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RESEARCH PAPER

Determination of homogeneous edaphoclimatic zones for the secondary forests of *Nothofagus dombeyi* in central-southern Chile

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Abstract

C. Esse, PJ. Donoso, V. Gerding, and F. Encina-Montoya. 2013. Determination of homogeneous edaphoclimatic zones for the secondary forests of *Nothofagus dombeyi* in central-southern Chile. Cien. Inv. Agr. 40(2): 351-360. *Nothofagus dombeyi* grows in a wide variety of sites in Chile (30-47°S), but there is little knowledge about its productive potential. This lack of information hinders decision-making to better guide the production of goods and services from these forests. This study was conducted in central-southern Chile (39°S-41°S), where this species is prominent, especially in secondary forests. The aim of the study was to determine the homogeneous edaphoclimatic zones for secondary forests of *N. dombeyi* based on the integration of environmental factors. The methodological approaches considered the spatial analysis and construction of geographic covers using geographic information systems, principal components multivariate analysis, and clustering techniques with CART analysis. Five homogeneous zones could be determined for *N. dombeyi* with a high level of accuracy. The spatial distribution of *N. dombeyi* secondary forests was explained in decreasing order by climate, soil and topography.

Key words: CART, biophysical factors, edaphoclimatic zones, k-means.

Introduction

In central-southern Chile, secondary forests dominated by *Nothofagus dombeyi* (Mirb.) Oerst. cover more than 200 thousand hectares (CONAF *et al.*, 1999) between 30ºS and 47ºS and from sea level to approximately 1000 m a.s.l. These are even-aged forests in the self-thinning stage of development (*sensu* Oliver and Larson, 1996) that originated after the occurrence of large-scale disturbances (*e.g.*, landslides, windstorms, and fires; Donoso *et al.*, 1999), which enabled colonization by this pioneer shade-intolerant species (Donoso *et al.*, 2006). Trees in these forests generally have a good shape (clean and straight stems), fast growth and timber of good quality, and thus, these forests are considered economically attractive with volume

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growths of 20 m^3 ha^{-1} yr^{-1} or more after age 20 (Donoso *et al*., 1999) and a rapid growth response to silvicultural interventions (Grosse and Quiroz, 1999; Donoso *et al*., 2006).

N. dombeyi occupies different sites within 10 of the 12 forest types described for Chilean forests, reflecting its adaptability to various soil conditions and climates (Donoso *et al*., 2006). It grows in a humid temperate climate with some dry summer spells (Donoso *et al*., 1999). It also grows on soils (Luzio *et al*., 2010) of medium to high fertility in the Intermediate Depression and Andes (andisols) and on low-fertility soils of metamorphic origin in the Coastal Range (inceptisols and ultisols). The wide variation in the site conditions in which *N. dombeyi* grows and the limited knowledge on the productive potential of these forests throughout their distribution makes it difficult to make decisions about the most convenient management prescriptions for the production of goods and services derived from these forests. According to studies by Chambers *et al.* (2013), Thiers (2004) and Schlatter and Gerding (1995), homogeneous areas defined by climate and soil factors are related to the growth and productivity of forest species.

The only approach used for the determination of site quality in secondary forests of *N. dombeyi* has been the site index curves developed for a spatially restricted region by Esse *et al*. (2007), which has limited applications because of its local character. A study about the productivity of *N. dombeyi* secondary forests should consider the most relevant factors that determine site quality at larger spatial scales. Therefore, our objective was to identify homogeneous edaphoclimatic zones through spatial analysis and multivariate techniques of the factors of climate, soil, and topography within the regions covered by secondary *N. dombeyi* forests in central-southern Chile. This approximation has not been developed for forest analyses in Chile and has great potential for site classification once productivity variables become integrated within the defined zones.

Materials and methods

Study area

The study was conducted in the provinces of Cautín, Valdivia and Ranco in central-southern Chile (Figure 1). The climate is temperate and rainy but with a short summer dry season due to the Mediterranean influence in the region (DGF-Conama, 2006, CEPAL, 2012). Cautín is characterized by sufficient rainfall to allow continuous forest cover and a well-defined dry period from three to seven months (Schlatter *et al*, 1997). Valdivia and Ranco are characterized by high annual rainfall, a short dry period of 1-2 months, and a limiting temperature for some temperate species (Schlatter *et al*, 1995). In the Andes Range, the soil is deep to moderately deep (> 50 cm; Schlatter *et al.*, 2003), and its textural classes range from coarse sandy loam to silt loam, with well to excessive drainage. In the Intermediate Depression, the soils are mostly volcanic sediments originating from different geological epochs. At low elevations in the east side of the Coastal Range, the soils are deep and have developed from old volcanic ashes deposited on the metamorphic complex. At higher elevations of the Coastal Range, the soils are shallow and derived from metamorphic rock (Luzio *et al*., 2010).

