceae				
Aristotelia chilensis	X			
Eucryphiaceae				
Eucryphia cordifolia	X		X	
Fagaceae				
Nothofagus dombeyi		X		
Nothofagus obliqua	X			
Lauraceae				
Persea lingue	X	X	X	X
Mirtaceae				
Amomyrtus luma		X	X	X
Amomyrtus meli		X	X	X
Luma apiculata	X			
Myrceugenia planipes		X	X	X
Myrceygenia ovata				X
Monimiaceae				
Laurelia sempervirens	X	X		
Laureliopsis philippiana	X	X	X	X
Proteaceae				
Embothrium coccineum				X
Gevuina avellana	X	X	X	X
Lomatia dentata	X	X		X
*Lomatia ferru*ginea		X	X	X
Podocarpaceae				
Podocarpus saligna	X		X	
Saxegothaea conspicua				X
Podocarpus nubigenus				X
Thymelaeaceae				
Ovidia pillopillo			X	X
Verbenaceae				
Rhaphithamnus spinosus	X	X	X	X
Winteraceae				
Drimys winteri			X	X
Torricelliaceae				
Raukaua laetevirens				X

Table 2. Crown classes of the main tree species (n/900 m^2) in the second-growth forests of *Nothofagus obliqua* (Roble, NO), *Nothofagus dombeyi* (Coihue, ND), *Drimys winteri* (Canelo, DW) and the Mixed Evergreen (SV) forest. Crown classes: Emergent (E), Dominant (D), Co-dominant (C), Intermediate (I), Suppressed (S).

Study sites																					
		E	D	C	I	S	E	D	C	I	S	E	D	C	I	S	E	D	C	I	S
Rucamanque																					
		Roble					Ulmo					Olivillo					Lingue				
Roble	NO 10	5	16	7	0	0	0	4	2	16	3	0	0	0	10	7	0	0	0	11	1
	NO 6	0	17	17	5	0	0	0	0	1	1	0	0	0	13	2	0	0	0	9	6
	NO 2	0	14	10	4	0	0	0	1	2	2	0	0	0	6	72	0	0	0	5	7
	NO 4	0	14	11	4	0	0	0	0	0	0	0	0	0	3	14	0	0	0	9	1
Llancahue																					
		Coihue					Ulmo					Olivillo					Laurel				
Coihue	ND 5	0	32	5	1	0	0	1	1	5	6	0	0	0	0	8	0	0	0	1	6
	ND 2	2	20	9	3	0	0	0	5	22	7	0	0	0	7	16	0	0	0	0	8
	ND 7	0	32	4	1	0	0	0	0	3	0	0	0	0	1	15	0	0	0	11	11
	ND 6	0	22	2	0	0	0	0	1	5	3	0	0	1	5	3	0	0	1	5	3
		Canelo					Ulmo					Olivillo					Tepa				
Canelo	DW 1	0	28	20	25	12	1	0	0	2	0	1	0	0	0	3	2	0	1	2	7
	DW 2	2	11	17	26	3	0	0	0	0	1	1	4	0	1	0	2	5	7	18	8
	DW3	14	92	70	56	30	0	2	1	5	2	0	0	3	0	0	1	2	14	43	34
	DW4	1	8	13	3	0	1	0	0	0	0	0	0	0	0	0	2	10	14	20	11
	DW5	4	81	45	13	6	0	3	1	4	1	2	0	0	5	2	3	15	23	32	16
	DW6	1	29	16	7	3	1	1	0	1	0	0	1	0	1	3	10	11	7	9	7
		Avellano					Ulmo					Trevo					Mirtaceae species				
SV	SV 4	0	20	22	43	6	0	70	40	18	1	0	7	1	1	0	0	18	35	59	6
	SV 5	0	65	59	29	5	0	4	1	1	0	0	8	9	2	0	0	48	86	82	7
	SV6	0	54	13	13	1	0	2	0	0	0	0	0	2	0	0	0	71	56	98	12
	SV 7	0	51	26	14	4	0	3	0	2	0	0	2	0	0	0	0	75	102	83	35
	SV8	0	8	27	1	1	0	15	19	9	0	0	8	4	1	4	0	7	59	76	7

