AN ABSTRACT OF THE THESIS OF

Héctor E. Gonda for the degree of Doctor of Philosophy in Forest Resources presented on May 1, 1998. Title: Height-Diameter and Volume Equations, Growth Intercept and Needle Length Site Quality Indicators, and Yield Equations for Young Ponderosa Pine Plantations in Neuquén, Patagonia, Argentina.

Abstract approved: ______________________________

Steven D. Tesch

Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) is the most widely planted species in the Patagonian Andes region of Argentina for economic development. However, information on site quality and yield is so limited that potential forest investors and managers do not have a reliable basis on which to make sound decisions. To ameliorate this problem I completed five silvicultural studies in Neuquén, the northernmost province where ponderosa pine is planted. Data were collected in 127 stands throughout Neuquén. 1) Four height(H)-diameter(D) equations were tested and $H = 1.3 + e^{(\beta 0+(\beta 1/(D+1)))} + \varepsilon$ was selected to predict individual tree H at the stand level. 2) Nineteen volume (V) equations were fitted with $V = \beta_0 + \beta_1 D^2H + \beta_2 D + \varepsilon$ and $V = \beta_0 + \beta_1 D + \beta_2 D^2 + \varepsilon$ selected to predict total inside-bark tree V when H data are and are not available respectively. The effect of crown ratio was not significant when added to D and H. A comparison demonstrated that trees of the same D and H appeared to have more volume in Neuquén than in western United States. 3) The ability of 13 growth intercepts to predict stand top height and crop height was examined between ages 12 and 20 years. A growth intercept index (GII) was developed to determine site quality based on the length of the five internodes starting at or above breast height. 4) The ability of needle length, measured around the bud on the terminal leader (TNL) and on the tip of first order lateral branches (LNL), to predict top height at age 20 was tested. A preliminary needle length index to determine site quality based on LNL was developed. 5) Yield equations based on stand age, GII, trees/ha (or basal area), and longitude, were developed. These equations predict higher volumes for Neuquén stands than those attained by highly productive California ponderosa pine plantations of the same age, dominant height, and trees/ha. Neuquén stands support very high stocking and they exhibit negligible mortality despite their very high basal areas and relative densities by North American standards.

Height-Diameter and Volume Equations, Growth Intercept and Needle Length Site Quality Indicators, and Yield Equations for Young Ponderosa Pine Plantations in Neuquén, Patagonia, Argentina

by

Héctor Eduardo Gonda

A THESIS

submitted to

Oregon State University

in partial fulfillment of
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Presented May 1, 1998
Commencement June 1999

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APPROVED:

Major professor, representing Forest Resources

Head of Department of Forest Resources

Dean of Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Héctor E. Gonda, Author

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My two and a half year stay in the Pacific Northwest allowed me to interact with many experienced researchers from OSU and other institutions. Dr. William Oliver, Dr. Douglas Maguire, Dr. Michael Newton, Dr. Robin Rose, Dr. John

Walstad, Dr. William Emmingham, Dr. Steven Daniels, Dr. Gregory Filip, Dr. Darrel Ross, and Dr. Steven Sharow contributed dramatically to the enrichment of my perspective about forest resources. The College of Forestry was a perfect environment to widen my thinking about other issues besides traditional silviculture. The content of several courses, intense discussions with faculty members, as well as the easy access to innumerable sources of information made me realize the vital importance of public involvement, policy, wildlife, etc., in the management of forests.

The moral support provided by my father as well as my brother and his family made my overseas stay more enjoyable. The patience and understanding of Carolina Barroetaveña kept me sane during my studies.

CONTRIBUTION OF AUTHORS

Dr. Steven D. Tesch was involved in the design, analysis, and writing of each manuscript. Gustavo O. Cortés participated in the design of each study. David D. Marshall collaborated in the design and analysis of three manuscripts, namely Chapters III, IV, and VI. Dr. Douglas A. Maguire assisted with the analysis and writing of the first manuscript, Chapter II.

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DEDICATION

In loving memory of my mother.

HEIGHT-DIAMETER AND VOLUME EQUATIONS, GROWTH INTERCEPT AND NEEDLE LENGTH SITE QUALITY INDICATORS, AND YIELD EQUATIONS FOR YOUNG PONDEROSA PINE PLANTATIONS IN NEUQUÉN, PATAGONIA, ARGENTINA

I. INTRODUCTION

PONDEROSA PINE PLANTATIONS IN NORTHERN PATAGONIA

Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) is the most widely planted species in the Patagonian Andes region of Argentina, where it grows vigorously and without any serious pest problems. Preliminary studies suggest that the average yield of these stands would be similar to or even higher than those growing on highly productive regions in the United States, such as in northern California (Gonda and Lomagno 1995, Urzúa 1991).

Even though there are currently only about 30,000 hectares of ponderosa pine plantations (Urzúa 1991), there are approximately a million hectares of grasslands suitable for commercial afforestation throughout the piedmont of the Patagonian Andes (Enricci 1993, Ferrer et al. 1990, Mendía and Irizarri 1986). However, information on site quality and yield of ponderosa pine in Patagonia is so scarce that potential forest investors and managers do not have a reliable basis on which to make sound decisions.

Distribution

Ponderosa pine is mainly planted between 37° and 44° south latitude throughout the provinces of Neuquén, Río Negro and Chubut (Figure I.1). At higher latitudes, the area of land suitable for commercial afforestation is dramatically reduced. The isohyet of 500 mm/year of precipitation (considered the minimum necessary to support ponderosa pine), is located near the Chilean border, leaving an extremely narrow piece of land with enough precipitation for ponderosa pine to grow successfully. At latitudes below 37° the possibility of growing commercial stands is doubtful because of the lengthy summer droughts. Most of the plantation forest area is located in Neuquén, since it is the province that first and most aggressively started planting about 20 years ago (Figure I.1).

In the eastern foothills of the Patagonian Andes, the primary source of moisture is humid winds blowing from the Pacific ocean. These mountains