Selection and integration of biophysical factors

The determination of climatic and soil zones was based on the methodological approaches described by Gómez-Orea (1999), which consist of the identification of homogeneous environmental units. Based on the result obtained by Thiers (2004) for *N. obliqua*, the three factors selected for the analysis of *N. dombeyi* were climate, soil, and topography. For the climate factor, the variables recorded were the mean annual temperature, annual precipitation, maximum temperature, minimum temperature and thermal oscillation. For the soil factor, the variables were effective depth, textural class, bulk density in the first 25 cm of the soil, internal drainage and total pore volume as determined from the textural class. For the topography factor, the variables considered were slope, aspect and altitude (Table 1). The climate information was obtained from Worldclim (Hijmans *et al*., 2005) and complemented with data from the Ordination System of Land (SOT) (Schlatter *et al*., 1995) and the study of climate variability for the XXI century (DGF-Conama, 2006). The soil data were obtained from CIREN (1999, 2003) and Luzio *et al*. (2010). The percent participation of each constituent soil particle (clay, silt, sand) was obtained from the textural triangle developed by the USDA (U.S. Department of Agriculture of the United States). The topographic variables were obtained from a digital elevation model (DEM) of the satellite sensor ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer). The integration of biophysical factors was based on spatial analysis (GIS) using ArcGIS 9.3 and ERDAS 8.7. The spatial database had information for each stand of *N. dombeyi* according to CONAF *et al*. (1999).

Statistical analysis and spatial delimitation

We performed an exploratory principal components analysis to identify the soil, climate and topographic variables that best explain the variability of the data set (Quinn and Keough, 2002). This selection was based on the criteria of the *scree test* of Cattell and Kaiser-Guttman (Quinn and Keough, 2002). With the information reduced, a cluster analysis was developed (K-means). Finally, as a complementary analysis, CART (Classification and Regression Tree) was applied using the QUEST (Quick, unbiased, efficient, statistical tree) classification type. The decision tree procedure created a classification model based on the trees and classified the cases into groups or predicted values of a dependent variable (target) based on the values of independent variables (predictors). The procedure provides validation tools for exploratory analysis and confirmatory classification (McCune, 1988; SPSS Decision Trees 17.0. SPSS Inc., Chicago, IL, USA, 2007; Pesch *et al*., 2011). For statistical analyses, we used R 2.11 (R Core Team, Vienna, Austria, 2012) and SPSS 17.0 (SPSS Inc., Chicago, IL, USA, 2007). For the spatial delimitation of the resulting homogeneous zones, we used the vectorial geographic covers of the site classification system developed by Schlatter and Gerding (1995) and Schlatter *et al*. (1995).

Results

Multivariate statistical analysis

A total number of 205,165 polygons containing *N. dombeyi* secondary forests was included in the final analysis, which represents a total area of 173,062 ha. The principal components analysis indicated that the first three factors accounted for 64.37% of the variation (35.71, 16.68 and 11.98%, respectively) (Figure 1). The analysis identified the eight most important biophysical variables. These variables were thermal oscillation, minimum temperature, mean annual temperature and annual precipitation for climate; effective depth, internal drainage and porosity for soil; and altitude for topography.

The cluster analysis allowed the generation of five groups with maximization among the groups for each cluster. For all variables and all clusters obtained, the average values of each centroid were highly significant ($P \leq 0.001$). The greatest difference among the clusters was given in the number of observations assigned to each one. Zones 1, 2 and 3 represented 89% of the total area covered by *N. dombeyi*, which indicated that the highest concentration of stands are located in the Andean Range in the province of Valdivia and in the Intermediate Depression and foothills of the Andes in the province of Cautín. The QUEST analysis (Figure 2) showed a decision tree that allows the identification of the variables that contribute most to the classification of the five growth areas: thermal oscillation, precipitation, soil porosity and soil drainage. The reliability of

Table 1. Ranges for each variable considered in the study.

