PRELIMINARY SITE INDEX MODELS FOR NATIVE ROBLE (*NOTHOFAGUS OBLIQUA*) AND RAULÍ (*N. ALPINA*) IN CHILE

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ABSTRACT

Few growth models have been published relating to native tree species in Chile. The objective of this study was to develop site index curves for two of the most valuable native species in Chile — Roble (*Nothofagus obliqua* (Moerb.) Oerst.) and Raulí (*Nothofagus alpina* Oerst. et Endl.). The study was based on stem analysis data. The method used for the reconstruction of each stem profile corresponded to one proposed previously. Site index models were generated using the difference equation method. The resulting site index systems revealed different growth patterns for both species. Among the two light-demanding species, Raulí is characterised by better initial growth.

Keywords: site index; polymorphic curves; difference equation method.

INTRODUCTION

Studies carried out in natural forests in Chile indicate that the forest communities with the highest commercial value are the second-growth forests, known as *renovales* (Ulloa 1984). The ecology and structural characteristics of the *renovales*, which cover a total area of about 300 000 ha (CONAF & CONAMA 1999), have been described by several authors and will not be repeated here (Wadsworth 1976; Corvalán 1977; Puente *et al*. 1979; Donoso 1981; CONAF 1994). The most important species in the second-growth forests, and those that represent a high proportion of the trees, belong to the genus *Nothofagus*. The most valuable species are *Nothofagus obliqua* (Roble) and *N. alpina* (Raulí). Because of the large area,

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commercial importance, and ecological characteristics of this forest type, a number of investigations have been carried out during the past 30 years with the aim of understanding the specific structural attributes and natural dynamics of the *renovales* (Cisterna 1989; Castillo 1992; Donoso 1993) and the productivity (De Camino *et al.* 1974; Paredes 1982; Burgos 1986; Donoso 1988; Grosse 1989; Donoso *et al.* 1993) and growth of *N. obliqua* and *N. alpina* (Vita 1974; Donoso *et al.* 1984; Núñez & Peñaloza 1986; Castillo 1992).

Based on information gathered from established management trials* a number of silvicultural treatment options have been proposed for the *renovales* forest type. Among the the most important ones are the investigations and proposals made by Rocuant (1967, 1974), De Camino *et al.* (1974), Vita (1974), De la Maza (1976), Wadsworth (1976), Herrera & May (1976), Soler (1979), Puente *et al.* (1979), Gallardo (1986), Núñez & Peñaloza (1986), Grosse (1987), Pincheira (1993), and Aviléz (1995).

Although the existing empirical knowledge about the *renovales* and their tree species is impressive, there are few studies presenting concrete and practical tools for managing the resource. Such studies include a proposal for delineating growth zones for Roble and Raulí (Donoso *et al.* 1993), the development of individual tree diameter-growth models (Cubillos 1987; Exss 1991; Bahamondez 1995; Trincado 1994), the evaluation of density and competition indices (Sánchez 1994), the estimation of merchantable volume in deciduous trees (Higuera 1994; Trincado *et al*. 1997; Trincado & Vidal 1999) and the development of a stand growth model for second-growth forest of Roble-Raulí-Coigüe (Ortega & Gezan 1999).

One of the basic requirements for estimating tree growth and defining suitable forest management strategies is the ability to determine the productivity of the site, and a great variety of methods for determining site productivity have been published†. The most common approach involves the use of site index, the dominant stand height at a given reference age, which is related to the total volume yield at that age and which is assumed to combine the effects of all the growth-relevant site factors (Clutter *et al.* 1983; Newnham 1987; Thrower 1989; Gadow & Hui 1999).

The objective of this study was to develop a much-needed site index system for Roble and Raulí in Chile, which could be used for estimating the productive capacity of the growing sites where the species are found.

DATA

The data set used in this analysis, and described in detail by Donoso *et al.* (1993), was derived from 22 representative localities in second-growth forests of Roble and Raulí distributed from the province of Curicó (VII region) to the province of Malleco (IX region) in Chile. Information about the geographical location and physiographic characteristics of each locality are presented in Table 1.