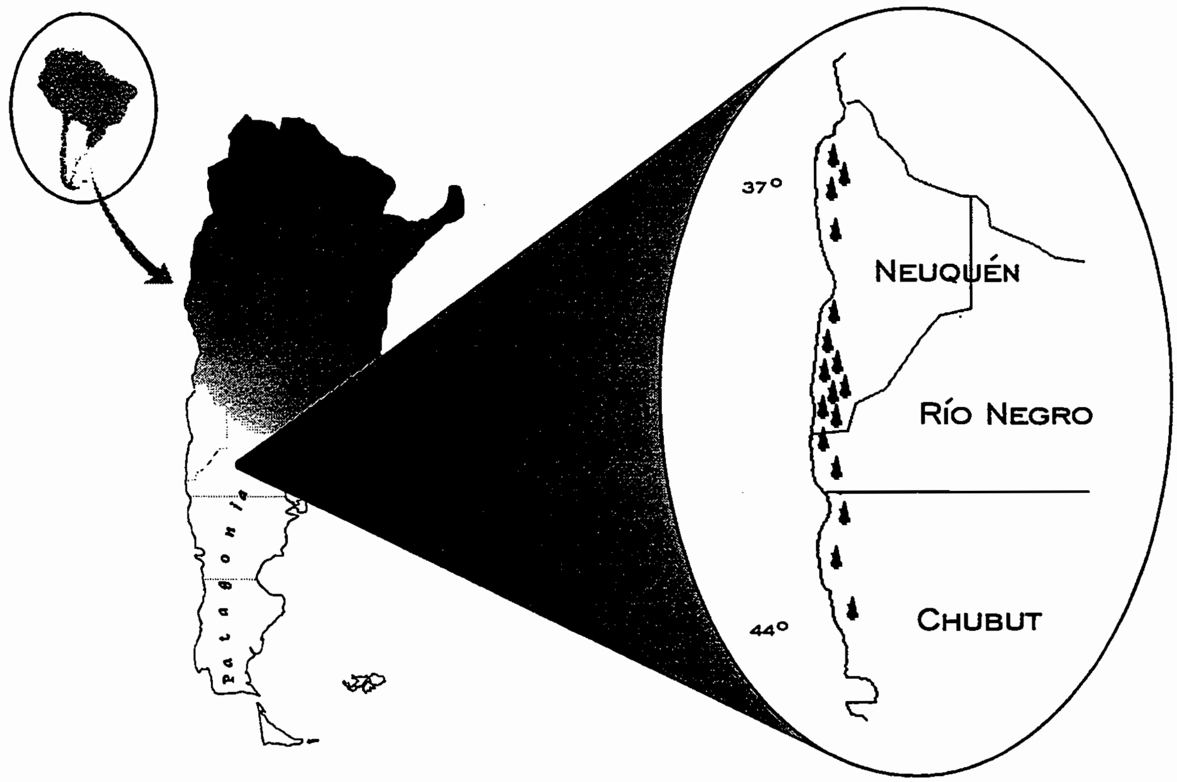

Figure I.1. From left to right: maps showing the position of Argentina in South America, Patagonia within Argentina, and the current distribution of the ponderosa pine plantations in the provinces of Neuquén, Río Negro, and Chubut. The number of pine trees is proportional to the plantation area.

produce a rain shadow effect that results in a strong annual precipitation gradient. Ponderosa pine is typically planted between the lower edge of the native forests on the west, down to the beginning of the steppe in the east. Thus stands are established almost exclusively on grasslands, mainly between the isohyets of 1000 and 500 mm/year of precipitation. Stands are generally not established where the annual precipitation is below 500 mm/year, because growth rates are not expected to justify the investment.

Replacing commercial native forests with ponderosa pine plantations is not proposed. Patagonian governmental organizations, as well as the general public want the native forests to be preserved and properly managed (van

Konynenburg 1995). Rapidly expanding environmental groups also raise their voice in favor of conserving and enlarging the native forests. Government subsidies and loans for afforestation with exotic species are only available for planting on grass or low-shrub occupied lands.

Some of the grasslands on which ponderosa pine plantations are established could have been covered with native shrubs before they were cleared for agricultural or grazing purposes. In most cases this is difficult to determine because the land use conversion occurred almost a century ago and there are no records about it.

Ecological Conditions

The environmental conditions in northern Patagonia are similar to those where ponderosa pine (variety ponderosa) forests grow naturally in the western United States. The piedmont of the northern Patagonian Andes and the interior Pacific Northwest share the following main characteristics:

1. The latitudinal ranges are similar in the respective hemispheres (Figure I.2)
2. Moisture is provided by humid winds blowing from the Pacific Ocean.
3. A rain shadow effect is produced by the Andes as well as by the Cascades and the northern Sierra Nevada ranges.
4. A Mediterranean climate prevails, imposing a well-defined dry season.
5. A high proportion of the soils are of volcanic origin.

Perhaps the most distinctive feature of the Patagonian Andes is the strong westerly winds that sweep the region almost constantly. Given their volcanic origin, a high proportion of the soils where ponderosa pine is planted contain volcanic ash with a high water holding capacity. In Neuquén, some of the most common soil subgroups are: Argixeroll vitrandic and calcic, Haploweroll vitrandic, Hapludand thaptic, Udivitrand thaptic and humic, Vitrixerand humic, and Xerorthent typic (Girardin and Broken 1995).

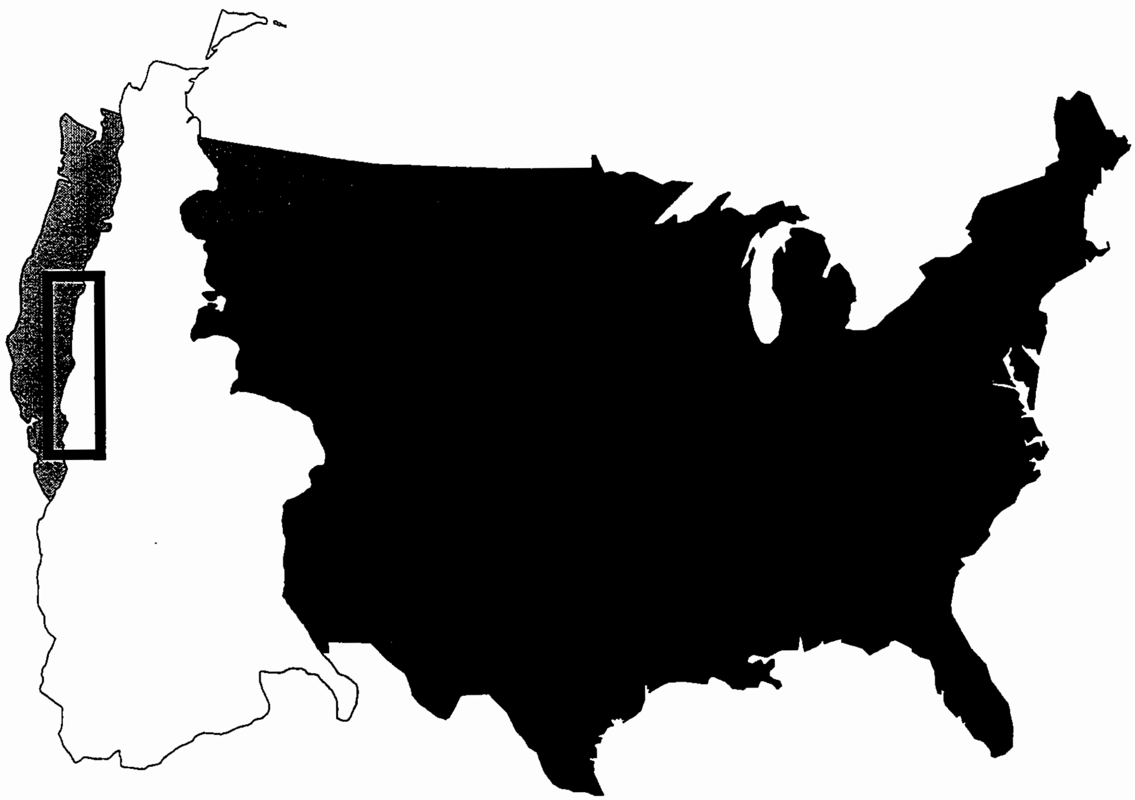

Figure I.2. A map superimposing the Patagonian Andes (Argentina) over the Cascades and northern Sierra Nevada (United States). The rectangle includes the current distribution area of the ponderosa pine plantations in Patagonia. The latitude of both countries match, and they are drawn at the same scale.

Seed Sources and Planting Stock

Only a few ponderosa pine stands in Neuquén were planted with the scopulorum variety (Rocky mountain ponderosa pine), as it was defined by Oliver and Ryker (1990). Trees of this variety are no longer established because, even though they have a superior cold resistance, they also typically have much slower growth rates, as it was demonstrated by some provenance trials in Patagonia (Enricci et al. 1995). Individuals of the ponderosa variety grow much faster, and have so far been able to withstand the low temperatures on most planting sites.

Tree nurseries buy the seed from commercial suppliers in the Western United States, or from local dealers. Foreign seed sources are typically from the eastern side of the Cascades in Oregon and Washington, and from the Sierra Nevada in northern California. The quantity of local seed collected every year is increasing dramatically, and a tree selection project to establish a seed orchard is being completed (Cortés and Tarifa 1995).

