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Growth patterns of secondary *Nothofagus obliqua–N. alpina* forests in southern Chile

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Abstract

The environmental factors that influence the diameter-growth of the *Nothofagus obliqua* and *Nothofagus alpina* were investigated in secondary forests in southern Chile. A total of 17 edaphic, topographic and climatic variables were studied. The annual periodic diameter increment (API) in 15 and 20 year-old trees was measured using dendrochronological techniques. A multiple correspondence factorial analysis (MCFA) indicated that longitude, minimum precipitation, summer humidity index, frost-free period, maximum drought period, and percentage of silt and sand in the soil were driving variables influencing diameter-growth. The first three factors accounted for 70% of the total variation. Higher diameter-growth rates were associated with intermediate annual rainfall, a short dry period, and sandy soil. Lower rates were associated with an intermediate frost-free period, a low summer humidity index, a long dry period and silty soil. A spatial pattern of the driving variables was found in the study area. The first two factors showed a longitudinal division separating the sites located in the Central Depression, Coastal Range and Andean Range. Using the results generated by MCFA, an ascendant hierarchic classification analysis (AHCA) was conducted to classify the study area into five sites of homogeneous productivity. The highest diameter-growth (>7.1 mm per year) sites were located in the pre-Andes of Valdivia Province, followed by sites in the northern pre-Andes of Cautin Province and the Andean Range of both provinces. Intermediate growth rates corresponded to the coastal site. The lowest diameter-growth (<5.3 mm per year) was located in the Central Depression in both provinces. The use of multivariate methods and the adequate selection of environmental variables enabled us to identify the diameter-growth driving variables, as well as to classify the study area into five productivity categories.

Keywords: Site productivity; Diameter-growth; *Nothofagus*; Second-growth forest; Chile

1. Introduction

Nothofagus obliqua–N. alpina forests cover 1.2 million hectares in south-central Chile ranging from 36°30′ to 40°30′S at the Coastal and Andean Ranges (Donoso, 1993; CONAF et al., 1999), but are also present in adjacent areas in Argentina. These deciduous forests may be either pure stands of species or mixed stands in various proportion of *N. obli*qua or *N. alpina*. *N. dombeyi*, an evergreen broad-leaved species, may also be dominant in these stands. *Nothofagus obliqua–N. alpina* forests occur from 100 to 900 m of elevation (Donoso, 1981). They grow both under a Mediterranean-type climate and under an Oceanic

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Temperate climate further south, with an annual rainfall ranging from 1000 to 3000 mm, on deep well, drained, volcanic spoils, that are loamy in texture (Donoso, 1993). Most of these forests are second-growth, relatively even-aged stands originating after recurrent large-scale human (e.g. fires and clear cuttings) and natural disturbances (e.g. landslides and volcanism) (Veblen and Ashton, 1978; Donoso, 1993; Veblen et al., 1997).

As a result of their simple structure and composition, different researchers have remarked the suitability of these forests for silvicultural management (Grosse, 1987; Donoso, 1988; Espinosa et al., 1988; Donoso et al., 1993b; Damby, 1994; Lara, 1996; Grosse and Quiroz, 1999; Lara et al., 1999; Martinez, 1999). Secondary *N. obiqua–N. alpina* forests are accessible and are characterized by their relatively rapid-growth rate compared to other forest types. Their high quality wood is used for furniture, building, and handicrafts. These young forests have a potential by high-productivity and it is important to develop silvicultural tools to promote their sustainable management (Donoso et al., 1993b; Damby, 1994; Otero and Monfil, 1994; Grosse and Quiroz, 1999; Lara et al., 1999). Adequate management of secondary *N. obliqua–N. alpina* forests has been promoted by specific guidelines that forest owners may decide to follow and further technical information is needed in order to improve their management and regulation (Lara et al., 1999, 2000).

Identification and classification of site productivity is of great importance for the definition of silvicultural methods best suited to particular sites. Previous studies have defined four large growth-zones throughout the entire range of secondary *N. obliqua–N. alpina* forests using yield parameters (Donoso et al., 1993a). Large areas may incorporate considerable physiographic variation (Daniel et al., 1982; Pritchett, 1991), where several environmental factors occur simultaneously. Therefore, it is recommended to subdivide such areas into smaller homogenous sites. Site classification requires an appropriate selection of the driving variables to ensure an adequate classification of tree growth (Vanclay, 1994; Vanclay et al., 1995; Davel, 1998; Curt et al., 2001; Wilson et al., 2001). Other researchers have acknowledged that the reliability of site classification depends on the quality and type of data set used in finding the driving variables (Gustavsen et al., 1998). Methods using multivariate statistics have proved to be a suitable method for defining sites of homogenous productivity using environmental factors (Hägglund, 1981).

Studies using tree-ring techniques have been conducted to understand the spatial and temporal patterns of tree growth of *Nothofagus pumilio* forests at tree-line in the Central Andes of Chile (35°40′–38°40′S, 1490–1720 m elevation) and southern Chilean Patagonia (51–55°S, 300–980 m elevation) (Lara et al., 2001; Aravena et al., 2002). Other tree-ring studies have described the spatial and temporal pattern of the distribution of *Austrocedrus chilensis* forests in northern Argentinean Patagonia (41°S) (Villalba et al., 1997) and central Chile (Le Quesne et al., 2000). These studies have focused on the influence of climate variability in tree growth. Nevertheless, no attempt to identify the relative importance of each of the local environmental factors affecting *N. obliqua–N. alpina* tree growth and their spatial distribution has been made in Chile.

Although many site factors can influence tree growth, some of them (e.g. soil depth, water, nutrient availability) become dominant since they restrict the physiological processes that result in tree growth (Fritts, 1976; Gerding and Schlatter, 1995; Roberts et al., 1996; Kimmins, 1997; Gustavsen et al., 1998; Goebel et al., 1999; Ditzer et al., 2000; Curt et al., 2001; Lara et al., 2001; Joslin et al., 2001). In coarse-scale analysis, the presence and growth of a plant species is strongly influenced by climate. As the area of analysis is gradually reduced, climate is less influential as a driving factor. Conversely, physical and chemical soil properties become a decisive factor in tree establishment, growth-rate and productivity (Kimmins, 1997; Schlatter et al., 1997; Lara et al., 2001).