Factor	Variable and Code	Rank	Class
Climate	Average annual temperature (°C)	7 - 9	8
		9 - 11	10
		11 - 13	12
		13 - 15	14
		15 - 17	16
	Thermal oscillation (°C)	16.2 – 17.7	17
		17.8 – 19.3	19
		19.4 – 20.9	20.2
		21.0 – 22.5	21.7
		22.6 – 24.0	23.3
	Minimum temperature (°C)	-3.4 - -1.74	-2.3
		-1.75 - -0.07	-0.8
		-0.06 – 1.58	0.8
		1.57 – 3.23	2.3
		3.24 – 4.90	4.0
	Maximum temperature (°C)	16.9 – 18.6	17.8
		18.7 – 20.4	19.6
		20.5 – 22.3	21.2
		22.4 – 24.1	23.5
		24.2 - 26	25
	Annual rainfall (mm)	< 750	750
		750- 1,550	1,150
		1,550 – 2,550	2,050
		2,550 – 3,550	3,050
		3,550 - 3950	3,750
		3,950 – 5,000	4,450
Soil	Deep physiological soil (cm)	< 25	25
		25 - 50	37
		50 - 75	62
		75 - 100	87
		100 - 150	125
		> 150	150
	Textural classes (mm)	< 0.122	0.122
		0.122 – 0.254	0.188
		0.254 – 0.456	0.355
		0.456 – 0.614	0.518
		0.614 – 0.634	0.624
	Bulk density in 0-25 cm	-	0
	(g cm^{-3})	-	0.74
		-	0.76
		-	0.82
		-	0.83
		-	0.88
		-	0.92
		-	1.16
		-	1.42
	Internal drainage	Excessive	1
		good	2
		Moderate	3
		Imperfect	4
		Poor	5
		Very poor	6
	Porosity (%)	Sandy-Clay Soils	40
		Sandy Soils	42.5
		Clay Soils	45
Topography	Slope (%)	0 - 15	7.5
		15 - 30	22.5

Table 1 continued

Factor	Variable and Code	Rank	Class
		30 - 45	37.5
		45 - 60	52.5
		60 -100	75
	Aspect (°)	0	0
		0 – 22.5	11
		22.5 – 67.5	45
		67.5 – 112.5	90
		112.5 – 157.5	135
		157.5 – 202.5	180
		202.5 – 247.5	225
		247.5 – 292.5	270
		292.5 – 337.5	315
		337.5 - 360	349
	Altitude (m)	0 - 200	100
		200 - 400	300
		400 - 600	500
		600 - 800	700
		800 – 1,000	900
		1,000 – 1,200	1,100
		1,200 – 1,400	1,300