The most successful stock type is the 1+1 transplant (Davel et al. 1995). Occasionally 1+0s, 1+2s, or 2+0s are also planted (Tarifa et al 1995). Typically, these seedlings have an adequate top-root ratio and abundant fine roots, but seedling quality varies noticeably among nurseries. Survival rates are usually acceptable (70-80%), but in drier areas replanting is often necessary. Hare browsing can be a serious problem in some places (Cwielong 1992). Sites do not receive any kind of preparation before planting.

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) is the second most widely planted species in Patagonia, but the planting area with ecological conditions suitable for this species is smaller than that for ponderosa pine (Enricci 1993, Girarden and Broken 1995). Small stands of other exotic species such as western white pine (*Pinus monticola* Dougl.), grand fir (*Abies grandis* (Dougl.) Lindl.), and lodgepole pine (*Pinus contorta* Dougl. ex Loud), etc., have also been planted in the region with promising results.

Objectives and Products

The area planted annually with ponderosa pine is rapidly increasing as a result of subsidies and credits that the Patagonian provinces and the federal government provide for planting fast-growing exotic species. The primary objective of this support is to promote afforestation as a means to improve the socio-economic conditions of the region.

Afforestation with exotic species such as ponderosa pine may make a significant contribution toward ameliorating the troubled economy of the Patagonian Andes countryside. Ranchers and farmers of the region have traditionally relied on wool and beef production. In spite of the recent improvement in world wool prices, sheep raising is not nearly as profitable as it used to be a few decades ago. Sheep and cattle have been traditionally managed in such an extensive manner that it often led to severe cases of soil erosion, with the consequent decrease in land productivity (Marcolín and Fiorio 1995, van Konynenburg 1995). In addition, some small land owners and native Indian communities raise goats, whose eating habits almost always leave the land susceptible to erosion processes.

The population of Patagonia is so small that it could only consume a small portion of the timber to be potentially produced from the ponderosa pine plantations. Thus, lumber will have to be shipped either to Argentina's large cities (2000 km distance) or exported through the Atlantic ocean ports (700 km distance). These long distances call for the production of good quality lumber with the highest possible value. Intensive management practices such as pruning and thinning are strongly encouraged by all Patagonian institutions as well as the federal government (Laclau 1995). Preliminary studies on thinning (Gonda and Lomagno 1995), pruning (Gonda and Cortés 1995), and proper bucking techniques (Cordone 1995), have been recently published. Other important issues such as wood density, ring width, and certification are also starting to be taken into consideration.

Environmental Benefits

An important proportion of the grasslands suitable for afforestation have been overgrazed, showing different degrees of erosion. Erosion can be effectively halted by establishing fast growing trees. Thus, planting ponderosa pine would not only be commercially feasible but also environmentally beneficial (Marcolín and Fiorio 1995, van Konynenburg 1995).

Planting commercial native tree species on grasslands is currently difficult for two main reasons. First, the technology to successfully outplant their seedlings is not available (van Konynenburg 1995); some trials suggest they would require a moderate to high degree of protection to ensure establishment. Second, native species grow more slowly than ponderosa pine, and thus landowners are less inclined to invest in them. First-rotation ponderosa pine trees could provide the protection needed to establish some of the commercial native species, as well as the cash flow to enable landowners to wait for the longer second rotation. Hence, afforestation with exotic conifers may provide a means to expand the area covered with valuable native trees.

Covering large areas of steppe land with trees could produce some impact on the environment. For example, pine forests could potentially transpire large quantities of water from the ground that could affect the water table and perhaps the level of the rivers and streams, which in turn can produce an effect on some wildlife species. The assessment of those potential impacts should be carried out as the plantation area increases. On the other hand, increasing the woodland area with exotic tree species will enlarge the habitat suitable for forest wildlife species, with the potential of increasing biodiversity.

Main Factors Preventing a More Rapid Increase of the Planted Area

Afforestation is limited for the following reasons: landowners' reluctance, lack of confidence in the subsidies and credits available for afforestation, high fire hazard, and insufficient knowledge of tree growth.

Patagonian landowners are usually uncertain about growing trees; it is a new activity they are not familiar with and the economic benefits are hard to demonstrate since none of the stands have reached rotation age and timber markets are undefined. It will take extension education efforts and time for afforestation with ponderosa pine to become a customary practice in the foothills of the Patagonian Andes.

Government subsidies and low interest loans are currently available for afforestation with ponderosa pine and make it affordable to almost any landowner in northern Patagonia. However, during the political turmoil in Argentina during the 1960's and 1970's, these subsidies and credits were sometimes mismanaged by delaying the payments or lowering the amounts originally offered. Despite the dramatic political and economic improvement of the country since the beginning of the 1980's, it is going to take potential investors some time to feel more confident about public financial aid.

Argentina has been politically stable since 1983 and has experienced rapid economic growth since 1990. These improvements, as well as active forestry extension campaigns carried out by several institutions, such as the provincial forest offices, the Patagonian Andes Forest Research and Extension Center (CIEFAP), the National Institute of Agricultural Technology (INTA), the School of Forestry at University of Patagonia, and those in many cities, make it reasonable to assume that the problems stated above will be progressively solved in the near future.

Dry summers and the presence of tourists make fire a real threat to ponderosa pine plantations in most areas. Only a hand full of communities have effective fire protection systems and fire insurance policies are not available.

The main technical problem affecting a more rapid expansion of the planted area is the limited quantitative information on the growth and yield of ponderosa pine. This insufficient knowledge can dissuade potential investors from planting trees and frustrate efforts to develop sound management plans. Because species that are grown outside their native range typically exhibit growth and developmental patterns that differ significantly from those of the species within its native range, it would be risky to extrapolate growth predictions from other geographic areas, such as the ponderosa pine forests of Western United States (Zobel et al. 1987). To ameliorate these problems CIEFAP, the University of Comahue Forest Technical School, and the government of Neuquén have started quantitative silvicultural studies on ponderosa pine plantations throughout Neuquén province, covering an area that includes about 80% of the present plantation forests of this species in Patagonia (Figure I.1). These studies constitute the Neuquén Ponderosa Pine Site Quality and Yield (NPPSQY) project.

THESIS OBJECTIVE

The overall objective of this thesis is to build yield equations for the ponderosa pine forests of Neuquén province, enabling prediction of total volume production. In order to accomplish this objective, several supporting studies were also conducted. These included the development of height-diameter and volume equations, as well as two systems of site quality determination based on the growth intercept method and needle length.

LITERATURE AVAILABLE

Information on the yield and growth of ponderosa pine in Patagonia is limited and only a few papers have been published. Fortunately, this situation is changing rapidly and researchers from different Patagonian institutions are completing numerous studies that will soon provide knowledge of the growing habits of this exotic conifer. However, information on plantations older than 25 years is scarce, since only a very few and small stands (usually 1/2 ha) have reached that age.

Ponderosa pine plantations in Patagonia are distributed throughout a long latitudinal range of about 1000 km (Figure I.1). Thus, most research studies involve either the northern or the southern range of these forests. This thesis deals with the plantations located in Neuquén province in the northern range of the species (Figure I.1). For this range, Colmet Daage (1989) and Ferrer et al. (1990) presented classification systems to determine the capacity of large areas to grow ponderosa pine trees based mainly on soil characteristics. Girarden and Broquen (1995) studied height and volume growth in plantations from 2 to 16 years of age on three transects running east-west in northern, central, and southern Neuquén. They defined site quality based on the dominant height of the stands at age 14, and looked at the relationships between growth and soil types.