The objectives of this study were to identify the relative importance of environmental factors influencing diameter-growth of secondary *N. obliqua–N. alpina* forests in south-central Chile (38°30′–40°S). We also analyzed the spatial distribution of these factors and determine homogenous sites for tree growth and forest potential productivity. This is the first study done on this forest type using a multivariate approach.

2. Methods

2.1. Study area and sampling design

A total of 32 sampling plots were established in undisturbed secondary *Nothofagus obliqua–N. alpina*

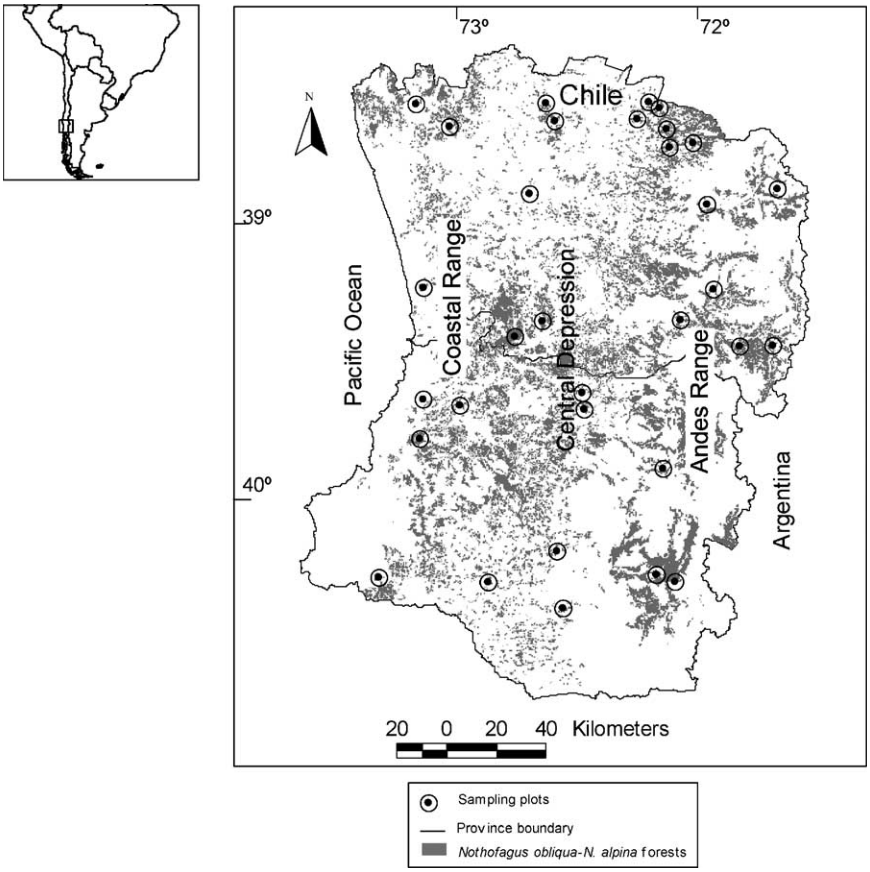

Fig. 1. Distribution of secondary *Nothofagus obliqua–N. alpina* forests and sampling plots in the study area (Provinces of Cautin and Valdivia).

forests in the Provinces of Cautin and Valdivia (38°30′–40°S and 71°40′–73°75′W) (Fig. 1). Two plots were $250\,m^2$, 29 were $500\,m^2$ and one was $1000\,m^2$. Plot size was dependent on tree density. The characteristics of each sampling plot regarding density, basal area, mean age and other are shown in Table 1. This study is focused on stands dominated by a mixture of *N. obliqua–N. alpina*, whose percentage of basal area ranged from 60 to 100% (Table 1). The 60% threshold was taken from specific forest legal guidelines which use the basal area of *Nothofagus* spp. for classification of the stands within various forest sub-types (CONAF, 1994). In terms of basal area, *N. obliqua* was the dominant species in 28 plots, whereas only four plots were dominated by *N. alpina*. Semi-dense and dense forest stands (crown cover = 50%), with a high or intermediate stocking, covering the geographic range of the forest type in the provinces were selected. Open low-stocked stands or highly disturbed stands due to logging, fire or other human disturbances were not sampled in this work. Stands of this forest type occurring to the north of the study area (36°30′S) and further south (41°S) were not considered.

These second-growth stands have developed by regeneration from seed, coppice or a mixture of both, following land clearing for pasturelands, as well as burning, clearcuts or a combination of these disturbances on old growth forests occurred 20–60 years ago. The species composition of the former old growth forests was similar, but with higher dominance of shade-tolerant tree-species, such as *Laurelia*

Table 1
Description of the sampled stands

Sampling plot	Elevation (m a.s.l.)	Density (N/ha)	Basal area (m^2/ha)	Mean DBH (cm)	Mean age	*N. obliqua–N. alpina* basal area[a] (% of the total)
1	187	1360	30.8	17.0	29	95
2	354	1440	32.4	16.9	40	87
3	66	1820	60.3	20.5	60	82
4	111	1200	25.4	16.4	45	65
5	139	960	43.5	24.0	34	64
6	189	1600	26.0	14.4	27	100
7	102	940	37.7	22.6	58	99
8	59	980	36.3	21.7	61	78
9	436	1460	52.5	21.4	48	87
10	489	1600	30.0	15.5	42	99
11	39	920	25.0	18.6	47	81
12	211	1000	33.4	20.6	60	60
13	588	3880	36.0	10.9	36	60
14	400	1040	14.1	13.1	52	83
15	300	1340	53.4	22.5	62	85
16	325	2340	33.7	13.5	39	83
17	300	990	34.0	20.9	58	100
18	300	1100	34.0	19.8	45	80
19	388	1500	34.5	17.1	42	86
20	500	900	24.7	18.7	43	96
21	253	940	34.5	21.6	58	98
22	800	1360	44.2	20.3	58	87
23	552	1420	35.5	17.8	52	86
24	200	2740	23.7	10.5	23	68
25	150	4300	31.8	9.7	26	70
26	306	1060	38.3	21.4	58	100
27	461	2060	40.6	15.8	44	91
28	50	990	52.1	25.9	25	94
29	300	1940	45.5	17.3	45	99
30	250	1380	62.6	24.0	39	93
31	425	3060	42.3	13.3	38	84
32	800	1855	40.7	16.7	55	86

