ABOVE-GROUND BIOMASS ACCUMULATION AND GROWTH IN A MARGINAL *Nothofagus macrocarpa* FOREST IN CENTRAL CHILE

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SUMMARY

Nothofagus macrocarpa *forests are situated in the northern limit of Nothofagus genus distribution in South America. Data related to their growth conditions are insufficient. Above-ground biomass accumulation and growth were evaluated in a secondary* N. macrocarpa *forest located in the northern limit of the species natural distribution. Nine plots were established, and 240 sprouts of different diameter classes were harvested. The age and volume of each sprout were determined, and tree growth in terms of diameter and height was also analyzed. Total above-ground biomass was measured in a subsample of 62 sprouts, according to the components: stem, branches and foliage. The forest had an uneven-aged coppice structure, the mean age being 39 years. Average diameter growth rate was 0.23cm/year, height growth rate was 32.3cm/year and the mean volume growth rate was 0.43m^3·ha^{-1}/year, which are lower than the values indicated for other species of the same genus. The accumulated above ground biomass reached 35.2ton·ha^{-1}. The low values measured are explained by the marginal condition of the forest as well as its degradation status due to anthropogenic activity. This condition requires of setting measures that assure the survival and the recovery of this forest.*

Introduction

Nothofagus genus is a key element in the phytogeography of the southern hemisphere due to its special disjointed distribution (Van Steenis, 1972), and it is the most important component of the forest formations in the austral end of South America (Gajardo, 2001). Furthermore, some of the forest species show a distribution restricted to a relatively small geographic area (San Martín and Ramírez, 1987).

The forest ecosystems in the central zone of Chile, where a significant part of the species belonging to *Nothofagus* genus grow, have been subjected to intensive exploitation pressure for more than 300 years. This has resulted in a reduction of the area covered by the genus and a deterioration of the forest (Camus, 2006).

Nothofagus macrocarpa (DC.) F.M. Vásquez & A. Rodr. is known as "Roble de Santiago" and is an endemic Chilean specie. It belongs to the *Nothofagus* group, characterized by big deciduous leaves and develops in a Mediterranean climate (Ramírez, 1987; Vásquez and Rodríguez, 1999) that represents the northernmost distribution of the genus in America (Ormazábal and Benoit, 1987).

N. macrocarpa has been considered as a remnant species. Their populations appeared thousands of years ago under very different climatic conditions to the current ones, representing a very complex example of what natural vegetation dynamics has been in the area (Gajardo, 2001). Currently, it grows as disjointed populations in the highest mountains throughout its distribution area. Similarly to other Mediterranean ecosystems, *N. macrocarpa* populations have been subjected to strong anthropogenic alterations, despite the fact that they are a potential biodiversity niche for the different communities that are living within them (Pauchard and Villarroel, 2002). Additionally, given its sensitivity, the species represents an outstanding element for the monitoring of global climate changes.

The current status of acquaintance with certain concepts, such as species dynamics and basic forest structure relationships, with specific measurable parameters like growth rates, forest productivity, accumulated biomass, leaf area and regeneration capacity, among others, is scarce or does not exist. This fact greatly impedes the different actions that should be implemented for the protection and monitoring of the species (Hechenleitner *et al*., 2005; Donoso, 2007). Consequently, there is a need for appropriate and detailed information about the species, upon which actions focused on preservation management may be oriented.

The aim of this study was to quantify the amount of above-ground biomass and to evaluate volume and diameter growth in *Nothofagus macrocarpa* forest located at a dry marginal site in Mediterranean zone of central Chile.