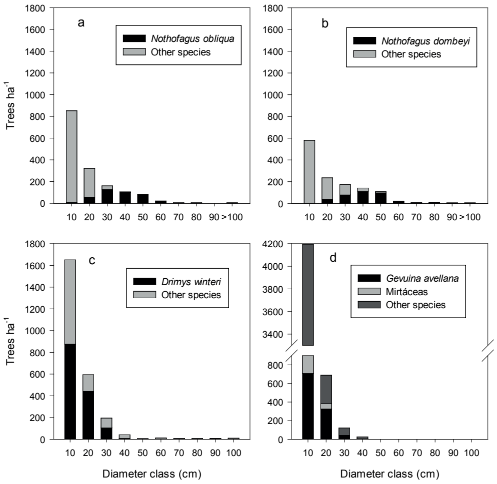

Figure 1. Diameter structure of second-growth forests dominated by a) *Nothofagus obliqua*, b) *Nothofagus dombeyi*, c) *Drimys winteri*, and d) *Gevuina avellana, E. cordifolia, P. saligna, S. conspicua, A. meli,* and *A. luma,* among the principal species of the mixed evergreen secondary forest. The diameter mark class is every 10 cm, for trees > 5 cm DBH

The *N. obliqua* stand has an average density of approximately 1295 trees ha^{-1} and an average basal area of 85 m^2 ha^{-1}, and *N. obliqua* itself has an average density of 369 trees ha^{-1} and an average basal area of 59 m^2 ha^{-1}, which represents 29% and 70% of the total number of trees and basal area of the stand, respectively (Table 3). Together, the accompanying species *A. punctatum* and *P. lingue* have an average density and average basal area of 517 trees ha^{-1} and 10.9 m^2 ha^{-1}, which is equal to 40% and 13% of the total number of trees and basal area, respectively. Although the average density of *E. cordifolia* is relatively low, with 89 trees ha^{-1} (7%), the average basal area is 7.4 m^2 ha^{-1} (9%), which is explained by the large size of surviving trees.

The origin of this second-growth forest is associated with a severe fire that likely occurred at the beginning of the 20th century and affected a mixed old-growth forest dominated by *N. obliqua*, similar to the old-growth remnants in Rucamanque. The fire, which occurred in approximately 1901, resulted in the destruction of the original patch, followed by the rapid and massive post-fire establishment of *N. obliqua* and other species, such as *E. cordifolia* (Figure 2a). The post-fire establishment of *N. obliqua* occurs in a period of between 20 and 40 years (Figures 3a and 4a), in this case, between 1910 and 1950. The presence of surviving trees plays an important role, as they are a source of seeds that serve to reestablish the patch. Some additional fires circa 1937 and 1945, which were less intense and extensive, likely promoted the establishment of new *N. obliqua* trees.

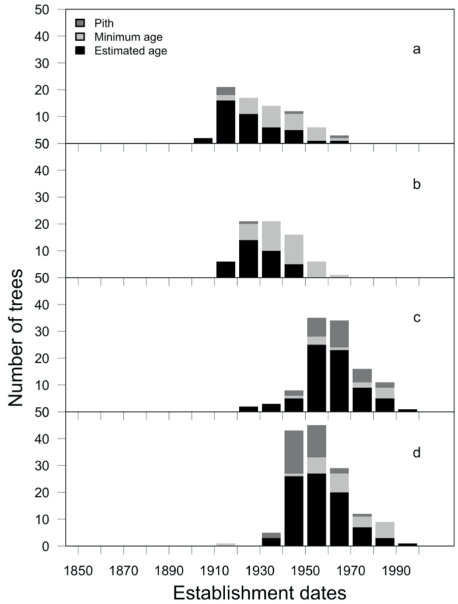

Figure 2. Post-fire establishment period of individuals of a) *Nothofagus obliqua*, b) *Nothofagus dombeyi*, c) *Drimys winteri*, and d) *Gevuina avellana, E. cordifolia, P. saligna, S. conspicua, A. meli,* and *A. luma,* among the principal species of the mixed evergreen secondary forest.