[a] Remaining basal area corresponds mainly to the following shade or semi-shade-tolerant tree-species: *Persea lingue*, *Gevuina avellana*, *Laurelia philippiana*, *Lomatia hirsuta*, *Aextoxicom punctatum*, *Amomyrtus meli*, and *Dasyphyllum diacanthoides*.

philippiana, *Gevuina avellana*, *Aextoxicom punctatum* (Donoso, 1993). At present, there is no evidence of genetic differences between these second-growth forests and the former old growth forests.

Plots were distributed throughout the study area using a Geographic Information System (GIS) in order to capture the growth variability throughout the entire range of site conditions. GIS information included stratified secondary forest distribution (CONAF et al., 1999) and climate/soil data (Schlatter et al., 1995, 1997). For each plot, environmental variables commonly registered for site classification or growth analyses were registered following the selection of variables used in other studies (Roberts et al., 1996; Battaglia and Sands, 1997; Bork et al., 1997; Gustavsen et al., 1998; Goebel et al., 1999; Ditzer et al., 2000; Curt et al., 2001).

For each plot the following topographic variables were registered: longitude (UTM), latitude (UTM), elevation (m.a.s.l.), slope (degree), and aspect (north, south and flat). Three soil pits were dug in randomly selected points for each sampling plots to measure total soil depth (cm) and A-horizon depth (cm). In each pit, soil samples were taken from A-horizon and then mixed up to prepare a representative soil sample of 500 cm^3 for each sampling plot. These soil samples were analyzed in laboratory to provide data on the organic matter (%), pH, nitrogen (%), and texture (percentage of sand, silt and clay in the A horizon). This field and laboratory information was complemented with local soil information in literature (IREN and UACH, 1978). Climatic variables included: mean annual precipitation (mm) (average of annual rainfall registered in the last 30 years), summer humidity index (ratio between rainfall and mean potential evapotranspiration of the three warmest months), frost-free period (days per year) (number of consecutive days without occurrence of frost), and dry period (months per year) (number of months in which the rainfall does not represent the 50% of potential evapotranspiration) and were obtained from the literature (Schlatter et al., 1995, 1997).

The selected growth variable was radial increment (mm per year). One or two increment cores from 15 to 20 dominant or co-dominant *N. obliqua* and/or *N. alpina* trees were obtained from each plot for determination of radial increment.

2.2. Data processing and analysis

Tree cores were mounted, sanded using sandpaper of increasingly finer grain, and measured under a microscope to the nearest 0.001 mm and stored in a microcomputer (Stokes and Smiley, 1968; Robinson and Evans, 1980). Then, a validation process was conducted, comparing each radial-growth with a regular annual periodic increment (API) curve of an undisturbed stand (Prodan et al., 1997). This was done to distinguish those trees in which growth-rates had been altered by human disturbances (e.g. growth releases following selective cutting). This validation was supported by field information on human disturbances.

In order to find the period of diameter-growth (radial increment multiplied by two) that is best correlated with site factors in each plot, four API intervals were analyzed. Attempts were made to include the maximum diameter-growth periods and a sufficient range of at least 5 years (Espinosa et al., 1988). The mean diameter API was estimated for the periods 5–10, 10–15, 5–15, and 15–20 years of age in each plot.

Multivariate statistical techniques enable the identification and analysis of the driving factors of biological and ecological processes. Multiple correspondence factorial analysis was applied (MCFA) using SPADN®[2] statistical package for identification of the driving environmental variables of diameter-growth. In the MCFA, API in diameter was considered to be an objective variable and the 17 edaphoclimatic variables to be active variables. SPADN has the ability to distinguish a variable of interest (or objective) and to treat it independently from the set of driving variables in order to avoid its influence on the definition of correspondence factors (see footnote 2).

The number of classes for each variable and their widths were determined using class frequency histograms which were divided into at least five classes according to the variation range of each variable. Then, the number of classes that contributed most importantly to explain the data set variation was fitted using MCFA reducing the number of classes into two or three categories (Table 2).

Because of the use of slope aspect, a discrete variable, the MCFA was chosen as the method of analysis and the 17 variables were converted into two or three discrete classes according to the range of variation of each variable. For the analysis of the spatial distribution of the driving variables and their relationship to diameter-growth, we generated Surfer®[3] contour maps using the MCFA-generated projection coordinates of each plot for the first three factors.

We used ascendant hierarchic classification analysis (AHCA), computed by SPADN®, to classify site productivity into categories. The AHCA identified the number of categories based on the analysis of level indices which were determined from the distances between plots' projection coordinates generated previously by MCFA. The classification used thresholds to define groups based on SPADN's statistics, including test value, between-group inertia, and within-group inertia. The AHCA classified the sampling plots into site productivity categories according to the driving variables and their correspondence with diameter-growth.

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[2] Portable System for Numeric Data Analysis, Version 2.5, 1993.

[3] Surface Mapping System, Version 6.04. Golden Software, Inc.