Materials and Methods

The area considered is located on "El Roble" hill (37°58´S, 71°01´W), in the coastal mountain range 75km northeast of Santiago urban area, or *Region Metropolitana*, Chile. The zone

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ACUMULACIÓN DE BIOMASA AÉREA Y CRECIMIENTO EN UN BOSQUE MARGINAL DE *Nothofagus macrocarpa* EN CHILE CENTRAL

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RESUMEN

Los bosques de Nothofagus macrocarpa *se encuentran en el límite norte de la distribución del género Nothofagus en Sudamérica. El conocimiento sobre sus condiciones de crecimiento es insuficiente. Se evaluó el crecimiento y la acumulación de biomasa aérea, en un bosque secundario de* N. macrocarpa *situado en el límite septentrional de su distribución natural. Se establecieron nueve parcelas y se cosecharon 240 vástagos a lo largo de las diferentes clases diamétricas. Se determinó la edad y volumen de cada vástago, así como el crecimiento en diámetro y altura de los árboles. En una sub-muestra de 62 vástagos, se midió la biomasa aérea total y la de sus componentes (fuste, ramas y hojas). El bosque presentó una estructura de monte bajo irregular con una edad media de 39 años. El crecimiento medio anual en diámetro fue de 0,23cm/año, en altura de 32,3cm/año y en volumen de 0,43m³·ha⁻¹/año, valores inferiores a los indicados para otras especies del género. La biomasa acumulada alcanza a 35,2ton·ha⁻¹. Los bajos valores determinados se explican por la condición marginal del bosque y el grado de degradación generado por la actividad humana. Esta condición requiere definir medidas para asegurar la sobrevivencia y recuperación de este bosque.*

ACUMULAÇÃO DE BIOMASSA AÉREA E CRESCIMENTO EM UM BOSQUE MARGINAL DE *Nothofagus macrocarpa* NO CHILE CENTRAL

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RESUMO

Os bosques de Nothofagus macrocarpa *se encontram no limite norte da distribuição do gênero Nothofagus na América do Sul. O conhecimento sobre suas condições de crescimento é insuficiente. Avaliou-se o crescimento e a acumulação de biomassa aérea, em um bosque secundário de* N. macrocarpa *situado no limite setentrional de sua distribuição natural. Estabeleceram-se nove lotes e se colheram 240 hastes ao longo das diferentes classes diamétricas. Determinou-se a idade e volume de cada haste, assim como o crescimento em diâmetro e altura das árvores. Em uma sub-amostra de 62 hastes, foi medida a biomassa aérea total e a de seus componentes (caule, ramos e folhas). O bosque apresentou uma estrutura de capim baixo irregular com uma idade media de 39 anos. O crescimento médio anual em diâmetro foi de 0,23cm/ano, em altura de 32,3cm/ano e em volume de 0,43m³·ha⁻¹/ano, valores inferiores aos indicados para outras espécies do gênero. A biomassa acumulada alcança 35,2ton·ha⁻¹. Os baixos valores determinados se explicam pela condição marginal do bosque e o grau de degradação gerado pela atividade humana. Esta condição requer definir medidas para garantir a sobrevivência e recuperação deste bosque.*

is included within a *Nothofagus macrocarpa* formation, covering 996ha (Espinosa *et al*., 2002). There is a substantial population of trees growing on El Roble hill, which represents the northern limit of the species natural distribution (Figure 1).

The climate is classified as lower temperate mesothermal stenothermal semiarid Mediterranean type. The thermal regime is characterized by temperatures varying from a maximum of 26.9°C in January to a minimum of 4.1°C in July. The frost-free period lasts up to 206 days, and there is an average of 13 frosts per year. The rainfall regime is characterized by an annual mean precipitation of 656mm, a water deficit of 897mm, and a 7-month dry season (Santibáñez and Uribe, 1993).

The soils are mainly of granite origin. The three main types of igneous rocks present in the area are part of the coastal batholite conformed by granite, granodiorite and diorite (Espinosa *et al*., 2002). Given the presence of hills with steep gradients exceeding 30°, the soils are highly susceptible to rainfall erosion.