More literature on site quality determination and height growth is available for the southern range of the ponderosa pine plantations located in the provinces of Río Negro and Chubut (Figure I.1). Mendía and Irisarri (1986) presented a classification system to determine the capacity of large areas to grow ponderosa pine trees based on soil characteristics. Andenmatten and Letourneau (1996b) developed a site index equation to predict top height up to age 35 from age at breast height based on the stem analysis of 57 trees collected in 22 plots. They also examined the ability of different growth intercepts to predict site index on data collected from 22 dominant trees (Andenmatten and Letourneau 1996a). Andenmatten and others (1995) developed outside bark volume functions. Letourneau (1996) fitted stem profile equations to predict outside bark diameter. Andenmatten and Letourneau (1996c) demonstrated that stand volume can be computed reasonably well when it is based on height-diameter data collected from only the three largest and the three smallest trees per plot.

THE USEFULNESS OF FOREIGN LITERATURE

Yield Comparisons

In the Western United States where ponderosa pine is a native species, abundant literature exists concerning its yield and growth up to advanced ages. This information provided useful references for designing our studies, and made it possible to compare the productivity of the species in both countries.

Main References

In the Western United States, most height(H)-diameter(D) functions have been fitted to older stands, and thus they cover a wide range of Ds and Hs (e.g. Dolph et al. 1995, Larsen and Hann 1987, Moore et al. 1996). However, Wang and Hann (1988) developed H-D equations for young ponderosa pine trees in Oregon's Central Willamette Valley. These smaller trees were similar in size to those in Neuquén province.

In United States most ponderosa pine volume equations were also fitted to larger trees than those growing in Patagonia (e.g. MacLean & Berger 1976, and Walters et al. 1985). But two functions developed for younger stands (Chapman et al. 1982, Oliver and Powers 1978) allowed us to make more meaningful comparisons with the Neuquén functions.

In Neuquén most ponderosa pine plantations are still young, so we considered that the growth intercept method was a more appropriate approach to determining site quality than the traditional site index (SI) method, as has been demonstrated for several tree species (e.g. Alban 1979, Beck 1971, Day et al. 1960, Ferree et al. 1958, Wakeley and Marrero 1958, Warrack and Fraser 1955). Oliver (1972) demonstrated that growth intercept can accurately estimate SI in young ponderosa pine plantations and natural stands in northern California.

Literature about the use of needle length as a site quality indicator was the most scarce. However, a few papers that discuss the capacity of tree needles to reflect the application of different treatments provided some basis for our study (Tappeiner et al. 1987, Harrington and Tappeiner 1991, Fritts et al. 1965, McDonald et al. 1992, MacDonald and Fiddler 1990).

Several models have been developed for ponderosa pine growing in different regions of the western United States, such as the Forest Vegetation Simulator (FVS) (formerly PROGNOSIS) (Wykoff et al. 1982), CACTOS (Wensel et al. 1986), and ORGANON (Hann et al. 1993). However, we considered the yield functions developed by Oliver and Powers (1978) as the most useful because they were based on data collected from young plantations growing on high quality sites.

THESIS CONTENT

The thesis contains an introduction, five technical chapters, and a comprehensive discussion (Table I.1). The results from Chapter II make it possible to estimate the height of the sample trees whose heights were not measured. Results from Chapter III provide an equation to compute the volume of each sample tree. The H-D relationship, as well as the volume equations, will be useful tools for Neuquén foresters. Chapter IV provides a method to determine site quality based on the growth intercept concept. Chapter V explores the potential of needle length as site quality indicator. Chapter VI presents whole-stand yield equations to predict the volume of the ponderosa pine plantations in Neuquén.

The results from this thesis will provide Neuquén foresters with simple models that can accurately predict the current yield of the ponderosa pine plantations in the Province. Up to the current ages of existing plantations, these models are expected to produce an important part of the information needed to develop sound management plans, and to allow potential investors to forecast the productivity of different sites.

Table I.1. Topics of the seven chapters of the thesis.

Chapter	Content
I	Introduction
II	Stand level height-diameter equations
III	Tree volume equations
IV	A growth intercept index
V	Needle length as site quality predictor
VI	Variable density yield equations
VII	Summary and synthesis

A group of INTA researches led by Ernesto Andenmatten, has been carrying out yield and site quality studies in the ponderosa pine plantations of Río Negro and Chubut provinces, the southern range of the ponderosa pine plantations. Thus, this thesis and their studies complement each other by providing models to predict the productivity of ponderosa pine along the whole range. The differences in methodology will be resolved over time in order to make both approaches compatible.

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II. STAND-LEVEL HEIGHT-DIAMETER EQUATIONS FOR YOUNG PONDEROSA PINE PLANTATIONS IN NEUQUÉN, PATAGONIA, ARGENTINA. A COMPARISON WITH EQUATIONS DEVELOPED IN THE WESTERN UNITED STATES

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and Steven D. Tesch

ABSTRACT

Two linear and two nonlinear height-diameter models commonly used in the Western United States were tested for the young ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) plantations of northern Patagonia, where it is the most widely planted species. The equations were fitted to each of 127 plots, scattered throughout the whole range of the species in Neuquén province. The four equations were compared using Furnival's (1961) index of fit. Even though there were no important differences among models tested, the nonlinear model previously applied by Wykoff et al. (1982), $H = 1.3 + e^{(\beta 0 + (\beta 1 / (D + 1)))} + \varepsilon$ was preferable because it converged more efficiently than the other nonlinear equation and was more flexible than the linear functions. Differences in the behavior of plot-level and region-wide equations demonstrated the biases possible if region-wide equations are applied to estimate missing heights within a plot.

INTRODUCTION

The Importance of Ponderosa Pine in Patagonia

Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) is the most widely planted species in the Patagonian Andes region of Argentina, where it grows vigorously and without any serious pest problems. Preliminary studies suggest that the average yield of these stands could be similar to or even higher than those growing on the more productive regions of the western United States (Gonda and Lomagno 1995, Urzúa 1991). The environmental conditions in northern Patagonia are similar to those where ponderosa pine (variety ponderosa) forests grow naturally in the western United States. The piedmont of the northern Patagonian Andes and the interior Pacific Northwest share the following main characteristics:

1. The latitudinal ranges are similar in the respective hemispheres (Figure II.1).
2. Moisture is provided by humid winds blowing from the Pacific Ocean.
3. A rain shadow effect is produced by the Andes as well as by the Cascades and the northern Sierra Nevada ranges.
4. A Mediterranean climate prevails, imposing a well-defined dry season.
5. A high proportion of the soils are of volcanic origin.