Table 2
Classes and codes for variable used in the preliminary analysis

Variables	Code of class	Range
Longitude (UTM)	LON1	640877–693888
	LON2	693888–746899
	LON3	746899–799910
Latitude (UTM)	LAT1	5530150–5611395
	LAT2	5611396–5652017
	LAT3	5652018–5733262
Elevation (m a.s.l.)	ELE1	0–250
	ELE2	251–500
	ELE3	501–800
Slope (°)	SLO1	0–15
	SLO2	16–25
	SLO3	26–50
Aspect	S	South, south-west, south-east
	N	North, north-west, north-east
	F	Flat (without aspect)
Mean annual rainfall (mm)	MAR1	700–1300
	MAR2	1301–1900
	MAR3	1901–2500
Summer humidity index	SHI1	0.4–0.55
	SHI2	0.56–0.69
	SHI3	0.70–0.80
Frost-free period (day per year)	FFP1	0–50
	FFP2	51–150
	FFP3	151–250
Dry period (month per year)	DP1	1–2
	DP2	3–4
	DP3	5–6
A horizontal depth (cm)	AHD1	0–15
	AHD2	16–25
	AHD3	26–40
Total soil depth (cm)	TSD1	40–79
	TSD2	80–100
	TSD3	$\geq$100
Sand (%)	SAN1	5–15
	SAN2	16–45
	SAN3	46–66
Silt (%)	SIL1	22–45
	SIL2	46–67
Clay (%)	CLY1	12–25
	CLY2	26–37
Organic matter (%)	OM1	<15
	OM2	$\geq$15
pH	PH1	5–5.5
	PH2	5.6–6
Nitrogen (%)	N1	0.17–0.49
	N2	0.50–0.69
	N3	$\geq$0.7

3. Results

3.1. Driving variables and diameter-growth

The analysis for the initial screening of the independent variables considered 17 independent variables. This number is acknowledged to be small compared to the number of observations (32 sampling plots), but it was necessary to assure an adequate consideration of all the potential variables that could explain the variation in diameter increment. SPADN software is recommended in cases when a limiting number of observations is available or when the number of independent variables is relatively large, providing reliability in the results of the initial screening.

The preliminary analysis using MCFA determined that 6 out of the 17 variables that were studied significantly contributed to the variance explained. At the same time, these six variables had a high correspondence with the API of 15–20 years, and therefore, this period was selected as the diameter-growth variable (Table 3). The classes determined for this API were—API1: <5.39 mm per year; API2: 5.39–7.00 mm per year, and API3: ≥7.01 mm per year.

The six most important variables identified as driving variables of the API were: longitude, mean annual rainfall, summer humidity index, frost-free period, and content of sand and silt in the soil (Table 3). Using just these driving variables for a new MCFA, the first three factors accounted for 70.4% of the total variation (Factor 1: 34.0%, Factor 2: 20.1% and Factor

Table 3
MCFA statistics for the variables driving growth

Variable/class	Coordinates			Contribution			Square cosine			Test value		
	1	2	3	1	2	3	1	2	3	1	2	3
LON1	0.61	1.42	0.27	2.5	23.0	1.0	0.13	0.68	0.03	2.0	4.6	0.9
LON2	0.85	−1.05	0.18	6.1	15.7	0.6	0.33	0.51	0.02	3.2	−4.0	0.7
LON3	−0.96	−0.06	−0.29	10.8	0.1	2.0	0.71	0.00	0.06	−4.7	−0.3	−1.4
MAR1	1.12	0.05	−0.29	11.5	0.0	1.6	0.66	0.00	0.04	4.5	0.2	1.2
MAR2	−0.41	−0.33	−0.42	1.8	2.0	4.0	0.11	0.07	0.12	−1.9	−1.5	−1.9
MAR3	−0.88	0.47	1.08	5.1	2.5	16.1	0.26	0.07	0.39	−2.8	1.5	3.5
SHI1	0.73	−0.45	0.30	6.3	4.1	2.2	0.42	0.16	0.07	3.6	−2.2	1.5
SHI2	−0.15	0.49	−0.80	0.2	3.4	11.1	0.01	0.11	0.29	−0.6	1.8	−3.0
SHI3	−1.09	0.19	0.47	8.0	0.4	3.0	0.40	0.01	0.07	−3.5	0.6	1.5
FFP1	−1.19	0.04	−0.39	12.9	0.0	2.9	0.74	0.00	0.08	−4.8	0.1	−1.6
FFP2	0.64	−0.82	0.09	4.7	13.4	0.2	0.31	0.53	0.01	3.1	−4.0	0.5
FFP3	0.59	1.59	0.42	2.1	24.9	2.2	0.10	0.71	0.05	1.7	−4.7	1.2
DP1	−0.40	−0.03	0.86	2.0	0.0	19.4	0.14	0.00	0.66	−2.1	−0.2	4.5
DP2	−0.79	0.03	−1.50	3.7	0.0	27.6	0.18	0.00	0.63	−2.3	0.1	−4.4
DP3	1.15	0.02	−0.24	11.2	0.0	1.0	0.61	0.00	0.03	4.3	0.1	−0.9
SI1	−0.78	−0.58	0.36	6.6	6.3	3.0	0.42	0.23	0.90	−3.6	−2.7	1.7
SI2	0.53	0.40	−0.25	4.5	4.3	2.0	0.42	0.23	0.90	3.6	2.7	−1.7
SA1	0.85	0.48	0.08							2.7	1.6	0.3
SA2	0.22	−0.18	−0.15							1.2	−1.0	−0.8
SA3	−1.29	−0.13	0.22	n.a.[a]	n.a.	n.a.	n.a.	n.a.	n.a.	−4.1	−0.4	−0.7
API1	0.32	−0.04	−0.48							1.3	−0.2	−2.0
API2	−0.14	0.56	−0.12							−0.6	2.3	−0.5
API3	−0.20	−0.57	0.67	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	−0.7	−2.2	2.5

API was considered to be an objective variable for use in SPADN. A higher percentage of the total variation was accounted for when sand was not considered as an active variable. Criteria used for selecting driving variables were based on the analysis of four statistical parameters. These parameters included coordinates (≥0.5: variables contribute strongly to the formation of factors), contributions (high percentage contribution indicates variables contributing to the axes formation), square cosine (if the sum of two square cosines for two factors from one variable class is ≥0.4 then a variable is well represented in the spatial factorial projection), test values (values ≥|2| indicates that a grouping of individuals for a class of the variable is not random). API1: <5.39 mm per year; API2: 5.39–7.00 mm per year and API3: ≥7.01 mm per year.