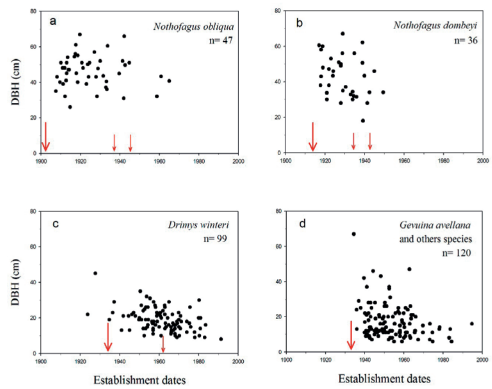

Figure 3. Relationship between the DBH (diameter at breast height) and the establishment dates of individuals of a) *Nothofagus obliqua* (arrows indicate fires in 1901, 1937 and 1945), b) *Nothofagus dombeyi* (fire dates in 1914, 1934 and 1942), c) *Drimys winteri* (fire dates in 1934 y 1962), and d) *Gevuina avellana, E. cordifolia, P. saligna, S. conspicua, A. meli,* and *A. luma,* among the principal species of the mixed evergreen secondary forest.

Table 3. Dasometric parameters for second-growth forests of *Nothofagus obliqua* (Roble, NO), *Nothofagus dombeyi* (Coihue, ND), *Drimys winteri* (Canelo, DW) and the Mixed Evergreen (SV) forest. N and BA indicate the number of individuals and basal area (m^2) per hectare, respectively.

		Number of trees and basal area per species											
Study sites	Plot	N	BA	N	BA	N	BA	N	BA	N	BA	N	BA
Rucamanque													
		Roble		Ulmo		Olivillo		Lingue		Otras		Total	
Roble	NO 10	311	72.4	278	26.1	189	5.1	133	7.6	2116	10	1122	121.2
	NO 6	433	51.7	22	1.0	278	5.4	167	8.0	355	7.1	1255	73.2
	NO 2	311	51.8	56	2.6	867	6.3	133	2.8	422	6.1	1789	69.6
	NO 4	422	59.9	0	0	189	1.1	111	7.2	289	7.0	1011	75.3
Llancahue													
		Coihue		Ulmo		Olivillo		Laurel		Otras		Total	
Coihue	ND 5	500	42.9	189	3.0	89	0.5	122	1.4	488	5.2	13888	53.0
	ND 2	433	53.0	389	11.0	255	2.6	0	0	632	7.8	1709	74.4
	ND 7	444	76.2	33	1.0	189	1.1	244	3.3	844	11.4	1754	93.0
	ND 6	289	60.4	100	2.1	78	2.0	588	11.2	344	3.0	1399	78.7
		Canelo		Ulmo		Olivillo		Tepa		Otras		Total	
Canelo	DW 1	1940	43.9	60	3.0	80	8.5	240	9.6	280	3.3	2600	68.3
	DW 2	1340	31.7	20	0.1	120	27.6	820	38.5	240	2.9	2540	100.8
	DW3	2250	48.5	83	1.1	25	1.4	808	10.7	125	3.6	3291	65.3
	DW4	520	9.8	20	49.5	0	0	1160	35.6	140	1.1	1840	96.0
	DW5	1324	35.1	83	0.7	75	11.3	750	17.9	175	1.7	2407	66.7
	DW6	1240	20.0	60	16.2	100	2.2	980	31.8	140	0.9	2520	71.1
		Avellano		Ulmo		Olivillo		Tepa		Otras		Total	
SV	SV 4	1089	13.8	1478	16.8	100	2.7	1322	9.2	1522	16.6	5511	59.1
	SV 5	1867	25.4	67	1.2	211	7.8	2500	15.6	811	17.3	5456	67.3
	SV6	911	22.3	33	0.6	22	1.2	2644	15.4	900	18.9	4510	58.4
	SV 7	1078	22.8	56	0.5	211	3.2	3289	21.7	611	10.2	5245	58.4
	SV8	433	5.9	489	4.7	256	5.5	1689	9.0	1600	27.2	4467	52.3