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* A detailed description of the most important silviculture trials established in Chile for natural forest has been published by Lara *et al.* (2000).

† Hägglund (1981), Clutter *et al.* (1983), Prodan *et al.* (1997), and Gadow & Hui (1999) have described the main methodologies used to estimate the productivity in forestry.

TABLE 1–Location and physiographic characteristics of the localities where the sample plots were established (from Donoso *et al.* 1993).

Code	Region	Latitude S	Longitude W	Slope (%)	Exposition	Altitude	Selected sample trees by locality	
							Roble (n=26)	Rauli (n=24)
01	VII	35°04'	70°40'	49	NW	1000	1	2
02	VII	35°04'	70°40'	65	S	950	1	1
03	VII	35°25'	71°08'	31	SW	800	2	4
05	VII	35°25'	71°08'	31	SW	890	–	1
06	VII	35°25'	71°08'	30	SE	850	–	2
07	VII	35°26'	71°08'	30	SW	950	1	–
08	VII	35°36'	71°08'	25	N	1100	2	1
09	VII	35°36'	71°08'	5	S	1100	–	3
10	VII	36°14'	71°23'	32	SE	900	3	2
11	VII	36°14'	71°23'	3	S	900	1	–
12	VII	36°17'	71°30'	3	SW	650	–	2
13	VIII	36°48'	71°44'	25	SW	650	1	2
14	VIII	36°53'	71°33'	30	N	700	–	2
16	VIII	37°18'	71°41'	25	NW	850	2	–
17	IX	37°46'	72°50'	41	S	700	1	–
18	IX	37°49'	72°49'	48	SE	860	–	1
19	IX	38°07'	71°52'	17	S	650	2	–
20	IX	38°07'	71°53'	13	NE	600	2	–
21	IX	38°19'	71°56'	15	NW	750	3	–
22	IX	38°15'	71°52'	0	0	950	3	–
23	IX	38°16'	71°53'	15	N	900	–	1
24	IX	38°16'	72°07'	0	0	500	1	–

In each of the 22 localities, rectangular plots measuring 25 × 50 m were established. Inside each plot three of each tree species belonging to the codominant and dominant strata were selected for stem analysis. After a data validation of the sample trees, 26 Roble and 24 Raulí trees were selected from the material of Donoso *et al.* (1993) to provide the data for this study (Table 2).

In each sample tree, a stem section was obtained at stump height (0.3 m), at breast height (1.3 m), at a height of 2 m, and from then on every 2 m up to a height where the stem diameter was less than or equal to 10 cm. Subsequently, the number of growth rings and the average ring width were determined for each stem section in the laboratory (Donoso *et al*. 1993).

STEM ANALYSIS

A variety of methods may be used to reconstruct the growth of a tree from stem analysis data (Nagel & Athari 1982; Dyer & Bailey 1987). The most widely used technique corresponds to the method proposed by Carmean (1972), which was applied in this study. The tree height to section i with r_i growth rings and ring age t_{ij} was estimated as follows:

$$H_{ij} = h_i + (h_{i+1} - h_i)/[2(r_i - r_{i+1})] + (j - 1)(h_{i+1} - h_i)/(r_i - r_{i-1}) \quad (1)$$

TABLE 2–Descriptive statistics of the dominant and codominant sample trees for Roble (n=26) and Raulí (n=24).

	Statistic	Ddh (cm)	Height (m)	SI* (m)	Age† (year)
Roble	Min	15.00	13.20	9.00	22.0
	Max	39.00	32.50	19.00	56.0
	Mean	25.99	22.34	12.91	37.5
	C.V.	22.37	23.99	23.38	30.3
Raulí	Min	12.50	12.20	5.00	22.0
	Max	40.12	29.50	15.40	76.0
	Mean	25.49	19.27	9.97	42.8
	C.V.	28.57	21.06	23.46	29.9

* Site index with a reference age of 20 years
† Stump age
C.V.= coefficient of variation

where: H_{ij} = estimated height (m) to the age t_{ij}
h_i = height (m) of the *i*-th stem section
r_i = total number of growth rings for the *i*-th stem section (j=1, 2, .., r_i).