[a] Not applicable.

3: 16.3%). The variables were well represented in a two-dimensional projection formed by Factors 1 and 2. More than 70% of the sampling plots were well represented for the first two factors and this percentage increases to more than 80% for the first three factors (not shown). This high representation was revealed by the statistics used in the SPADN analysis (square cosine, coordinates and contribution) which also confirmed a certain degree of association among the sampling plots through the study area (not shown). Due to the high variation explained by the first three factors and a significant representation of the plots, it is possible to establish correspondences between environmental variables and individual plots.

Low and intermediate longitudes (Coastal Range and Central Depression, LON1 and LON2), low annual rainfall (700–1.300 mm, MAR1), low summer humidity index (0.4–0.55, SHI1), intermediate and long frost-free periods (51–250 days, FFP2 and FFP3), long dry period (5–6 months, DP3), and a high percentage of silt (46–67%, SIL2) and low percentage of sand (5–15%, SAN1) in the soil, contributed mainly to the formation of the positive axis of Factor 1 (Table 3, Fig. 2). For Factor 2, low longitude (Coastal Range, LON1) and long frost-free period (151–250 days, FFP3) contributed to the formation of the positive axis (Table 3, Fig. 2). Factor 3 positive axis is mainly formed by a high annual rainfall (1901–2500 mm, MAR3) and a intermediate dry period (3–4 months, DP2) (Table 3).

3.2. Spatial variation of environmental factors

The spatial variation of Factor 1 (34% of the total variation) indicates a longitudinal division given by the zero line with a clear north-south trend dividing the sites in the Central Depression and Coastal Range with positive values from those of the Andean sites (Fig. 3a). Positive value lines mean that the sites located in the northern portion of the study area towards the Coast are characterized by a low annual rainfall, a long dry period, and a low percentage of sand in the soil. The sites located in the pre-Andes and Andean Range (negative values) tend to a high summer humidity index, and low silt content in the soil (Fig. 3a). Similarly, Factor 2 (20% of total variation)

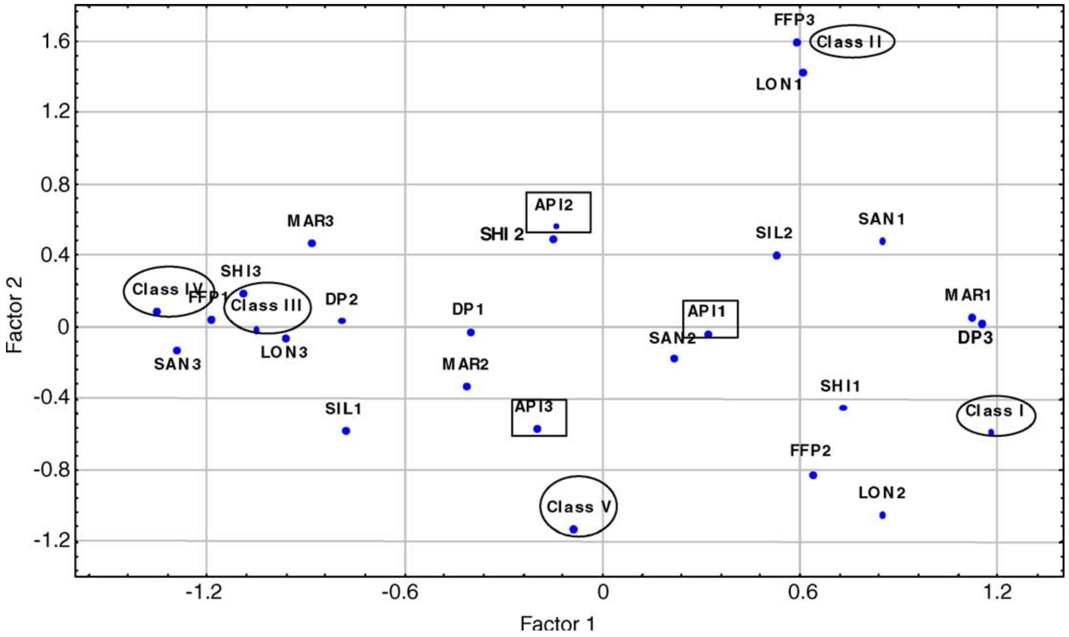

Fig. 2. Projection of sites and classes of driving variables and diameter-growth for Factors 1 and 2 generated by MCFA. The projection graph was elaborated using the coordinates of Factors 1 and 2 (Table 2) for each class of: driving variables, API and gravity center of each productivity site class determined by AHCA. The gravity center corresponded to the central point of a group of sampling plots with similar site characteristics of productivity. (⬭) Classes of site productivity; (▭) classes of mean API in diameter between 15 and 20 years.