The growth patterns of *N. obliqua* tree-rings show a rapid initial growth rate from the beginning of the 1900s (Figure 4a), which confirms the conditions of an opening in the canopy after a fire and which favored the accelerated growth of this pioneer species.

Nothofagus dombeyi second-growth forests

The second-growth forests of *N. dombeyi* have a richness of 14 tree species that belong to 10 families (Table 1). The main species that dominates the upper canopy is *N. dombeyi*, together in some cases with *E. cordifolia* (Table 2). In the intermediate and lower canopy, the main species present are *E. cordifolia*, *Aextoxicon punctatum* R. *et.* Pav., *Laurelia sempervirens* Looser, *Laureliopsis philippiana* Looser, and several species from the Proteaceae and Myrtaceae families. The diameter structure of *N. dombeyi* is similar to a normal curve, where trees conform to a relatively homogenous upper canopy (Figure 1b). This suggests a cohort that initiated its recruitment

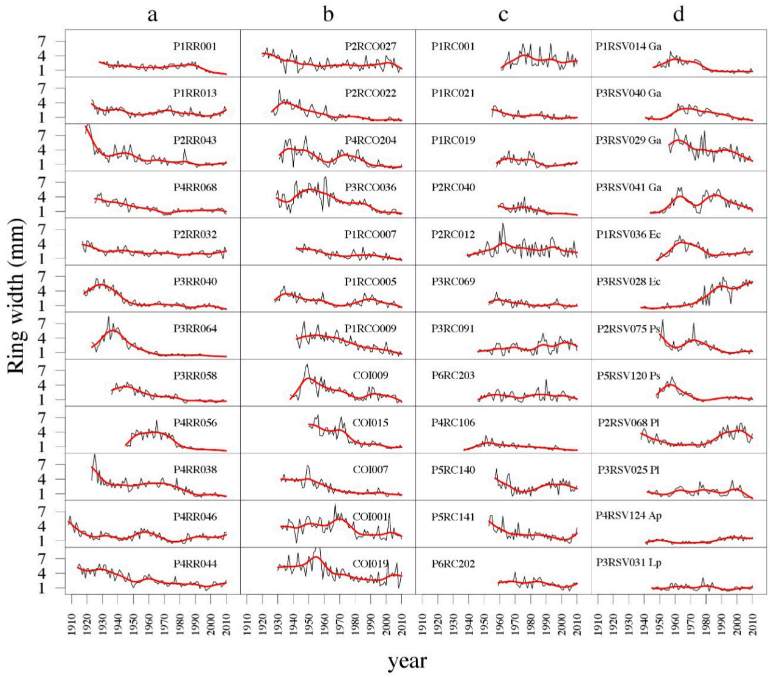

Figure 4. Tree-ring growth patterns of individuals recruited post-disturbances of a) *Nothofagus obliqua*, b) *Nothofagus dombeyi*, c) *Drimys winteri*, and d) mid-shade tolerant species *Gevuina avellana* (Ga)*, E. cordifolia* (Ec) and *Podocarpus saligna* (Ps) and the most shade tolerant species *Persea lingue* (Pl)*, Aextoxicon punctatum* (Ap) and *Laureliopsis philippiana* (Lp). The lines represent the tree-ring growth trend.

immediately after a disturbance. Similar to *N. obliqua*, there are large surviving *N. dombeyi* trees (>100 cm dbh) in this forest. The accompanying tree species that are tolerant and mid-tolerant to shade are found mainly in diameter classes below 30 cm.