The method assumes that the annual height growth is constant for each year for which height growth is wholly or partially contained within the section and that, on average, a crosscut will occur in the middle of a year's height growth (Dyers & Bailey 1987). The reconstruction of the stem radius and height profile for sample tree No.15, applying the method proposed by Carmean (1972), is shown in Fig. 1.

Based on the stem analysis, information was obtained which could be used to reconstruct the development of the dominant height for each species with respect to age.

DEVELOPING A SITE INDEX SYSTEM

Depending on the type of data available, it is possible to develop an *anamorphic* or a *polimorphic* site index system. The anamorphic system, which is developed when only information from temporary plots is available, assumes that the model parameters which define the form of the dominant height growth curve, are equal for all site qualities. This constraint is not imposed in a polimorphic system where the pattern of dominant height growth may be influenced by the site quality. For the development of this type, it is necessary to have information from permanent plots or stem analysis.

According to Clutter *et al.* (1983) three different methods may be applied for developing a site index system: the guide curve method, the difference equation method, and the parameter prediction method. In this study, we developed a polimorphic site index system based on the difference equation method proposed by Cieszewski & Bella (1989). The formula was derived from the growth function proposed by Hossfeld in 1822 (Peschel 1938) and corresponds to‡:

‡ Elfving & Kiviste (1997) present the derivation of the formula proposed by Cieszewski & Bella (1989)

