PRELIMINARY SITE INDEX MODELS FOR NATIVE ROBLE (NOTHOFGAGUS OBLIGUA) AND RAULÍ (N. ALPINA) IN CHILE

GUILLERMO TRINCADO V*
Institute for Forest Management, Austral University,
Casilla 567, Valdivia, Chile

ANDRES KIVISTE
Estonian Agricultural University, Department of Forest Management,
Kreutzwaldi 5, EE-2400 Tartu, Estonia

and KLAUS VON GADOW
Institute for Forest Management, Georg-August-University Göttingen,
Büsgenweg 5, 37077 Göttingen, Germany

(Received for publication 14 January 2002; revision 11 October 2002)

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,
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 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.

---

* A detailed description of the most important silvicultural 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.
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 \( t_i \) was estimated as follows:

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

(1)
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 (\( j=1, 2, \ldots, r_i \)).

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‡:

\[ \text{DEVELOPING A SITE INDEX SYSTEM} \]

† Elfving & Kiviste (1997) present the derivation of the formula proposed by Cieszewski & Bella (1989)
\[ H_2 = \frac{H_1 + d + r}{2 + 4 \cdot \beta \cdot A_{si}^{b_2}} \cdot \frac{A_{si}^{b_2}}{(H_1 - d + r)} \]  

where:  
\( H_1 \) = dominant height (m) at age \( A_1 \) (years);  
\( H_2 \) = dominant height (m) at age \( A_2 \) (years);  
\( d \) = \( \beta \cdot A_{si}^{b_2} \)  
\( r \) = \( \sqrt{(H_1 - \beta \cdot A_{si}^{b_2})^2 + 4 \cdot \beta \cdot H_1 \cdot A_{si}^{b_2}} \)  
\( A_{si} \) = Parameter constant estimated by trial and error.

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.
The parameters $\beta$ 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 $A_a$ 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, $A_1 = \delta$ 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).

$$CAI = \delta H = \frac{(H_{ref\,age} + d + r) \cdot 4 \cdot \beta \cdot b_2 \cdot A^{\cdot b_2 - 1} \cdot (H_{ref\,age} - d - r)}{2 + 4 \cdot \beta \cdot \frac{A^{\cdot b_2}}{(H_{ref\,age} - d + r)}}$$

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:

$$A_{max\,CAI} = \frac{k \cdot (-b_2 - 1) + 2 \cdot k \cdot b_2}{2 \cdot (b_2 + 1)}$$

where:

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

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).
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>
<thead>
<tr>
<th>Parameter</th>
<th>Roble</th>
<th>Raulí</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A_{si})</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>(\beta)</td>
<td>2133.329</td>
<td>332.5450</td>
</tr>
<tr>
<td>(b_2)</td>
<td>1.451976</td>
<td>1.217103</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.521</td>
<td>0.386</td>
</tr>
</tbody>
</table>

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.
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.

Accordingly, based on the available material the index curves show that Raúlí 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 Raúlí 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, Raúlí will attain maximum current height growth about 5 years earlier than Roble.

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

ACKNOWLEDGMENTS

This paper was prepared during a visit by the first author to the Institute of Forest Management at the University of Göttingen, Germany, in August-September 2001. The visit was supported for the German Academic Exchange Service (DAAD).

REFERENCES


PRODAN, M.; PETERS, R.; COX, F.; REAL, P. 1997: “Mensura Forestal”. Instituto Interamericano de Cooperación para la Agricultura (IICA)/Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GMBH.


ROCUANT, L. 1967: Antecedentes preliminares sobre el manejo de renovales en la cordillera de Nahuelbuta. Terceras Jornadas Forestales. 65 p


SOLER, M. 1979: Análisis evolutivo y comportamiento de renovales no intervenidos de Raulí
(Nothofagus alpina Poepp et Endl) según edad. Tesis de la Facultad de Ciencias Forestales,
Universidad de Chile. 59 p.

THROWER, J. 1989: Site quality evaluation using site index. Silviculture Institute of British
Columbia, Module III Training Course at Surrey, B.C. s.p.

TRINCADO, G. 1994: Construcción de modelos de crecimiento diametral independientes de la
distancia para Nothofagus obliqua (Mirb.) Oerst y Nothofagus glauca (Phil.) Kraser. Tesis de
Grado, Facultad de Ciencias Forestales, Universidad Austral de Chile. 58 p.


TRINCADO, G.; GADOW, K.v.; SANDOVAL, V. 1997: Estimación de volumen comercial en

ULLOA, F. 1984: Alcances sobre la disponibilidad del bosque nativo comercial en Chile. In Actas XI
Jornadas Forestales, Colegio de Ingenieros Forestales.

VITA, A. 1974: Algunos antecedentes para la silvicultura del Raulí, Facultad de Ciencias Forestales,
Universidad de Chile, Boletín Técnico No. 28. 17 p.

WADSWORTH, R. 1976: Aspectos ecológicos y crecimiento del Raulí (Nothofagus alpina) y sus
asociados en bosques de segundo crecimiento de las provincias del Bio-Bío, Malleco y Cautín,
Chile. Facultad de Ciencias Forestales, Universidad de Chile, Boletín Técnico No. 37. 47 p.