This forest has an average overall density of 1562 trees ha^{-1} and 75 m^2 ha^{-1} of basal area. *N. dombeyi* has an average density of 415 trees ha^{-1} and an average basal area of 58 m^2 ha^{-1}, which represents 27% and 78% of the total number of trees and the basal area of the forest stand, respectively (Table 3). Together, the species *E. cordifolia*, *A. punctatum* and *L. sempervirens* have an average density and basal area of 569 trees ha^{-1} and 9.8 m^2 ha^{-1}, which is equal to 36% and 13% of the total number of trees and basal area, respectively.

Similar to the second-growth forests of *N. obliqua*, the stand of *N. dombeyi* originated after a severe fire, which occurred circa 1914 and destroyed the original forest and promoted the rapid and dense post fire recruitment of *N. dombeyi*, and to a lesser extent, *E. cordifolia* through seeds (Figure 2b and 4b). Additionally, subsequent fires occurring in 1934 and 1942 that were of lesser severity and size presumably caused openings, and therefore, an opportunity for the establishment of new *N. dombeyi* trees in the following decades (Figure 3b). The post fire establishment of *N. dombeyi* occurs in a period of 10 to 40 years, which may be extended by future fires that favor new pulses of recruitment. The presence of surviving trees (Figure 1b) plays an important role as a source of seeds in the post fire establishment of the species.

Tree rings for the species show a rapid initial growth during the first decades following re-cruitment (Figure 4b). This clearly indicates an opening in the canopy as a result of an intense fire that affected this forest.

Drimys winteri second-growth forests

The second-growth forests of *D. winteri* (canelo) have a richness of 14 species that belong to 11 families (Table 1). The species that dominates the upper canopy is *D. winteri*, along with a few *Laureliopsis philippiana*, and in less abundance, *E. cordifolia* and *Aextoxicon punctatum* (Table 2). In some cases, *D. winteri* and *L. philippiana* species overtop the main canopy as emergent trees. In the intermediate and lower canopy, the principal species are *D. winteri*, *L. philippiana*, *Gevuina avellana* and *Lomatia ferruginea* from the Proteaceae family, and *Amomyrtus luma*, *A. meli* and *Myrceugenia planipes* from the Myrtaceae family. The diameter distribution of *D. winteri* shows a high density of individuals in the dbh classes of 10 and 20 cm, together with *L. philippiana* (Figure 1c). Moreover, in the stand there are remnant large trees (> 90 cm dbh) – survivors of previous cohorts – of the species *L. philippiana*, *E. cordifolia*, *Aextoxicon punctatum* and *D. winteri*. Other, more shade tolerant species participate abundantly in the diameter classes below 30 cm.

This forest stand has an overall average density of 2532 trees ha^{-1} and 78 m^2 ha^{-1} of basal area. *D. winteri* has an average density of 1512 trees ha^{-1} and an average basal area of 31.5 m^2 ha^{-1}, which represents 60% and 40% of the total number of trees and basal area of the patch, respectively (Table 3). *Laureliopsis philippiana*, with 793 trees ha^{-1} and 24 m^2 ha^{-1}, makes up 31% of both the total number of trees and the basal area of the patch. *E. cordifolia* and *A. punctatum* together present an average density and basal area of 121 trees ha^{-1} and 20 m^2 ha^{-1}, which is equal to 5 and 26% of the total number of trees and basal area, respectively.

According to the dates determined from the fire scars extracted from surviving *E. cordifolia, A. punctatum* and *L. philippiana* trees, this second-growth forest originated from a fire that occurred circa 1934, followed by another fire circa 1962. The first fire was of greater severity and destroyed the original stand. The original fire sparked a relatively slow recruitment, via seeds, of *D. winteri* (Figure 2c and 4c). The 1962 fire was less intense and more localized, affecting the forest in a heterogeneous manner, which promoted new recruitments of *D. winteri* and *L. philippiana* (trees in the 10 cm diameter class in Figure 1c; Figures 3c and 4c).

The tree-ring growth of this pioneer species shows a relatively moderate initial growth rate compared with the *Nothofagus* species, with a slight tendency towards a gradual decline in the following decades (Figure 4c).