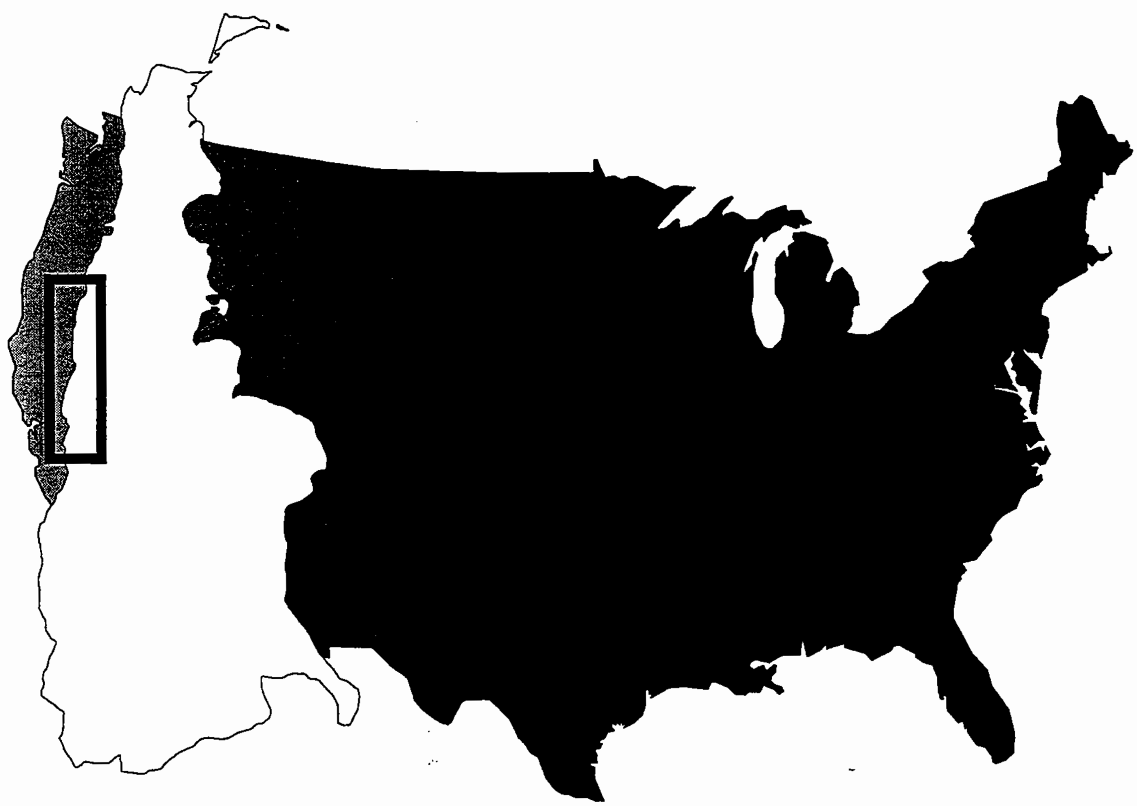

Figure II.1. A map superimposing the Patagonian Andes (Argentina) over the Cascades and northern Sierra Nevada (United States). The rectangle includes the current distribution area of the ponderosa pine plantations in Patagonia. The latitude of both countries match, and they are drawn at the same scale.

The area planted annually with ponderosa pine in Argentina is rapidly increasing due to the subsidies and credits that the Patagonian provinces and the federal government provide for planting fast-growing species. The primary objective of this support is to promote afforestation as a means to improve the socioeconomic conditions of the region. Currently there are about 30,000 hectares of ponderosa pine forests (Urzúa 1991), with about a million hectares of grasslands suitable for commercial afforestation throughout the piedmont of the Patagonian Andes (Enricci 1993).

Information on site quality and growth of ponderosa pine in Patagonia is scarce. This incomplete knowledge can dissuade potential investors from planting trees and frustrate efforts to develop sound management plans. Because species that are grown outside their native range typically exhibit growth and developmental patterns that differ significantly from those of the species within its native environment, it is also risky to extrapolate growth predictions to new geographic areas (Zobel et al. 1987).

To ameliorate these problems the Patagonian Andes Forest Research and Extension Center (CIEFAP), along with the University of Comahue Forest Technical School and the government of Neuquén, have started quantitative silvicultural studies on ponderosa pine plantations throughout Neuquén province, covering an area that includes about 80% of the present plantation forests of this species in Patagonia (Figure II.2). These studies constitute the Neuquén Ponderosa Pine Site Quality and Yield (NPPSQY) project.

Height-Diameter Equations

Several linear and non-linear height(H)-diameter(D) equations have been developed for ponderosa pine and other coniferous forests in the United States. Linear equations typically rely on logarithmic transformation of the response variable, H. Hence, they imply a different error structure that their non-linear counterparts.

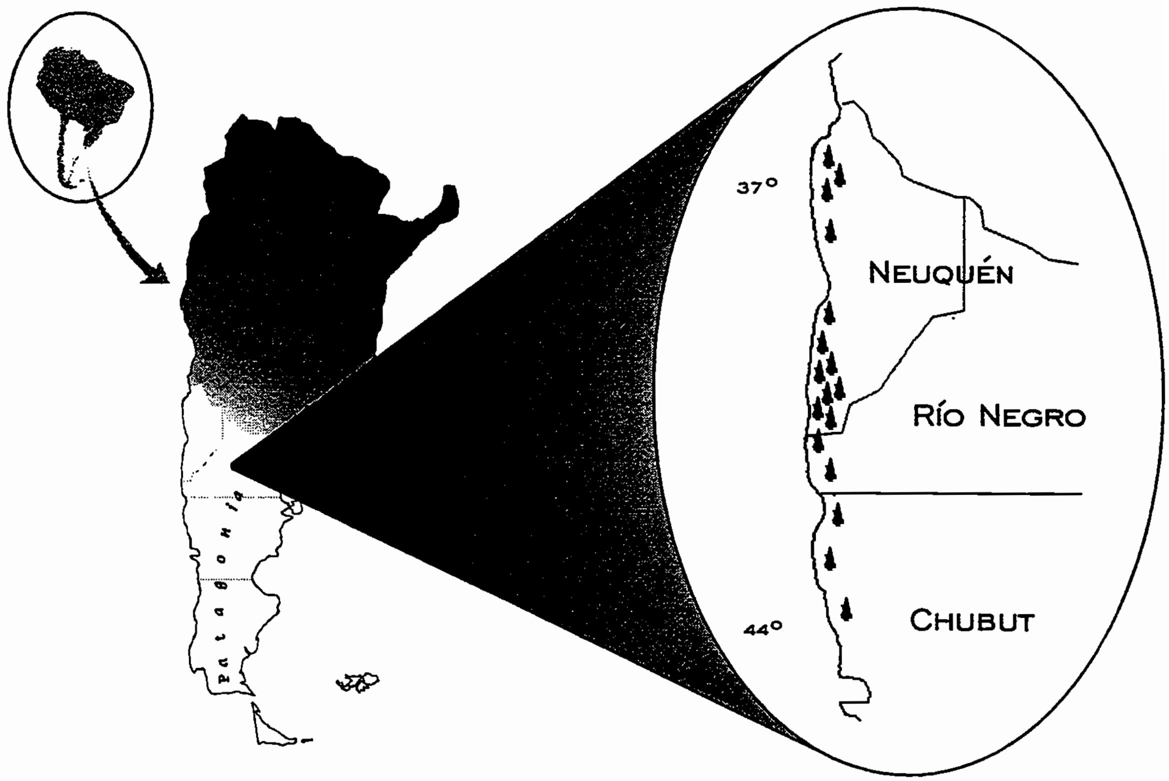

Figure II.2. From left to right: maps showing the position of Argentina in South America, Patagonia within Argentina, and the current distribution of the ponderosa pine plantations in the provinces of Neuquén, Río Negro, and Chubut. The number of pine trees is proportional to the plantation area.

Linear Equations

Linear models are more familiar to most foresters (Curtis 1967), can be fit with almost any statistical package or spreadsheet program, and are much easier to fit if data sets are small and do not represent the range of the D distribution. On the other hand, when linear models contain a logarithmically transformed response variable, they introduce some log bias that should be corrected (Baskerville 1972, Dolph et al. 1995, Payandeh 1981). Yet, this correction theoretically cannot be performed if the residuals are not normally distributed (Baskerville 1972, Bell et al 1981), and the choice of alternative correction factors is not always easy (Flewelling and Pienaar 1981).

Height-diameter curves should pass through the origin and have a positive slope that approaches zero as D becomes large (Curtis 1967). The sample available as the basis for the height-diameter curves is often quite limited, thus the equation selected should produce a reasonable relationship when data are inadequate to fully define the shape of the curve.