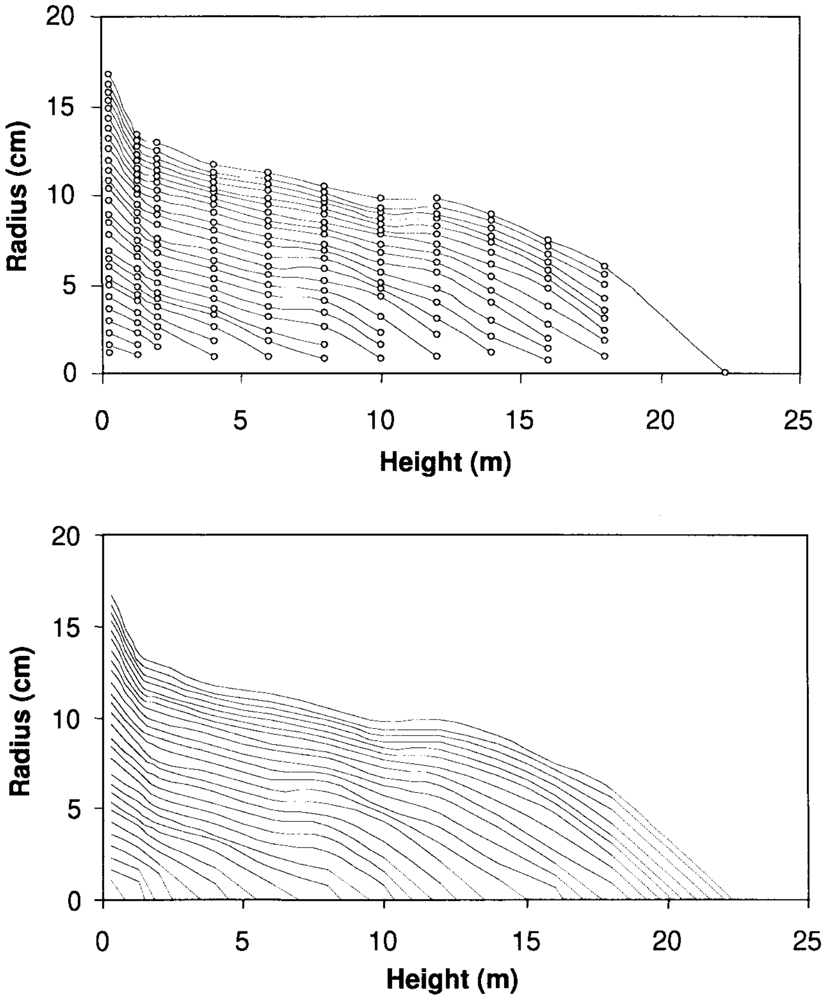

FIG. 1–Stem analysis for sample tree No. 15. Top: Radii of stem sections with the measured growth rings. Bottom: segmented lines showing the reconstructed stem radius and height profile.

$$H_2 = \frac{H_1 + d + r}{2 + 4 \cdot \beta \cdot \dfrac{A_2^{-b_2}}{(H_1 - d + r)}} \tag{2}$$

where : H_1 = dominant height (m) at age A_1 (years);

H_2 = dominant height (m) at age A_2 (years);

$d = \beta \cdot A_{si}^{-b_2}$

$r = \sqrt{(H_1 - \beta \cdot A_{si}^{-b_2})^2 + 4 \cdot \beta \cdot H_1 \cdot A_1^{-b_2}}$

A_{si} = Parameter constant estimated by trial and error.

The parameters β and b_2 were estimated using non-linear regression techniques, i.e., the *DUD* method, implemented in the *NLIN* procedure of the Statistical Analysis System (SAS Institute 1989). The parameter A_{si} may be considered a constant that has to be estimated by trial and error (Elfving & Kiviste 1997; Kasesalu & Kiviste 2001). Where the site index of the stand ($H_{ref\,age}$) is known, A_1 = may be replaced with the reference age (A) and H_1 with $H_{ref\,age}$. The current height growth can be obtained using the first derivative of the growth function (2).

$$CAI = \frac{\delta H}{\delta A} = \frac{(H_{ref\,age} + d + r) \cdot 4 \cdot \beta \cdot b_2 \cdot \dfrac{A^{-b_2-1}}{(H_{ref\,age} - d - r)}}{\left[2 + 4 \cdot \beta \cdot \dfrac{A_2^{-b_2}}{(H_{ref\,age} - d + r)}\right]^2} \tag{3}$$

The age ($A_{max\,CAI}$) of maximum current height growth can be determined when the first derivative of the current height growth (Eq. 3) is set equal to zero, using the following equation:

$$A_{max\,CAI} = \left[\frac{k \cdot (-b_2 - 1) + 2 \cdot k \cdot b_2}{2 \cdot (b_2 + 1)}\right]^{1/b_2} \tag{4}$$

where: $k = \dfrac{4 \cdot \beta}{(H_{ref\,age} - d + r)}$

RESULTS AND DISCUSSION

Dominant Height Growth

Based on the stem analyses it was possible to determine height development with respect to the age of each of the dominant Roble and Raulí sample trees growing in the different localities in Chile (Fig. 2).