Mixed Evergreen second-growth forests

Mixed Evergreen second-growth forests have 17 species that belong to 9 families (Table 1). In this type of multispecies forest, the upper canopy is dominated by different species, among which the most important are *G. avellana*, *E. cordifolia*, *D. diacanthoides*, *A. meli* and *A. luma* (Table 2). *D. winteri* and *L. philippiana* can be found in the upper canopy as well, but at lower densities. The main species found in the intermediate and lower canopies are *G. avellana*, *A. meli* and *A. luma*, along with *Lomatia ferruginea*, *Podocarpus saligna* and *Persea lingue*. The species *Embotrium coccineum,* which is shade-intolerant, can occasionally be found in the upper canopy.

The diameter distribution of the Mixed Evergreen forest shows a high density of trees in the 10 cm class, where more than 80% of the trees are concentrated. The most abundant species are *G. avellana*, *E. cordifolia*, *D. diacanthoides*, and particularly, *A. meli* and *A. luma*, which have between 24% and 63% of the total number of trees per hectare (Figure 1d; Table 3).

The Mixed Evergreen forest has a total average density of 5036 trees ha^{-1} and 59.1 m^2 ha^{-1} of the basal area. The species *G. avellana* has an average density of 1075 trees ha^{-1} and an average basal area of 18 m^2 ha^{-1}, which represents 21% and 31% of the total number of trees and the basal area of the patch, respectively (Table 3). *A. meli* and *A. luma* (Myrtaceae), with 2289 trees ha^{-1} and 14.2 m^2 ha^{-1}, make up 45% and 24% of the total number of trees and the total basal area of the stand, respectively. The accompanying species *E. cordifolia* and *D. diacanthoides* together have an average density and basal area of 584 trees ha^{-1} and 8.8 m^2 ha^{-1}, which is equal to 12% and 15% of the total number of trees and the total basal area, respectively. Other species (e.g., *D. winteri*, *L. philippiana*, *Ovidia pillo-pillo*, *Lomatia ferruginea*), with an average density of 1088 trees ha^{-1} and an average basal area of 18 m^2 ha^{-1}, represent 22% and 31% of the total number of trees and the basal area of the patch, respectively.

In this forest, we did not find clear evidence of fire scars in the scarce surviving trees of past cohorts. However, in some of the surviving trees, charcoal could be observed on the trunk, which points to a possible fire in previous decades. Additionally, one of the principal structural characteristics of these forests was the presence of stumps of adult *Persea lingue, Weinmannia trichosperma* and probably *E. cordifolia* trees, which were cut more than 70 years ago. Logging and presumably fire at the beginning of the 1930s promoted the relatively rapid and dense recruitment of diverse species (Figures 2d and 3d), primarily through vegetative reproduction, as evidenced by the profuse sprouting of *G. avellana, A. luma, A. meli,* and *E. cordifolia* trees.

Mid-shade tolerant species such as *G. avellana*, *E. cordifolia* and *P. saligna* that became established after logging and fire show relatively slow to moderate radial growth during the establishment period, but the growth rate gradually increases in the following decades. The shade-tolerant species *P. lingue*, *A. punctatum* and *L. philippiana* show relatively low and stable radial growth during the majority of the observed growth period (Figure 4d).

Discussion

How forest fires and logging have shaped the forest landscape in south-central Chile

In south-central Chile, temperate forests have been shaped primarily by anthropogenic and natural disturbances of great magnitude, such as landslides, blowdowns, volcanic eruptions, and especially by logging (clearcutting or high-grading) and fires in old-growth forests. These agents and the common consecutive occurrence of these agents (i.e., logging and fire) have promoted the extensive development of different types of second-growth forests according to their geographic location (Veblen *et al.,* 1996; Donoso, 1993; Navarro *et al.,* 1999; González *et al.,* 2010; Romero-Mieres *et al.,* 2014).