The area is predominantly covered by scrubs and trees with sclerophyllous leaves as well as low xerophytic and succulent scrubs, thorny scrubs and trees, and very tall laurel-leaved trees (Gajardo, 1994). Vegetation in the study area corresponds to the Deciduous Montane Forest, the Sclerophyllous Forest, and the Sclerophyllous Andean Scrub. The main vegetal species growing on El Roble Hill are *Lithraea caustica*, *Quillaja saponaria*, *Peumus boldus*, *Maytenus boaria*, *Puya* sp. and several cacti species, with the presence of remnant *N. macrocarpa* formations being outstanding (Riedemann and Aldunate, 2000). Lubert and Pliscoff (2006), indicate that "Roble de Santiago" forests belong to the vegetative strata

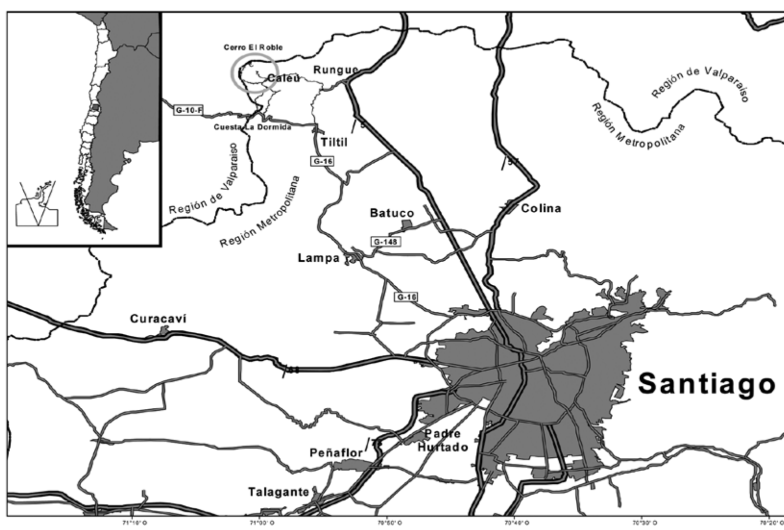

Figure 1. Location of the study area

denominated Deciduous Coastal Mediterranean *N. macrocarpa* and *Ribes punctatum* forest.

The study was carried out in a forest dominated by *N. macrocarpa*, with a crown cover close to 70% and located 1600-1800masl, in a south-west towards south-east exposure. A total of nine land plots of 500m^2, located in three sectors, were measured for forest characterization, considering three randomly replicate sample plots per sector. The sectors were relatively near each other, separated by less than 800m, and the only difference among them was their exposure. A total of 80 sprouts were harvested from each sector. Normal diameter at 1.3m (DBH) and total height (H) were measured, and age was determined at 0.3m in each stump. Based on stand tables, a total of 62 sprouts were selected within the diameter distribution range (1.0-22.5cm). A tree-ring analysis was undertaken, obtaining samples from the base and every meter along the stem. Additionally, DBH growth was measured. The volume of each sprout was calculated using the Smalian formula, which requires DBH data.

The above-ground biomass of the different components (stem, branches and foliage) was estimated. Branches correspond to components with a basal diameter <5cm. The anhydrous density of the wood and bark stem samples was determined, and stem biomass was estimated for each sprout as a sum of both components.

For leaf and branch components of each sprout, the material was stored and transported for manual separation in the laboratory. After separation, all collected and individualized material was oven dried at 65°C until constant weight. From the total number of 62 sprouts selected for above-ground biomass estimation, 29 were harvested during winter and 33 during summer; therefore the foliage biomass was determined only for the last ones. Equations were developed to estimate above-ground biomass, where all different components of the sprout were considered.

Comparisons of age, volume and basal area were carried out by variance analysis (ANOVA) with the F-test. Significant differences were separated with standard error of the means, to evaluate least significant differences (LSD). All tests were evaluated at $p<0.05$. Statistical analyses were carried out using the Statgraphic statistical package (Statgraphics, 2001).