Among the most widely used linear equations, the following two are simple and yet give reasonable results when complying with the conditions above (Curtis 1967):

$$\log(H-1.3) = \beta_0 + \beta_1 \log D + \varepsilon \qquad \text{[Equation 1]}$$

$$\log(H-1.3) = \beta_0 + \beta_1 D^c + \varepsilon \qquad \text{[Equation 2]}$$

Equation 1 does not possess an inflection, but it works well for young stands (Curtis 1967). In equation 2, the 'c' parameter can be -1 for older plantations, but other values may give better results for younger plantations (Curtis 1967). Logically, constraining the height-diameter curve to pass through (0, 1.3) by specifying log(H-1.3) as the dependent variable, is especially important when measurements include very young trees (Curtis 1967), as it is the case in this study. When dealing with older trees forcing the origin is of almost no practical importance (Curtis 1967).

Nonlinear Equations

Many nonlinear equations have been used to explain height-diameter relationships of the commercial tree species of North America (e.g. Huang et al. 1992, Zhang et al. 1995), but two of them are preferred for ponderosa pine and other conifers in the Pacific Northwest. The first one is used in the Forest Vegetation Simulator (FVS) (formerly Stand Prognosis Model), a growth and yield model that is widely applied in the Inland Northwest (Wykoff et al. 1982):

$$H = 1.3 + \exp(\beta_0 + (\beta_1 / (D + 1))) + \varepsilon \qquad \text{[Equation 3]}$$

The second one showed good prediction performance when compared with other nonlinear equations (Zeide 1989, Zhang et al. 1995):

$$H = 1.3 + \beta_0 * \exp(\beta_1 * D^{\beta_2}) + \varepsilon \qquad \text{[Equation 4]}$$

On the western side of the Cascades, Wang and Hann (1988) and Larsen and Hann (1987), fitted equation 4 to ponderosa pine and other tree species in the Central Willamette Valley and in the mix-conifer zone of southwest Oregon respectively.

In northeastern California, Dolph et al. (1995) fitted equations 3 and 4 to several conifers on the Forest Service Blacks Mountain Experimental Forest. Ponderosa and Jeffrey pines were combined for growth and yield modeling purposes because they grow at about the same rate and have similar form (Hallin 1957). Equation 4 gave the best result since it had the smallest residual mean square for each species. Both equations had to be weighted since the variance increased with increasing values of D.

Moore et al (1996) fitted equations 3 and 4 to data from ponderosa pine forests covering a wide range of site productivities throughout northern Idaho, western Montana, northeastern Oregon, and eastern Washington. The two equations fit equally well and unequal error variances were not found. The main result was that either equation could be used for trees less than 50 cm in D since the models predicted virtually identical tree heights.

The main advantage of the nonlinear models is that their flexibility allows biologically reasonable shapes (Huang et al. 1992). This feature is highly desirable since users often extrapolate them (Vanclay 1994). Also, they do not require any log bias correction like the widely used logarithmic linear models, although nonlinear height-diameter curves often need to be weighted in order to correct for departures from homoscedasticity.

Regional vs. Stand Level Height-Diameter Equations

Curtis (1967) stated that when computing the volume and periodic increment on permanent plots, fitting the same H-D equation to all the remeasurement data for that plot will provide a more accurate and consistent estimate of H than can be obtained by fitting separate H-D equations to the data of each individual measurement.

In contrast, we hypothesize that region-wide H-D equations tend to present a biased stand structure at the plot level because the instantaneous slope of the curve would typically be shallower for plot-level curves (Figure II.3). The height-diameter relationship has a tendency to differ among sites, stand densities, ages and other factors; hence allowing the relationship to vary by stand (or plot) and growth period may yield more accurate results.

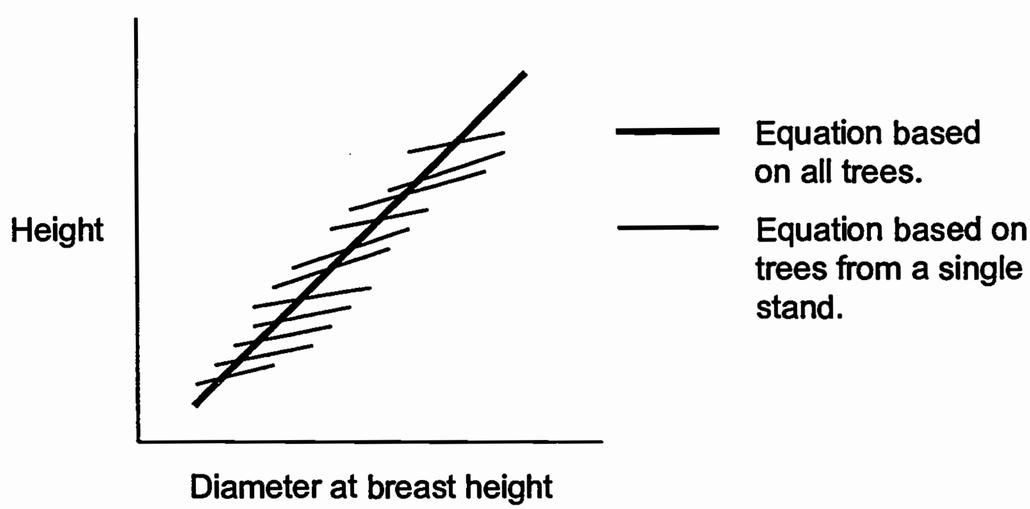

Figure II.3. Diagram depicting the theoretical differences in slope of an equation based on data pooled over a wide range of stand conditions and equations built with data from each individual stand.

Objectives

The first objective of this paper is to identify height-diameter equations capable of accurately describing plot-level height-diameter relationships for ponderosa pine plantations in Neuquén Province, Patagonia. These models will make it possible to estimate the height of trees when this parameter is missing. The selected equations will be used to develop the volume and yield equations for Neuquén province, and will represent a useful tool for Neuquén foresters.

The second objective is to compare the preferred equations with similar functions developed for ponderosa pine forests in the Western United States.

METHODS

Data Source

The height-diameter data utilized in the study were collected from 5263 trees located in 127 stands scattered throughout the current range of the ponderosa pine plantations in Neuquén province. The eight southernmost plots were located in Río Negro province, only a few kilometers from the Neuquén border; no ponderosa pine plantations were located in Neuquén province at those latitudes (Figure II.4). One plot was randomly located in each stand. All 127 plots were circular, but had different area in order to include at least 40 trees.

The sampled stands covered most of the age and number of trees/ha ranges, as well as the geographic distribution, of the ponderosa pine plantations in Neuquén province. Thus, sampled plots included the entire range of main factors that can be associated with tree growth and form, i.e. latitude, longitude, elevation, slope, aspect, precipitation, soil depth, age, and density (Table II.1).