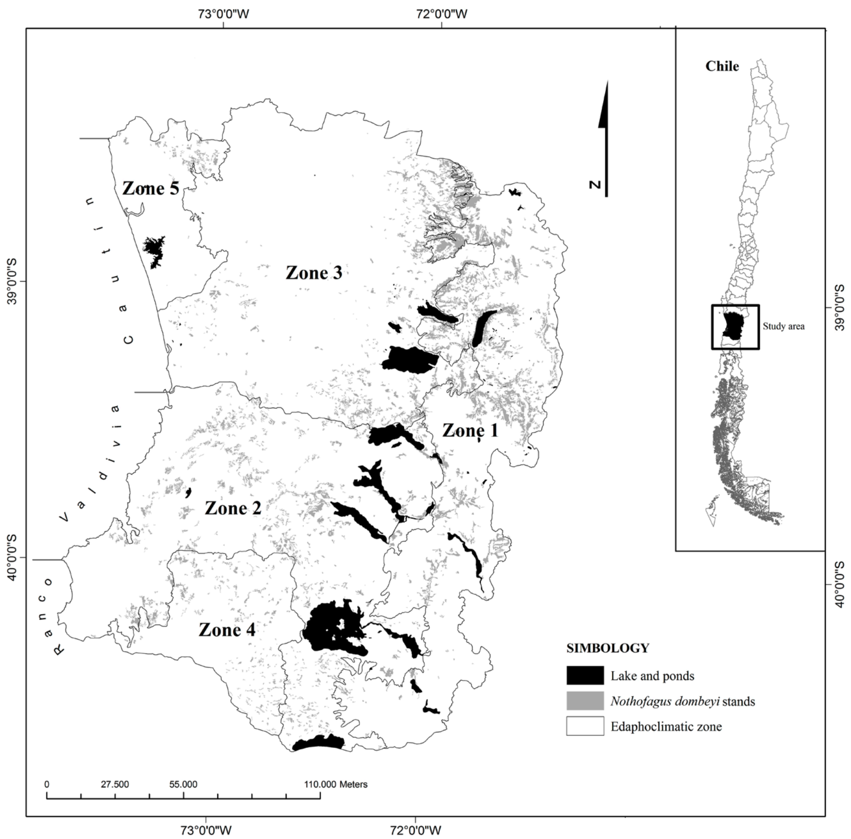

Figure 1. Edaphoclimatic zones for *N. dombeyi* determined from the integration of biophysical factors.

the results associated with this model is shown in the confusion matrix, which revealed that the classification was 100% correct in the allocation of units to growth areas.

Zone 1 was mainly in the Andean Range across the latitudinal distribution of the study area. The area of secondary forests of *N. dombeyi* represented 32% of the total area. The factor that helped define this area was climate, with the highest annual rainfall and thermal oscillation and the lowest minimum temperature. Zone 2 corresponded to the Coastal Range, Intermediate Depression and Andean foothills in the province of Valdivia and part of Ranco. The secondary forests of *N. dombeyi* corresponded to 30% of the total area. The factors that defined this area were soil, with the lowest porosity and physiological soil depth, and topography, with lower elevations (similar to Zone 4). Zone 3 represented the Coastal Range and the Intermediate Depression in the province of Cautín, in addition to the foothills of the Andes in the southern part of the study area. This area covered 27.3% of the stands of *N. dombeyi*. The factor that defined this area corresponded mainly to climate, as represented by the highest thermal oscillation, similar to Zone 1. Zone 4 corresponded to the Intermediate Depression in the province of Ranco and accounted for 6.2% of the stands of *N. dombeyi*. The factor that defined this area was climate, with the lowest annual rainfall and the highest average annual temperature. Zone 5 was located in the Coastal Range in Cautín Province. This area comprised 5.5% of all stands. The fac-