Results and Discussion

Forest structure

The woodland considered for this study is a secondary *Nothofagus macrocarpa* forest that has been harvested during the last decades, mainly for wood extraction, as firewood and for coal purposes. The upper canopy is mainly dominated by *N. macrocarpa*. Accompanying scrub and herb species were *Maytenus boaria*, *Schinus montanus*, *Ribes punctatum*, *Calceolaria meyeniana*, *Baccharis neaei*, *Mutisia latifolia*, *Solanum ligustrinum*, *Tanacetum pathenium*, and *Berberis actinacantha*. *N. macrocarpa* have a coppice structure, where several sprouts develop from each stump or rootstock. No primary forest trees were observed in the area. Vegetative reproduction from rootstock shoots is a common characteristic of Mediterranean ecosystems (Retana *et al.*, 1992) and some species of the *Nothofagus* genus. The coppice structure has been reported for *N. glauca* and *N. alessandrii*, among others (Mollenhauer, 1975; Santelices and Riquelme, 2007). There is no mention of *N. macrocarpa* in the literature, mainly due to the fact that until few years ago, this was considered as a variety of *N. obliqua* species.

The trees show a high vegetative regeneration from rootstocks, with up to 11 sprouts per stump. The forest has an average age of 39 ±10.5 years (range 10-64; Table I). Age dispersion characterizes not only the forest level, but also the rootstock level, where the ages of sprouts from the same rootstock are not homogeneous. Considering the variety, age standard deviation (n=14) is between 17.2 and 2.6 years, with an average of 7.8 years.

TABLE I
AGE DISTRIBUTION BY DIAMETER CLASSES

DBH (cm)	Number of sprouts	Age (years) Average	Minimum	Maximum	Standard deviation
<3	15	23	12	53	6.4
3.1-6.0	77	33	14	62	6.9
6.1-9.0	80	40	10	59	8.5
9.1-12.0	41	47	34	63	6.5
12.1-15.0	20	49	26	64	4.9
>15.1	7	52	46	60	4.6
Total	240	39			10.5

DBH: Normal diameter at 1.3m.

The uneven-aged structure of the *N. macrocarpa* forest has not been reported for other species of the *Nothofagus* genus. Mollenhauer (1975) established that *N. glauca* forests present even-aged coppice structures, especially in those areas that have been most intensively harvested. Santelices and Riquelme (2007) indicated that *N. alessandrii* coppice presents a homogeneous age, since there was a massive uniform regeneration of stumps and shoots resulting from fire, forest harvesting, and other large-scale alterations. In the case of *N. alpina* secondary forests, it has been indicated that, as a consequence of anthropic action and natural phenomena (fire, landslides, etc.), most of the stands presented a second-growth forest with an even-aged coppice structure (Donoso, 1993).

Wood damage status was also evaluated based on tree ring analysis. Generally, in the studied forest the sprouts were in good condition, since only 5% of the samples displayed a certain degree of brown stem rotting and only 1% showed damages, most probably of mechanical origin (fall of neighboring trees, snow, landslides).

The average height of sprouts is 7.8m, ranging between 2.5 and 12.7m. Normal diameter (DBH) ranges from 1.3 to 17.9cm, with an average of 8.7cm ±3.5cm (Table II).

Volume equation

The model used to estimate total over bark volume (TOBV) is a local equation, where DBH is the independent variable. The model was selected due to its statistical fit and because it fairly represents the biological development of the trees. The following equation and statistics were obtained:

$$\text{TOBV (m}^3\text{)} = 0.000115439 \times \text{DBH (cm)}^{2.48824}$$

$r^2 = 0.97$

$F_{(76)} = 1717.3$ ($P<0.01$)

Standard error of the estimate= 0.17m^3

According to the forest inventory plots carried out within

TABLE II
DASOMETRIC CHARACTERISTICS OF THE STUDIED FOREST

Forest structure variables	Average	Standard deviation	Frequency distribution DBH (cm)	Trees/ha
DBH	8.7cm	3.5cm	<3	72
Total height	11.3m	3.5m	3.1-6.0	310
Density	1598 sprouts/ha	293 sprouts/ha	6.1-9.0	475
Density	497 stumps/ha	75 stumps/ha	9.1-12.0	452
Basal area	11.3m^2·ha^{-1}	3.5m^2·ha^{-1}	12.1-15.0	210
Age	39 years	10.5 years	>15.1	77

DBH: Normal diameter at 1.3m.