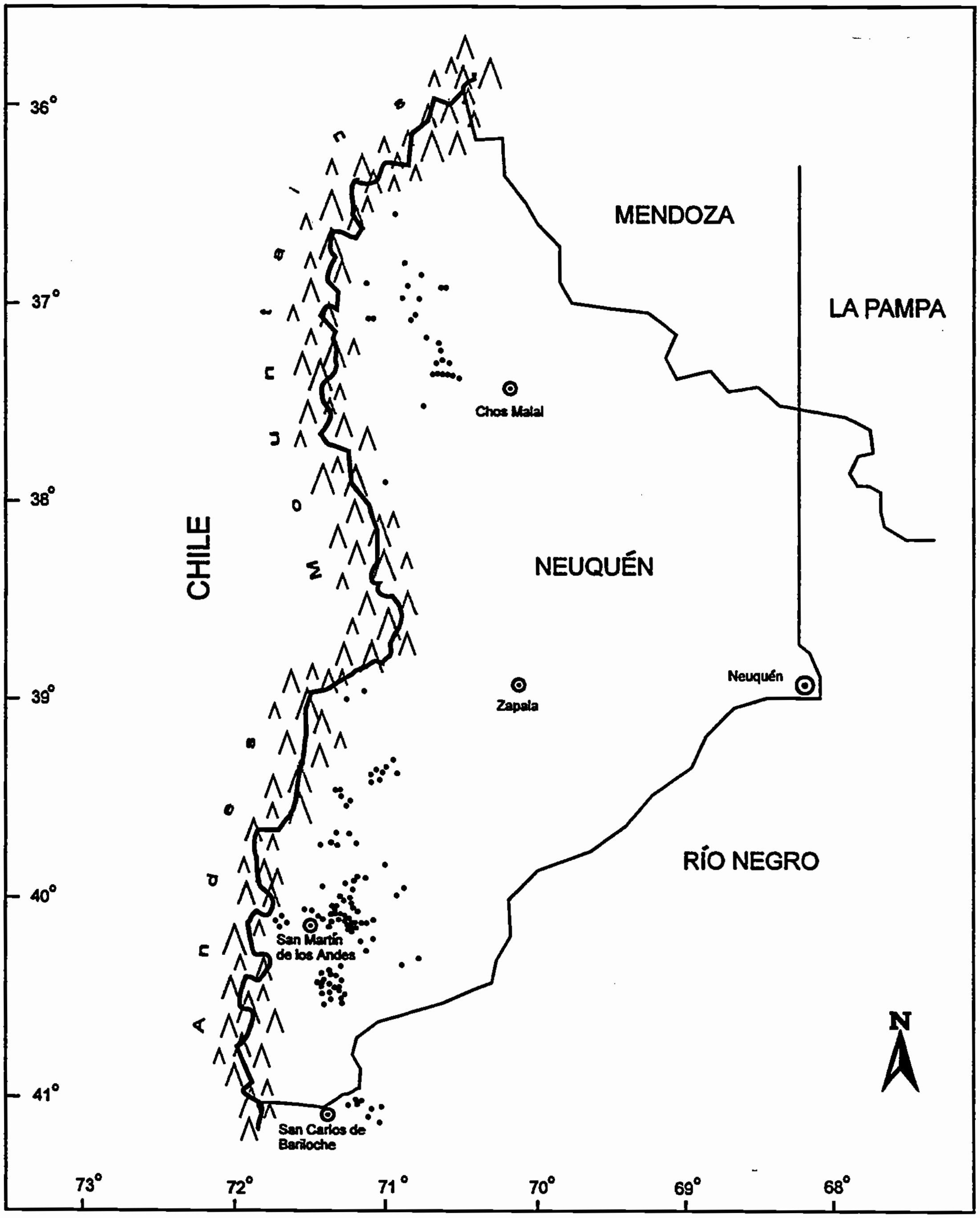

Figure II.4. Location of the 127 plots where the height-diameter data were collected in Neuquén province.

Table II.1. Minimum (min), maximum (max), and mean values of latitude, longitude, elevation (elev), slope, aspect, annual precipitation (precip), soil depth (soil d), age, and density (tr/ha) ranges of the 127 plots sampled throughout Neuquén province.

	Latitude	Longitude	Elev (m)	Slope (degr)	Aspect (degr)	Precip (mm/yr)	Soil D (m)	Age	Tr/ha
Min	36°30'00"	70°35'22"	650	0	0	400	0.4	10	307
Mean	38°47'58"	71°04'18"	1059	8.6	140	929	1.0	17	1314
Max	41°05'57"	71°33'15"	1715	30.0	350	2229	1.8	41	2500

Sampling Procedures

Choice of the best model form for describing height-diameter relationships is typically clouded by sampling error associated with selection of a subsample of trees within a plot to be measured for both diameter at breast height and total height, as used for fitting a relationship. This data set largely eliminates uncertainties due to within-plot sampling error, because in 83 of the plots D and H were taken on all trees; hence the total population within the plots was measured. In the other 44 plots, the Ds of all trees were recorded but, due to time constraints, the Hs of only 2/3 of the individuals were measured for the site classification and yield studies. This procedure resulted in at least 25 trees being measured for H from each plot, with three exceptions: in one plot H was measured on 16 individuals, and in two others on 19 trees. In order to sample the whole range of Hs in each plot, Hs were measured on trees from all diameter classes, paying special attention to include the tallest and shortest individuals.

The vast majority of the 5263 sample trees were healthy and undamaged. Only 55 individuals, scattered among 30 plots, were forked below 6 meters, bent, or had broken tops. None of these 30 plots contained more than 3 "abnormal" trees, except for one plot that had 6 individuals bent by the snow. The 55 abnormal trees were included in the analysis and their impact on the tested equations was evaluated.

One of the plots contained 43 ponderosa pine and 10 Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) trees. The Jeffrey pines were retained because the proportion of the latter species was low, and because these pines exhibit similar growth characteristics (Hallin 1957).

Some of the sample trees had been pruned, but it was assumed not to affect tree shape since the standard pruning procedure consists of eliminating no more than 1/3 to 1/2 of the live crown, and most stands had been pruned recently.

The H of trees less than 12 meters tall was measured directly with a telescopic fiberglass pole to the nearest cm. Taller trees were measured indirectly with clinometer (either *Blume-Leiss* or *Suunto*) to the nearest 5 cm. The D was measured to the nearest 0.1 cm with diameter tape at 1.3 m from the ground.

Data Analysis

The four most widely used H-D equations presented in the Introduction were fitted separately to data from each of the 127 plots. For equation 2 the power "c" was allowed to vary between -4 and 2, and the model with the lowest mean square error was selected for each plot. The most frequent "c" values varied between -1 and 1, most of them being negative. The four equations were compared using Fumival's (1961) index of fit. This index has the advantage of reflecting both the size of the residuals and possible departures from linearity, normality, and homoscedasticity (Fumival 1961).

The coefficients of the 30 plots that contained bent, forked, or broken top trees were recalculated without including the affected individuals, in order to determine whether those trees produced a significant effect on the preferred model. Equations 3 and 4 were also fitted to the whole data set containing the height-diameter data in English units in order to compare the coefficients of these two equations with the ones fitted by Dolph et al. (1995), Larsen and Hann (1987), Moore at al. (1996) and Wang and Hann (1988) in the Western United States.

RESULTS AND DISCUSSION

Characteristics of the Sample Trees

In Neuquén most plantations are less than 25 years of age, so the ranges of D and H were typical of young stands (Figure II.5) and hence much smaller than the ranges used to fit H-D equations for ponderosa pine stands in the western United States (e.g. Dolph et al. 1995, Larsen and Hann 1987, Moore et al. 1996, and Wang and Hann 1988) (Table II.2).

The 5263 sample trees used in this study constituted a large sample size when compared with the number of trees used to build similar functions for ponderosa pine in the western United States; Dolph et al. (1995), Larsen and Hann (1987), Moore et al. (1996), and Wang and Hann (1988), used 2844, 1327, 1856, and 61 trees respectively.

Height-Diameter Equations

No important differences were observed among the four equations tested in terms of their indices of fit, when either comparing them for each stand (Appendix), or when comparing means from all stands (Table II.3).

Equation 3 was easy to fit since it converged for all stands using the same initial coefficients. On the other hand, equation 4 was rather time consuming to fit since at least 5 or 6 different sets of initial coefficients per plot often had to be entered before the model converged. Even so, this equation never did converge for three plots (41, 83, and 123).