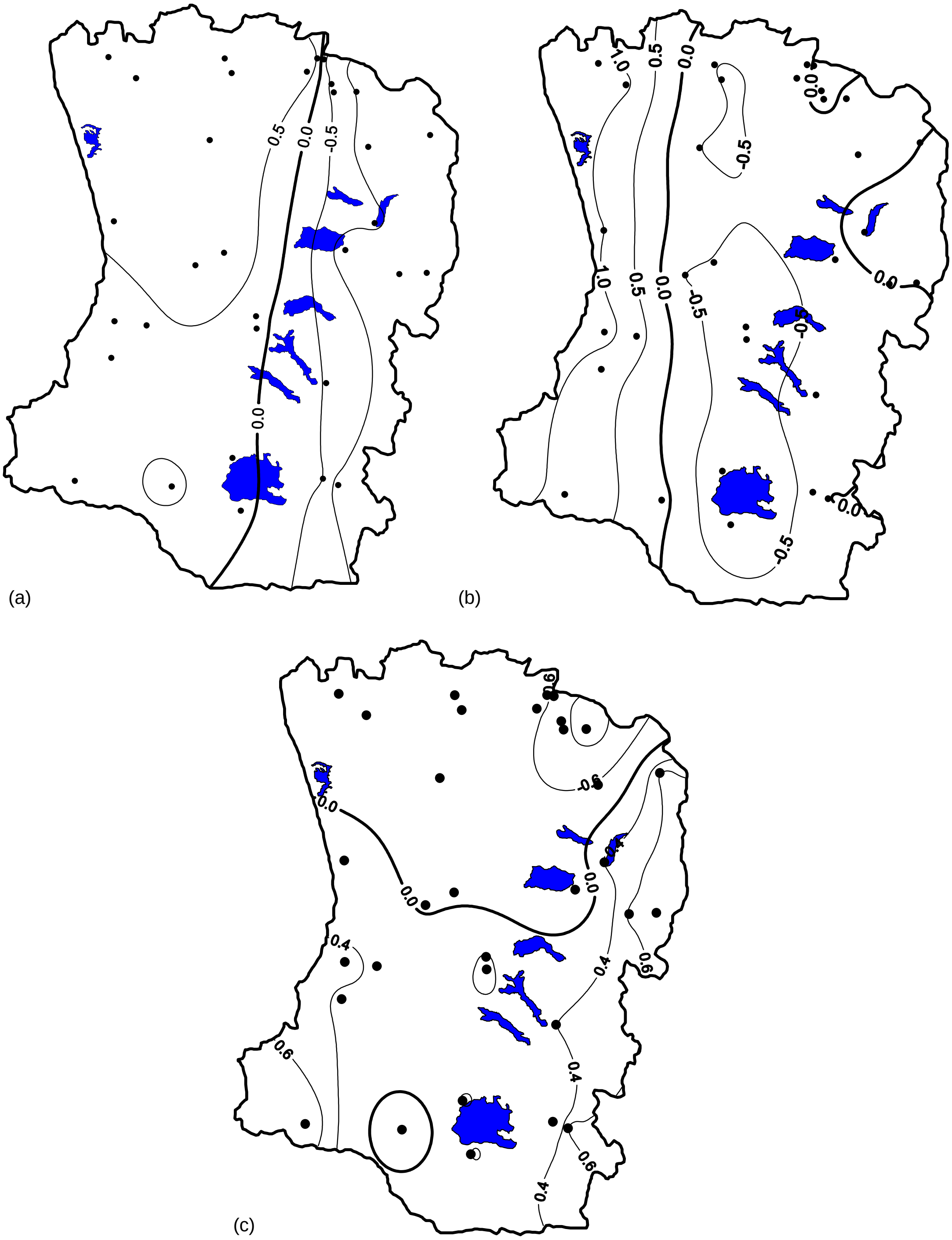

Fig. 3. Spatial variation of the variables driving diameter-growth for secondary *Nothofagus obliqua–N. alpina* forests in the Cautin and Valdivia provinces. Three contour maps were developed using the coordinates generated by MCFA for each sampling plot. (a) First factor accounted for 34%, (b) second factor 20.1%, and (c) third factor 16.3%. Zero line separates sites of significant different edaphoclimatic conditions.

shows a longitudinal variation of the driving variables, separating sites located in the Central Depression with the rest (Fig. 3b). Sites located in the Coastal Range are characterized by a longer frost-free period than those located in the Central Depression. Factor 3 (16% of the total variation) follows a different spatial pattern compared to Factors 1 and 2, indicating a significant difference between the northern and southern portions of the study area, separated by the zero line (Fig. 3c).

3.3. Site productivity classification

The AHCA classified the 32 sampling plots into five site productivity classes (Table 4). All the classes have test values >2 or <−2 in Factor 1 or 2. This indicates that each class has similar ranges of certain edaphoclimatic driving variables with their corresponding diameter-growth and that each class is not randomly associated with the variables (Table 4). The higher value of inter-class inertia compared to intra-class inertia shows that the partition of sampling plots is appropriate (Table 4). The homogeneity of the values of intra-class inertia indicates that the total variation is distributed proportionally among the various classes. These statistics demonstrate that both the number of classes and the classification of the sampling plots within these classes was objective. Therefore, the sampling plots can be classified within these five site productivity categories. The projection of the coordinates of each plot for Factors 1 and 2 computed by SPADN encircled within their respective site productivity class shows clear grouping patterns (Fig. 4). This grouping stresses that the sites within each class are characterized by a similar range of edaphoclimatic variables. The location of each sampling plot enabled us to outline the spatial boundaries of each site productivity class within the study area (Fig. 4).

Knowing the location of the sampling plots that were classified into a specific site by the AHCA, the boundaries for each type of site (class) were drawn in the study area (Fig. 5). For each of these classes the average diameter increment (expressed as API) between 15 and 20 years old was determined (Table 5). Classes I, II and IV presented a wide deviation of the API between 15 and 20 years old, being Classes I and IV those that have the widest range of deviation (1.62 mm per year, Table 5). The API of each plot was used in a non-parametric Kruskal–Wallis test which revealed a significant difference in the diameter increment among the classes in the study area.