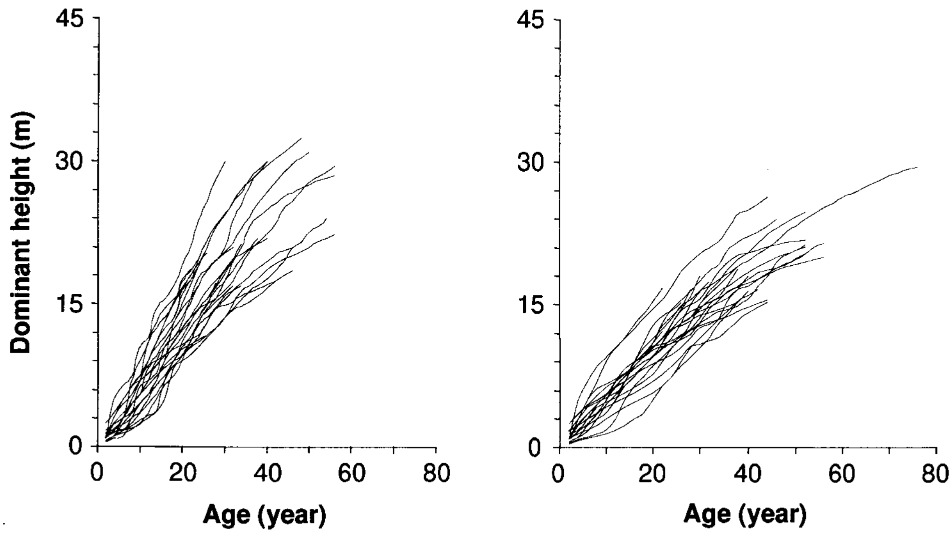

FIG. 2–Dominant height growth of (a) Roble and (b) Raulí sample trees based on stem analysis data.

Up to the age of about 50 years (i.e., the extent of the sampled data), the two species exhibited different patterns of dominant height growth (Fig. 2). The growth rates were generally higher in Roble. However, the site-related differences within the two species were considerable, but greater in Roble.

Site Index System

Pairs of observations [(A_1,H_1); (A_2,H_2)] at 2-year intervals were used for estimating the parameters of the Cieszewski-Bella model. The parameter estimates for the two species are presented in Table 3.

TABLE 3–Parameters for the Cieszewski-Bella model and residual variation (RMSE) for each species (Eq. 2).

Parameter	Roble	Raulí
A_{si}	15	5
β	2133.329	332.5450
b_2	1.451976	1.217103
RMSE	0.521	0.386

The selected A_{si} values, used as constants during the fitting process, resulted in the minimum root mean square error.

An advantage of the model is the fact that it is polymorphic and base-age invariant. The height is consistent with site index at the reference age and asymptote increases with increasing site quality. The model is parameter-parsimonious, having only two parameters which are biologically meaningful (Cieszewski & Bella (1989). Growth curves for site indices 10, 15, 20, and 25 m are shown in Fig. 3, developed for each species and considering a reference age of 20 years.

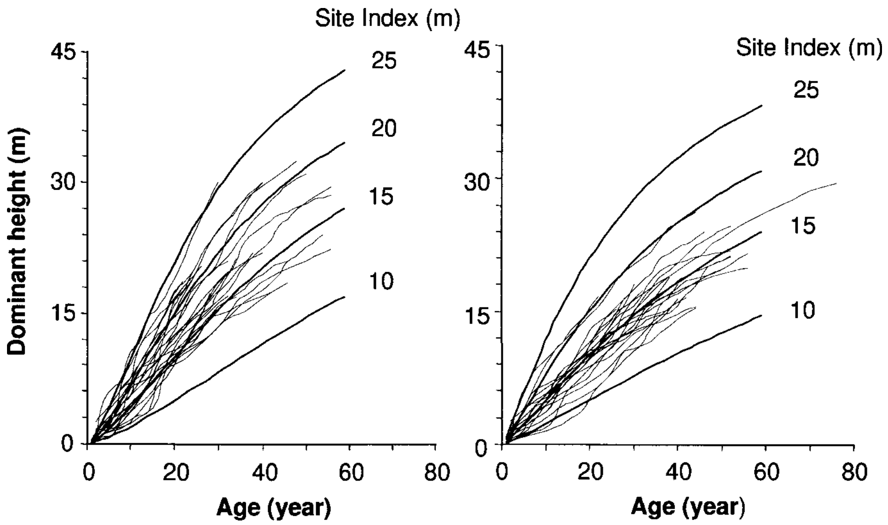

FIG. 3–Four curves for site indices 10, 15, 20, and 25 m with reference age 20 years for (a) Roble and (b) Raulí.

The different shapes of the site index curves indicate different patterns of dominant height growth in both species. The comparison is made easier when one follows the development of the dominant height between species for the same site index. This has been done in Fig. 4 with the growth curves of the two species for the site indices 10 and 20 m.