TABLE III
HEIGHT AND DIAMETER GROWTH FOR THE STUDIED FOREST

DBH classes (cm)	Height growth (cm/year)		DBH growth (cm/year)	
	Annual average	Last 2 years	Annual average	Last 5 years
<3	21.8	4.1	0.21	0.20
3.1-6.0	41.7	3.1	0.18	0.16
6.1-9.0	33.4	3.7	0.23	0.18
9.1-12.0	27.9	4.2	0.25	0.17
12.1-15.0	23.7	6.0	0.29	0.20
>15.1	38.0	4.9	0.37	0.20
Average	32.3	4.1	0.23	0.18

DBH: Normal diameter at 1.3m.

the studied stand, the forest volume was 52.0m^3·ha^{-1}. This value is very low compared to the typical values observed in secondary *Nothofagus* forests in Chile where, usually, volume largely exceeds 100m^3·ha^{-1} at similar stand ages (Donoso, 1988; Donoso *et al*., 1993).

Growth

The sprouts show a mean annual height growth of 32.3cm/year. However, during the last two years, growth rate decreased to 4.1cm/year (Table III). These values are below the rates observed for other *Nothofagus* species that grow in Mediterranean environments and have a coppice structure. For example, *N. glauca*, a species that in its northernmost distribution shares the same area with *N. macrocarpa*, shows a mean growth rate similar to those calculated within this study, of 28cm/year (Barrales, 1993) and 34cm/year^{-1} (Jara, 2006). Additionally, *N. obliqua* even-aged coppice which grows in a region with higher precipitation conditions, displays a growth rate of 40cm/year (Donoso, 1988).

The mean diameter growth presented no significant differences (p<0.05) among the different diameter classes (Table III). The growth rate decreased over the last five-year period. The values determined for *N. macrocarpa* were lower than those found in species of the same genus in Chile. Annual diameter growth in secondary *Nothofagus* forests varies according to site and tree ages. Values range from 0.3 to 0.8cm/year, and even values up to 1cm/year have been found (Wadsworth, 1976; Donoso, 1988; Grosse, 1989; Donoso *et al*., 1993; Echeverría and Lara, 2004; Santelices and Riquelme, 2007). However, *N. glauca* forests show a similar diameter growth to that of *N. macrocarpa* forests. Barrales (1993) determined growth rates ranging from 0.07 to 0.41cm/year, with an average of 0.23cm/year. Also Jara (2006) determined a growth of 0.24cm/year in a temperate Andean secondary forest.

Average volume growth during the last five years was 0.43m^3·ha^{-1}/year. This value is below the rates observed for other forests growing under the same climatic conditions. Higher values have been determined in forests growing under marginal conditions. In fact, Barrales (1993) has determined a productivity of 4.4m^3·ha^{-1}/year for *N. glauca*, and a similar value was indicated by Donoso (1988) for *N. obliqua*.

The growth values determined in the studied area represent the first data related to the variation of these growing parameters in *N. macrocarpa* forests. The low growth rates may reflect the geographical site conditions: low precipitation, warm summers and cold winters, including rainfall as snow and, also, the degradation due to anthropic activity. These characteristics should result in a high competition for light, water, and nutrients among individuals (Pacheco, 2008).

The application of selective cutting of the rootstocks in the study area produced a higher availability of water, which is especially apparent in those sectors where the largest basal area was harvested (60%). The individuals in these areas showed higher DBH growth (Pacheco, 2008). For this reason, it is possible to state that the application of silvicultural practices that enable an increase in light and water availability could lead to an increase in diameter and height growth rates.