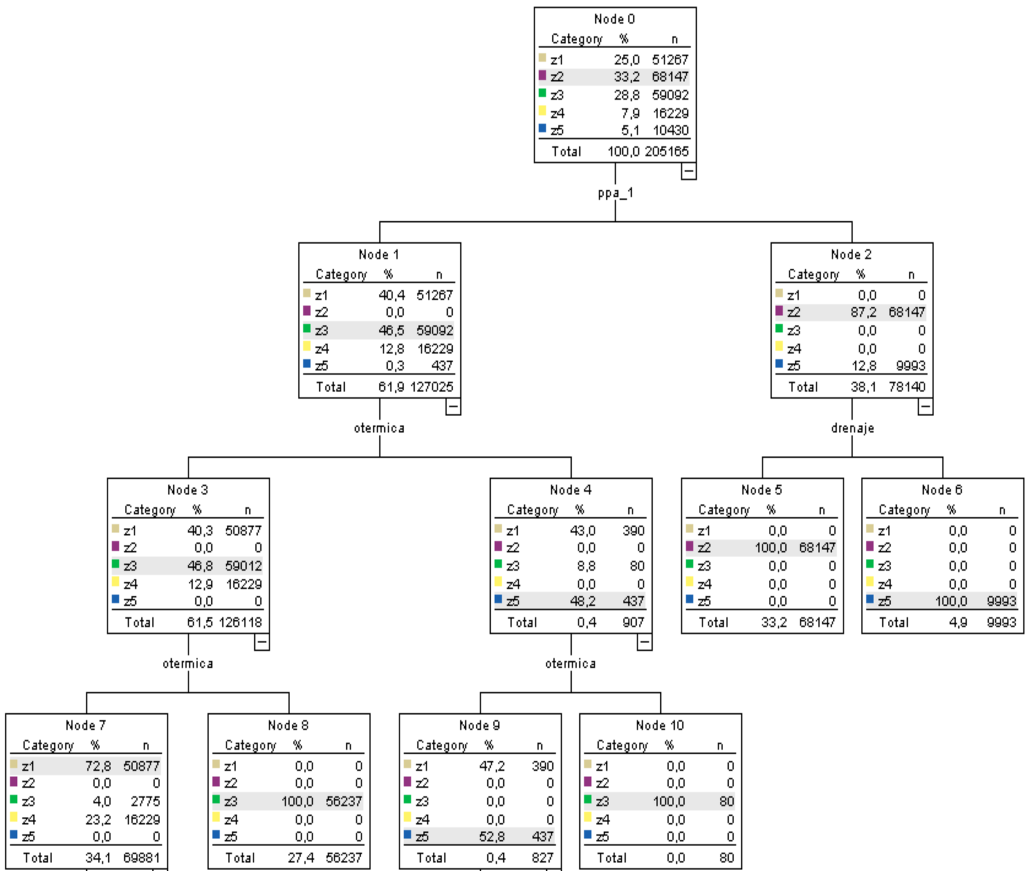

Figure 2. CART tree for the occurrence of *N. dombeyi* stands in each zone.

tors that defined this area mainly corresponded to climate and topography, with the lowest thermal oscillation and the highest altitude (Table 2).

Discussion

The climate and soil variables selected are consistent with zoning studies for other species and sites that were based on traditional mapping techniques (Gerding and Schlatter, 1995, Schlatter and Gerding, 1995, Schlatter *et al*., 1995, 1997, Thiers, 2004, Cruz *et al*., 2009). In particular, Schlatter *et al*. (1997) showed that, in general, the regional climate, and more specifically the water availability, determined the growth of plant species, which is explained by their direct influence on photosynthesis and indirectly through the opening and closing of the stomata of leaves (Alberdi, 1987). Another important factor is soil moisture, which is related to soil depth and drainage (Schlatter *et al*., 1995). *N. dombeyi* has been previously reported to adapt better to areas of higher humidity, where it reaches better growth rates (Donoso *et al*., 2006). This study showed that the main variables that enabled the classification of different homogeneous zones of growth for stands of *N. dombeyi* were annual average precipitation, thermal oscillation and soil drainage.

Zone 1 had soils originating from volcanic ashes (inceptisols and andisols) at different stages of development (Luzio *et al*., 2010). This zone was characterized by the highest humidity and lowest temperature values (-1.3 °C). These factors allowed for the permanent availability of soil moisture. The average temperature (10 °C or less) tended to be low for other *Nothofagus* species, also favoring *N. dombeyi* in this region, as reported by Weinberger and Ramírez (2001) for an elevation range from 700 to 800 m.a.s.l. At these elevations and above, *N. dombeyi* forest stands tend to be pure due to their greater tolerance to low temperatures compared with other species (Weinberger and Ramirez, 2001, Donoso *et al*.,

Table 2. Descriptive analysis of biophysical explanatory variables for each edaphoclimatic zone.

ZEH (ha)	Statistics	T.O (°C)	MT (°C)	AAT (°C)	ALT (m.a.s.l.)	AR (mm)	PSD (cm)	DR	POR (%)
1 (55,339)	min.	21	-1.4	10	700	3250	62	1	40
	max.	23.1	0.1	10	1300	3750	87	6	42.5
	mean	23	-1.3	10	720	3656	85	1.4	42.3
	CV, %	0.6	30.8	0	9.6	1	9.4	-	1.7
2 (51,553)	min.	19.6	3.5	12	100	2250	87	1	40
	max.	19.6	3.5	12	100	2250	87	1	40
	mean	19.6	3.5	12	100	2250	87	1	40
	CV, %	0	0	0	0	0	0	-	0
3 (47,314)	min.	16.6	1.2	10	700	1750	62	1	40
	max.	22.8	3.4	12	1100	2450	125	3	45
	mean	21.9	2.3	11	797	2102	102.5	1.6	42.5
	CV, %	6.4	17.4	9	12.5	12	20.5	-	2.1
4 (10,786)	min.	19.8	3.4	14	100	1350	125	2	45
	max.	19.8	3.4	14	100	1350	125	2	45
	mean	19.8	3.4	14	100	1350	125	2	45
	CV, %	0	0	0	0	0	0	-	0
5 (8,070)	min.	16.6	1.2	10	500	1200	62	1	40
	max.	20	2.7	12	900	3000	125	2	45
	mean	18.4	2	10.5	809	1900	122.4	1.9	43.8
	CV, %	4.9	20	8.6	20.6	31.6	8.4	-	4.6

T.O: Thermal Oscillation; MT: Minimum Temperature; AAT: Average Annual Temperature; ALT: Altitude; AR: Annual Rainfall; PSD: Physiological Soil Depth; DR: Drainage; POR: Porosity; CV: Coefficient of Variation.