In the forest stands studied, logging and fire were the most important disturbance factors in determining the structure and composition of the second-growth forests. The numerous fire scars found on surviving trees show the pervasiveness of fire (human-set, in this case) as the principal process in the origin of *N. obliqua*, *N. dombeyi* and *D. winteri* second-growth forests, and this is likely also the case for the Mixed Evergreen forests. Usually, after this type of severe stand-replacing disturbance, there was a rapid establishment of trees from the main pioneer shade-intolerant tree species of the original forest. This demographic process, depending on other fires or subsequent alterations, usually took about two to three decades. Thus, the post-disturbance establishment process fits the general development model of forest stand dynamics proposed by Oliver (1981) and the catastrophic regeneration mode proposed by Veblen (1992).

In the case of the second-growth forests dominated by *N. obliqua* and *N. dombeyi,* both species are considered pioneer and opportunistic species in areas recently opened by disturbances (Veblen *et al.,* 1996; Donoso, 2013). This condition is explained by their autecological traits, such as intolerance to shade, rapid initial growth, and efficient dissemination of seeds by wind, as well as the vegetative reproduction capacity of *N. obliqua* (Donoso *et al.,* 1993; Veblen *et al.,* 1996). Both reproductive processes (generative and/or vegetative) are favored by the survival of old-growth trees following a disturbance (González *et al.,* 2010).

The second-growth forests dominated by *D. winteri* are formations typically found within the forest landscape of old-growth evergreen forests in the coastal region and southern Andean region (40° – 43° S). Their origin is usually the consequence of the destruction of old-growth forests by fires or clearcutting (Donoso, 1993). However, it is interesting to note that in old-growth evergreen forests, the density of the species (*D. winteri*) is usually low, with a few adult trees dispersed in the forest. It is striking then that the capacity of *D. winteri* to create very dense and pure stands after re-establishment in forest areas cleared by disturbances. This response is determined in large part by its ability to tolerate a wide range of light conditions and, in some cases, seasonal flooding (Donoso, 2013), the high production and effectiveness of the dispersion of its fruits and seeds by birds (Armesto and Rozzi, 1989), low susceptibility to attacks from fungi and insects, along with the vegetative reproductive capacity and rapid initial growth (Navarro *et al.,* 1999; Romero-Mieres *et al.,* 2014).

Mixed Evergreen second-growth forests show a severe human impact. The evidence of fire and the presence of the stumps of adult *Persea lingue* and *Weinmannia trichosperma* trees suggest that the forest was subject to high-grading ("cut the best and leave the rest or worst") of its primary species and was later clear-cut and burned in the 1930s. The post disturbance response was characterized by the rapid establishment, principally through vegetative reproduction, of multiples stems of *G. avellana*, *A. luma*, *A. meli*, and *E. cordifolia* species, among others, which showed a relatively slow to moderate radial growth during the beginning of their establishment. The difference in the growth patterns between these mid-shade tolerant species and those observed from *Nothofagus* can be explained by the strong early competition (in *G. avellana*, *A. luma*, *A. meli*, and *E. cordifolia)* derived from the extremely high initial density of stems and shoots.

Overall, these results support our hypothesis that fires and logging have been the main causes of the formation of second-growth forests in south-central Chile, which have had a pervasive impact on the landscape of this region, which is currently dominated by second-growth forests.

Implications for the management and restoration of the forest landscape in south-central Chile

During the last century, fire and logging have been key processes in determining the structure and composition of native forests and in shaping the forest landscape in south-central Chile (González, 2005; Zamorano-Elgueta *et al.,* 2014). The consequence of these processes for the landscape, in addition to their fragmentation and degradation, is a relative homogenization of native forests in terms of their age and size structure, i.e., second-growth forests 60-150 years old (González, 2005). Therefore, the landscape has become dominated by forests in their initial successional stages at the expense of old-growth forests. This cultural landscape, highly influenced by past fires and logging, is different from one dominated by natural disturbances (e.g., before arrival of Spaniards), among which, natural fires have been historically less frequent.