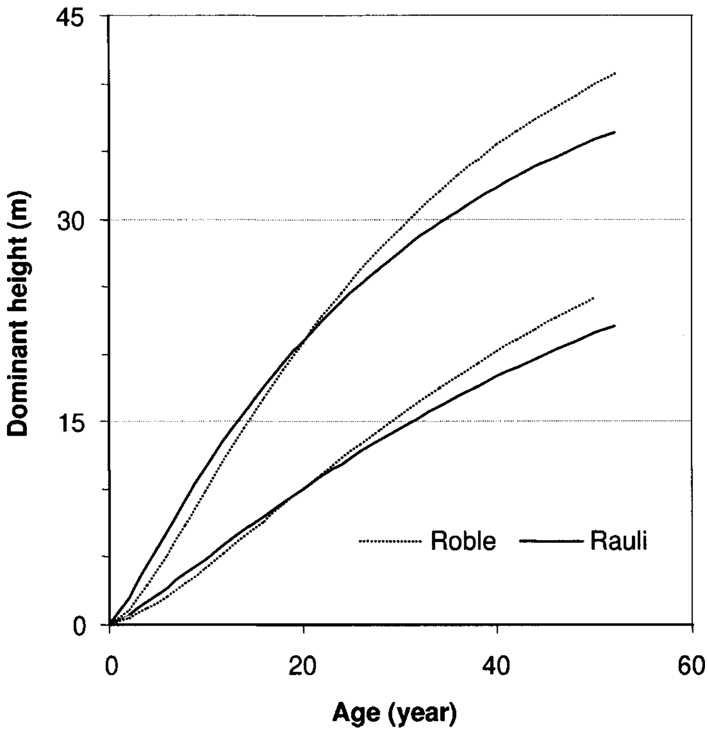

FIG. 4-Dominant height growth curves for Roble and Raulí, considering site indices of 10 and 20 m (reference age = 20 years).

Accordingly, based on the available material the index curves show that Raulí dominant height growth initially exceeds that of Roble. However, at a later stage the situation is inverted. This observation may be an indication of the light demand of the two species. Early culmination of current height growth is usually observed in the more light-demanding species, while that of shade-tolerant species culminates at a later age*. Table 4 presents the ages at which the height growth culminates, for the two species and for different site indices.

Current height growth culminated earlier on the better sites (Table 4), which is consistent with general experience. It was also evident that Raulí reaches the maximum current height growth at an earlier age than Roble for the same site index. For a site index of 20 m, for example, Raulí will attain maximum current height growth about 5 years earlier than Roble.

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* Read & Hill (1985) compared the photosynthetic response of seedlings of the two species, indicating that of the species Raulí is more tolerant of shade.

TABLE 4–Age of height growth culmination considering site indices of 10 and 20 m.

Site index	Roble Maximum current height growth at age	Raulí Maximum current height growth at age
10	15.9	9.1
20	9.5	4.4

CONCLUSIONS

The new preliminary polymorphic site index system for the two major species of the important *renovales* forest type in Chile was developed using the particularly flexible and practicable Cieszewski-Bella model. This model has several advantages. It is polymorphic and base-age invariant. The height is consistent with site index at the reference age, and the asymptote increases with increasing site quality. The model is parameter parsimonious having only two biologically meaningful parameters.

Based on the limited, available, sample tree data which were derived from a great variety of 22 growing sites, it could be shown that the species exhibit different patterns in dominant height growth. Raulí is initially superior on poor as well as good sites, whereas Roble shows higher growth rates at older ages. Again this is valid for all site indices. The site index system developed reflects for both species a logical generalisation of observed growth, which can be seen when the calculated site curves are superimposed on the observed dominant height-age curves.

The results are acceptable and this first site index system can be recommended for practical use in Chile. It is necessary to emphasise, however, that the proposed site index system should be revised and improved as soon as more data are available.

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