4. Discussion

The multiple correspondence factorial analysis (MFCA) determined that longitude, three climatic variables (i.e. mean annual rainfall, summer humidity index, and frost-free period) and two edaphic variables (i.e. sand and silt contents) were associated with the diameter-growth in the forest stands studied (Table 3). These six variables contributed to the formation of the first three factors accounting for 70.4% of the total variance. The topographic variables such as elevation, slope angle and aspect did not explain the variation in growth in the study area. Similarly, some edaphic

Table 4
Test values, coordinates and inertia of each class estimated by AHCA

Site productivity class	Test values			Coordinates			Intra-class inertia	Inter-class inertia	Total inertia global
	Factor 1	Factor 2	Factor 3	Factor 1	Factor 2	Factor 3			
I	−0.2	−3.0	1.7	−0.09	−1.13	0.62	0.1042	1.3269	1.8333
II	3.8	−1.9	−1.0	1.18	0.59	0.30	0.1141	1.3269	1.8333
III	1.7	4.7	1.2	0.59	1.59	0.42	0.1885	1.3269	1.8333
IV	−3.2	0.2	2.6	−1.35	0.09	1.10	0.0173	1.3269	1.8333
V	−2.8	0.0	−4.4	−1.05	−0.01	−1.63	0.0824	1.3269	1.8333

Test values ≥|2|: indicates that a grouping of classes is not random. Coordinates ≥0.5: variables contribute strongly to the formation of factors. Inter-class inertia ≥ intra-class inertia: indicates that the division of the site productivity into five classes is significant. Total inertia global ≥ intra-class inertia: shows that the site productivity classes accounts for a high percentage of the total variance, which indicate that none class was unnecessarily defined.

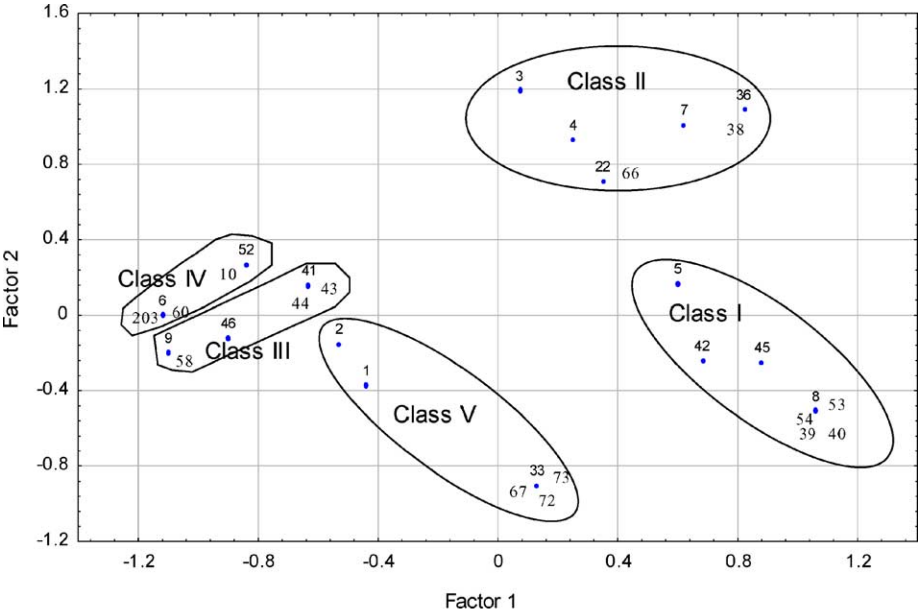

Fig. 4. Projection of sampling plots for Factors 1 and 2 generated by MCFA. Grouping of sampling plots was determined by AHCA using the growth driving variables. Each group of sampling plots exhibits similar edaphoclimatic conditions and annual diameter increment.

variables such as the A-horizon depth, total soil depth, organic matter, pH and Nitrogen were not significant. This may probably be explained due to their relative narrow variation ranges in the study area, compared to the other variables. Nevertheless, these variables might be significant at a local scale that cannot be properly identified at the scale used to develop the MFCA. Similarly, a site classification analysis conducted for *Pseudotsuga menziesii* plantations in the northwestern part of the French Massif Central, in which soil variables were correlated to tree growth, climatic variables were not significant because of their low variation within the study area (Curt et al., 2001).

Table 5
Mean, standard deviation and range of variation to API for each site productivity class

Site productivity class	Annual periodic increment, API (mm per year)		
	Mean[a]	S.D.	Range
I	5.3	1.62	2.4–7.9
II	5.8	1.19	3.4–7.5
III	5.7	0.88	4.8–6.9
IV	7.1	1.62	4.9–9.0
V	7.5	0.88	6.6–8.9

[a] Mean annual diameter increment between 15 and 20 year old.

The use of factorial design techniques for identifying the most important variables has similarly been conducted in various forest types and geographic areas (Gomory and Gomoryova, 1997; Goebel et al., 1999; Canettieri et al., 2001). Different variables, such as latitude, longitude, elevation, slope, aspect, soil depth, and texture, were used for developing a growth model for *Eucalyptus globulus* in southeastern Tasmania and in Western Australia (Battaglia and Sands, 1997). In our study only one of these variables, longitude, was significant in explaining *Nothofagus alpina–N. obliqua* growth. Other studies have demonstrated the influence of soil water potential in controlling the growth of an oak stand in Tennessee, USA (Joslin et al., 2001). Although the soil chemical variables analyzed in this study did not explain the variation in growth, pH, A-horizon depth, and the availability of minerals have shown to be of particular importance to determine understory composition in different ecosystems (Goebel et al., 1999; Brosofske et al., 2001; Weckstrom and Korhola, 2001; Wilson et al., 2001).