Biomass accumulation

The models selected to estimate total and per-component above-ground biomass were exponential equations (Table IV). This type of equation has been widely used by different authors with an accurate fit (Schönenberger, 1984; Caldentey, 1995; Hart *et al*., 2003; Cañellas *et al*., 2004). The obtained models corresponded to local equations, presenting a good correlation and included DBH as an independent variable.

At the sprout level, biomass values as a function of DBH fall within the wide range of values determined for different *Nothofagus* formations (Caldentey, 1995; Silva, 1997; Peri *et al*., 2008). For *N. pumilio* trees with a DBH of 8.9cm, the biomass determined by Silva (1997) was 17.4kg, with component proportions of 83, 14 and 3% for stem, branches and foliage, respectively. The estimated value for a *N. macrocarpa* sprout of a similar size was 13.4kg, with the same percentages per component as those determined by Silva (1997). The forest above-ground biomass obtained from the forest inventory reached to 35.2ton·ha^{-1}, the different components showing 29.0, 5.4 and 0.9ton·ha^{-1} for stem, branches and foliage, respectively. The total amount of biomass is below that measured in several other biomass studies. For *Fagus sylvatica* forests it was indicated (Huet *et al*., 2004) that above-ground biomass values range from 75 to >400ton·ha^{-1}, depending on the site and the age of the stand. Higher values are reported for *Nothofagus* forests growing in Chilean Mediterranean environments. In fact, Pedrasa (1989) estimated a total above ground biomass of 201ton·ha^{-1} for a *N. alessandri* forest, and Gómez (1976) estimated an amount of 351ton·ha^{-1} for a *N. glauca* forest. A review of data carried out by Magni (1995) indicates that biomass variation in *Nothofagus* forests globally ranges from 75 to 680ton·ha^{-1}, considering natural forests with different levels of development and human intervention. However, Peri *et al.* (2008) estimated an above-ground biomass of 64.6ton·ha^{-1} in a marginal *N. antarctica* forest 40-60 years old. The values determined within the present study for *N. macrocarpa* are below the above mentioned reported values. This is explained by the fact that it grows under restrictive environmental conditions that severely limit its development.

The studied forest is particularly sensitive to climate changes (IPCC, 2007), being two the major limiting envi-

TABLE IV
TOTAL AND PER-COMPONENT BIOMASS EQUATIONS FOR *Nothofagus macrocarpa*

Biomass equations	Statistic parameters		
	r^2	E.E.E	F (p<0.01)
Foliage biomass (kg)= $e^{(-3.3268 + 0.259742*DAP\ (cm))}$	0.79	0.55	123.3
Branches biomass (kg)= $e^{(-2.10769 + 0.302921*DAP\ (cm))}$	0.78	0.60	219.2
Stem biomass (kg)= $e^{(-0.0123226 + 0.27176*DAP\ (cm))}$	0.88	0.38	444.1
Total biomass (kg)= $e^{(0.154574 + 0.277754*DAP\ (cm))}$	0.87	0.41	216.4

E.E.E: standard error of estimation, F: calculated value of Fisher test.

ronmental factors: the decrease of the usually low level of precipitations on one hand, and the increase of summer maximal temperatures on the other hand (Pacheco, 2008).

Conclusions

The growth and biomass values determined in the area under study are the first data related to the behavior of these variables in *N. macrocarpa* forests. The low growth rates reflect the marginal conditions of the site: low precipitation, warm summers and cold winters with snow, and important degradation due to anthropic activity.

The values hereby determined are markedly lower than those reported in other *Nothofagus* forests growing in Chilean Mediterranean environments, and this ratifies that the studied forest grows under marginal environmental conditions that severely limit its development.

It is necessary to determine the optimal actions to carry in order to allow these forests to survive and, more, to improve their capacity to adapt to global changes.

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