Projected climate change in south-central Chile, with an increase of temperatures, a decrease in precipitation and a greater occurrence of drought (DGF, 2006), will likely increase wildfires, making forests more susceptible to major fire events, especially large and homogenous areas of second-growth forests. Under this scenario, ecological forestry proposals (Seymour and Hunter, 1999) promote moving forest ecosystems closer to the natural range of structural and compositional variability at the landscape scale, which is a better alternative for increasing the adaptive capacity and resilience of forests. To recover mature and old-growth forests on the landscape (which are nearly absent in the lowlands of south-central Chile), restoration thinning aimed to restore old-growth attributes in young forests (Keyes, 2005) could be an important approach to apply at the stand level.

Forest management to increase the proportion of old-growth forests in the landscape has different expectations in second-growth forests, such as the ones of the present study. While old-growth attributes such as large trees, coarse woody debris, and snags, i.e., structural diversity, should be easier to accomplish in *Nothofagus*-dominated forests with larger trees and greater growth rates, it will be slower in the Mixed Evergreen forests composed of tree species with slower growth in high-density stands. Other old-growth attributes, such as the dominance of late-successional species or diversity, would likely be achieved more rapidly in Mixed Evergreen forests that have many more species, most of which are shade tolerant and typical of old-growth forests. Second-growth forests dominated by *D. winteri*, which are less common, are in an intermediate position in the lowlands of south-central Chile in regards to rapid old-growth forest attributes could be achieved in them through restoration thinnings. Overall, these efforts should be included in a greater framework of forest ecosystem management to increase the diversity of ecosystem goods and services that can be provided by native forests in Chile (Nahuelhual *et al.,* 2007; Donoso *et al*., 2014).

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Resumen

M.E. González, P. Szejner, P.J. Donoso y C. Salas. 2015. Fuego, madereo y patrones de establecimiento de bosques secundarios en el centro-sur de Chile: implicaciones para su manejo y restauración. Cien. Inv. Agr. 42(3): 427-441. Los bosques secundarios representan el mayor recurso forestal para el manejo y la restauración de gran escala en muchas regiones del mundo. En el centro-sur de Chile los bosques secundarios están dominados por *Nothofagus obliqua*, *N. dombeyi*, *D. winteri*, y Siempreverde mixtos. El presente artículo examina la influencia del fuego y tala en los patrones de establecimiento y desarrollo de bosques secundarios de la región centro-sur de Chile. Para la caracterización de la estructura y composición de cada bosque secundario se seleccionaron rodales representativos estableciendo 4-6 parcelas de 900 m^2. El tipo de disturbio y su fecha de ocurrencia fue establecido a través de evidencias tales como cicatrices de fuego y pulsos de establecimiento de árboles. La estructura de tamaños y composición indican un estado de desarrollo intermedio o de reiniciación del sotobosque presentando en promedio una densidad y área basal que varía entre 1294 y 5038 árboles ha^{-1} y entre 59 y 85 m^2 ha^{-1}, respectivamente. Incendios de gran severidad y/o madereo ocurridos en las primeras décadas de los 1900 promovieron un rápido establecimiento de las principales especies pioneras (*Nothofagus obliqua, N. dombeyi, D. winteri*). En los bosques secundarios Siempreverde mixtos, el establecimiento de especies tolerantes o semi-tolerantes a la sombra (ej., *Gevuina avellana, Eucryphia cordifolia*), fue principalmente por rebrotes vegetativos. El fuego y madereo han sido agentes clave en determinar la uniformidad estructural y composicional de los bosques nativos del centro-sur de Chile. La restauración ecológica a escala de paisaje, tanto de procesos ecológicos (frecuencia incendios) como de la estructura y composición de los bosques secundarios, ofrece una relevante aproximación para acelerar la generación de atributos de bosques antiguos que satisfagan los múltiples bienes y servicios ecosistémicos demandados por la sociedad.

Palabras clave*:* Disturbios, *Nothofagus*, restauración ecológica, sucesión secundaria.

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