Spatial patterns for Factors 1 and 2 of the driving climatic and edaphic variables follow clear

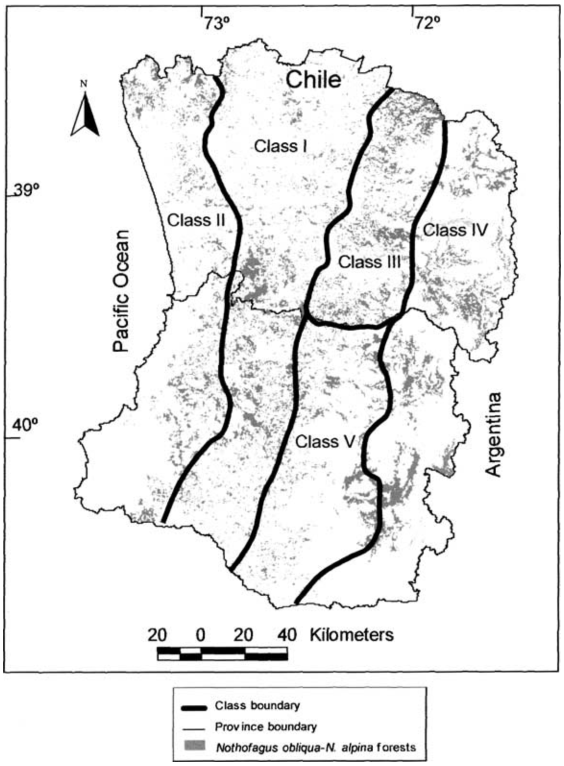

Fig. 5. Site classification for the secondary *Nothofagus obliqua–N. alpina* forests in the Cautin and Valdivia provinces based on the edaphoclimatic variables driving diameter-growth.

longitudinal belts, that can be associated to a west-to-east gradient determined by the main geographic units in the study area: Coastal Range, Central Depression and Andean Range (Figs. 1, 3a and b). The precipitation brought by the western winds from the Pacific Ocean, decreases in the Central Depression due to the rain shadow effect determined by the Coastal Range (Schlatter, 1994, 1999; Fig. 1). Summer humidity index and dry summer season duration increase and the frost-free period increases east of the Central Depression towards the Andes, following the patterns described by Schlatter and Gerding (1995). Soils in the Andes have a higher percentage of sand and less silt and clay, compared to those on the Coastal Range and the Central Depression, since they are relatively young soil developed from volcanic ash (Schlatter, 1999). The increase in total and summer precipitation associated with the reduction of Mediterranean influence explained a north-to-south gradient reflected in the contour map for Factor 3 (Fig. 3c). Both longitudinal and latitudinal gradients generate important edaphic and climatic changes, which produce important effects on the ecology and growth of plant species (Schlatter and Gerding, 1995; Donoso, 1993).

Our results demonstrate a clear definition of five categories of site productivity (Classes I–V) expressed as diameter-growth in secondary *Nothofagus* forests and their relationship to the spatial variation in the driving variables. Class I, located in the Central Depression show the lowest diameter-growth (5.39 mm per year) which is associated with the longest dry period (5–6 months), the lowest annual rainfall and summer humidity (700–1300 mm and 0.4–0.5, respectively), and an intermediate frost-free period (Figs. 2 and 4). Class II, located in the Coastal Range with a diameter-growth of 5.8 mm per year and the free-frost period is longest (151–250 days). Class III is located near the Andean Range and is associated with a intermediate diameter-growth of 5.7 mm per year, the shortest free-frost period (0–50 days), and an intermediate dry period (3–4 months) and annual rainfall (1300–1900 mm). Class IV is located in the Andes, with a diameter-growth of 7.1 mm per year and is characterized by the highest annual rainfall (1900–2500 mm), percentage of sand in the soil (46–66%), and summer humidity (0.7–0.8). Class V is associated with the highest diameter-growth (7.5 mm per year) near the Andean Range and is characterized by an intermediate frost-free period of 51–150 days, the lowest maximum dry period of 1–2 months, and the lowest silt content of 22–45% (Figs. 2 and 4).

The climatic variables and the type of soil are important to define jointly the development of plants in a site (Kimmins, 1997). In this study the combined effect of rainfall and soil characteristics determines a favorable site condition and confirms that the water availability in the soil is one of the main growth-limiting factors of the forests studied. Similar results have been reported for high-elevation *Nothofagus pumilio* in southern Chile where climate, through rainfall and evapotranspiration, and soil characteristics, through its available water capacity, are fundamental to assure the water supply for tree growth (Schlatter, 1994). Similarly, tree-ring growth of high-elevation *N. pumilio* forests located north of our study area (35°40′–37°30′S) is positively correlated with late-spring and early summer precipitation. Higher temperatures reduce radial-growth, probably because of an increase in evapotranspiration and a decrease in water availability (Lara et al., 2001).

Although some specific variable classes explain better the differences and similarities between sites, the integrated effect of the driving variables enabled the identification of sites with similar characteristics. The trend of higher diameter-growth rates for *N. alpina* and *N. obliqua* for sites located near and in the Andes (site Classes III–V of this study) coincides with the recognition of volcanic soils as favorable for vegetation growth (Schmaltz, 1973; INIA, 1985; Gerding and Schlatter, 1995; Schlatter and Gerding, 1995). A previous study determined growth-zones for *Nothofagus obliqua–N. alpina* forest stands along its entire geographical range also found higher growth rates for the Andes (Donoso et al., 1993a). Nevertheless, this study did not identified the growth driving variables using a multivariate analysis.

The understanding of the variation in site productivity for *N. obliqua* and *N. alpina* is a key information for the design and proposal of sustainable forest management schemes. The development and mapping of site classification based on ecological driving factors will enable to geographically understand the influence of abiotic factors on the *N. obliqua–N. alpina* forests. Similar ideas have been proposed for the definition of ecological site classification as a basis for improved management of the British forests (Wilson et al., 2001) and in southeastern New Brunswick in Canada (Matson and Power, 1996). Information on productivity is also useful for site selection in reforestation and restoration programs with *Nothofagus obliqua* and *N. alpina*. The success of these programs in high-productivity sites (Classes III–V) might be assured due to the high rates of growth expected in these sites.

Due to the high potential of the *N. obliqua–N. alpina* secondary stands through sustainable management practices, it is important to complement this work by studying site productivity throughout their entire geographic range (36°30′–40°30′S). Finally, the approach used in this paper may be applied to determine the productivity of other forest types in Chile.

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