1999), except when it meets with *N. pumilio* at elevations > 1000 m (Donoso *et al*., 2006). With these climate and soil characteristics, *N. dombeyi* secondary stands can reach growth rates close to 20 m^3 ha^{-1} yr^1 after age 20 (Donoso *et al*., 1999), illustrating the great growth potential of secondary forests in this zone.

Zone 2 deserves special attention. It is separated from Zone 3 due to the presence of the east-to-west mountain range of Loncoche, which is an extension of the Coastal Range that widens toward the east (Illies, 1970). This clear division illustrates the accuracy of the methodology used as both the soil and climate change in this Loncoche mountain range. The division of both zones is explained by the variation in the climate. In general, Zone 3 has a higher thermal oscillation (Table 2), which can reduce the competitive advantages of *N. dombeyi* and may explain why there were so few secondary forests of *N. dombeyi* in this zone. As a result, Zone 2 covers the Coastal Range and the Loncoche mountains, with most in the province of Valdivia, where the soils have the lowest porosity, depth and altitude range. Zone 4, in contrast to the others, showed *N. dombeyi* stands growing in areas of low rainfall and high temperatures, concentrated in the Intermediate Depression in the province of Ranco. The presence of these stands showed the ability of this species to establish and develop under various site conditions.

Zone 5 is characterized by a highly fragmented landscape with a low number of stands due to a strong land-use change to agriculture, especially since the mid-twentieth century (Camus, 2006). The stands of *N. dombeyi* were identified growing in areas of higher altitude (average 900 m) and low thermal oscillation in this zone.

Several studies in Chile have proposed growth areas for various exotic and native tree species (Donoso *et al*., 1993, Gerding and Schlatter, 1995, Schlatter and Gerding, 1995, Echeverría and Lara, 2004, Esse *et al*., 2007). However, edaphoclimatic zones for native species with high silvicultural potential and an ample spatial distribution are unknown. Overall, the methods used for zoning have considered traditional mapping techniques (Schlatter *et al*., 1995, 1997). However, in recent years, different multivariate statistical methods have been used to reduce the variables and to identify patterns (Echeverría and Lara, 2004, Thiers, 2004, Cruz *et al*., 2009, Chambers *et al*., 2013), and hierarchical methods have been used for defining forest types and classification tree analysis (Pesch *et al*., 2011). This study recommends a methodology that, through the integration of biophysical factors, contributes to the determination of homogeneous edaphoclimatic zones for the potential growth of species that have a high capacity to adapt to different environmental conditions and that are economically attractive. The present study illustrates that using these techniques to determine homogeneous zones for the potential growth of economically interesting species is viable and has an ecologically reasonable explanation. These results can have relevant applications for land use allocation, as in the case of forestry for the selection of zones of homogeneous growth for differential production or conservation purposes.

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Resumen

C. Esse, PJ. Donoso, V. Gerding y F. Encina-Montoya. 2013. Determinación de zonas edafoclimáticas homogéneas para bosques secundarios de *Nothofagus dombeyi* en el centro-sur de Chile. Cien. Inv. Agr. 40(2): 351-360. *Nothofagus dombeyi* crece en una amplia variedad de sitios en Chile (30-47 ° S), por ello existe escaso conocimiento sobre su potencial productivo. Esto dificulta la toma de decisiones que orienten de mejor forma la producción de bienes y servicios de estos bosques. Este estudio se llevó a cabo en el centro-sur de Chile (39° S-41° S), donde esta especie es prominente, especialmente en bosques secundarios. El estudio tuvo como objetivo determinar zonas edafoclimáticas homogéneas para los bosques secundarios de *N. dombeyi*, basado en la integración de factores biofísicos. Los enfoques metodológicos consideraron análisis espacial y construcción de coberturas geográficas por medio de sistemas de información geográfica, análisis multivariado de componentes principales y técnicas de agrupamiento con análisis CART. Fue posible determinar cinco zonas homogéneas para *N. dombeyi* con un alto nivel de precisión. La distribución espacial de la especie se explicó en orden decreciente por los factores biofísicos clima, suelo y topografía.

Palabras clave: CART, factores biofísicos, k-means, zonas edafoclimáticas.

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