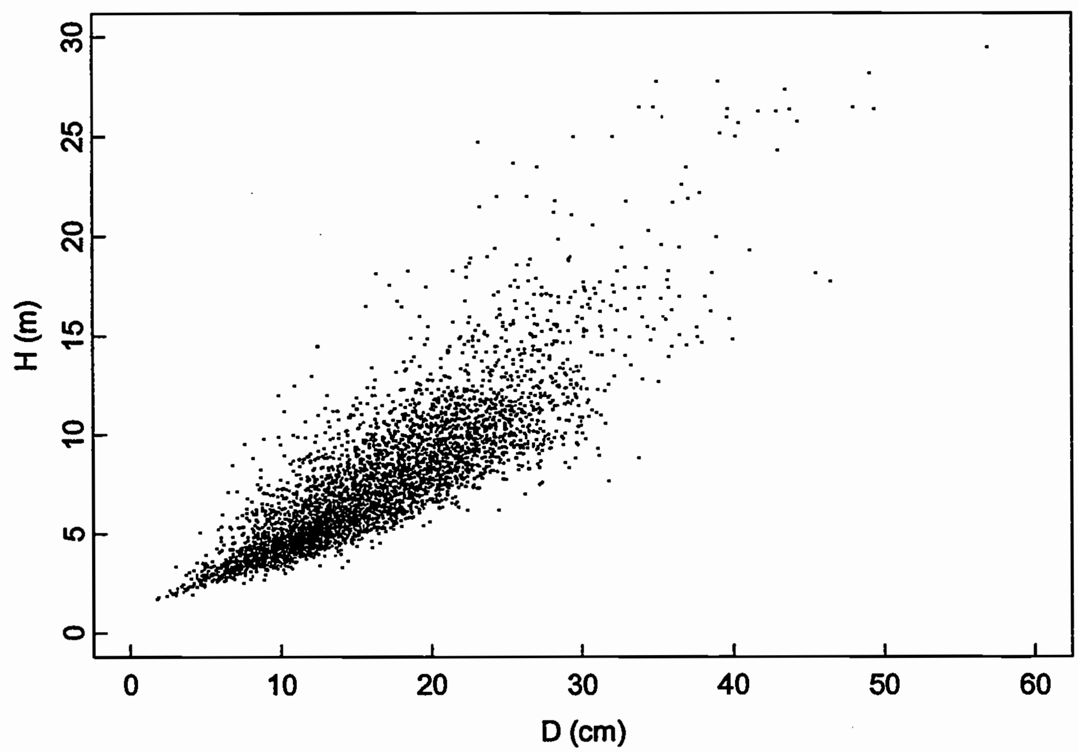

Figure II.5. Total tree height (H) plotted over diameter outside bark at breast height (D) for the 5263 trees measured to develop plot level height-diameter functions for unthinned ponderosa pine plantations in Neuquén province.

Table II.2. Ranges of total height (H) and diameter at breast height (D) of the sample trees measured for the present study and four others carried out for ponderosa pine in the Western United States by Dolph et al. (1995), Larsen and Hann (1987), Moore et al. (1996), and Wang and Hann (1988).

	Neuquén			Inland Northwest , USA						Western Oregon, USA					
	Gonda et al.			Dolph et al.			Moore et al.			Larsen & Hann			Wang & Hann		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
D (cm)	1.8	15.7	56.9	9.1	36.1	136.4	0.5	44.2	222.0	0.2	34.8	135.1	2.3	31.2	50.5
H (m)	1.7	7.2	29.5	2.7	17.4	44.8	1.5	24.4	59.4	1.4	22.0	58.6	2.7	17.3	25.5

Table II.3. Mean, minimum, and maximum Furnival index values for each equation.

Equation	Furnival's index of fit Mean	Minimum	Maximum
1	0.65	0.17	2.01
2	0.62	0.16	1.60
3	0.64	0.16	1.74
4	0.63	0.16	1.83

The fitting of equation 3 resulted in unequal variances in only 10 plots. The initial coefficients that we used for the 127 stands were: $\beta_0 = 2$, $\beta_1 = -3$. Final coefficients did not result in a very wide range in values (Table II.4).

Table II.4. Mean, minimum and maximum values of the converging coefficients of equation 3 for the 127 plots.

Coefficient	Mean	Minimum	Maximum
β_0	2.47223	1.63331	3.52815
β_1	-11.81193	-19.86992	-3.80778

Equation 3 behaved well when the respective regression line was drawn over the H-D scatterplot of each plot, even in the plot with the largest D range (Figure II.6) and in the plot with the smallest number of trees (Figure II.7).

The coefficients of equation 3 associated with the 30 plots that contained forked, bent, or broken top trees showed negligible changes when the function was refitted without the abnormal individuals.

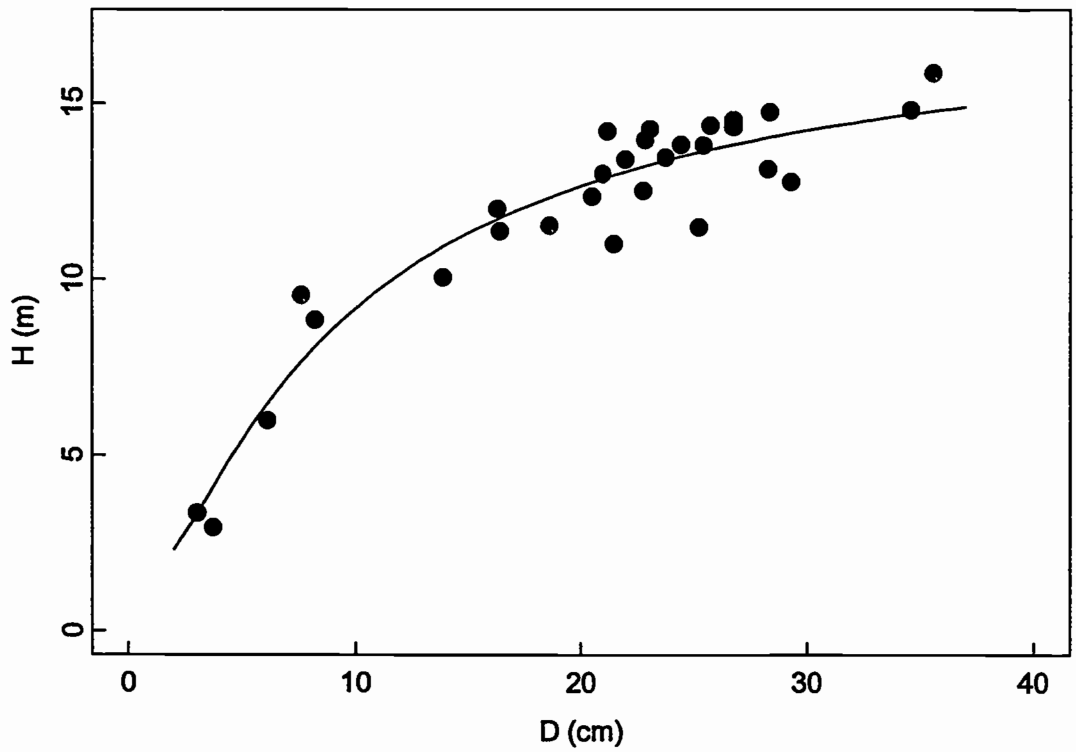

Figure II.6. Height (H)-diameter at breast height (D) data and regression line based on equation 3 for the plot with the largest D range.

When fitted to the whole data set using English units, equations 3 and 4 exhibited unequal error variances. Weights of 1/D, $1/D^2$, $1/D^3$, $1/D^4$, and 1 (un-weighted) were tested. Furnival's index of fit indicated that $1/D^2$ provided the best weight for both equations (Table II.5).

Selected Model

Overall, equation 3 was judged the preferable model since it converged much more efficiently than function 4. Function 4 is non-asymptotic (Garman et al. 1995) and thus may present extrapolation problems for trees whose Ds exceed the D range for the modeling data set, primarily in cases where the equation will be applied to forests with old-growth individuals (Garman et al. 1995). This is not the case in industrial plantations such as the ponderosa pine forests of Neuquén,

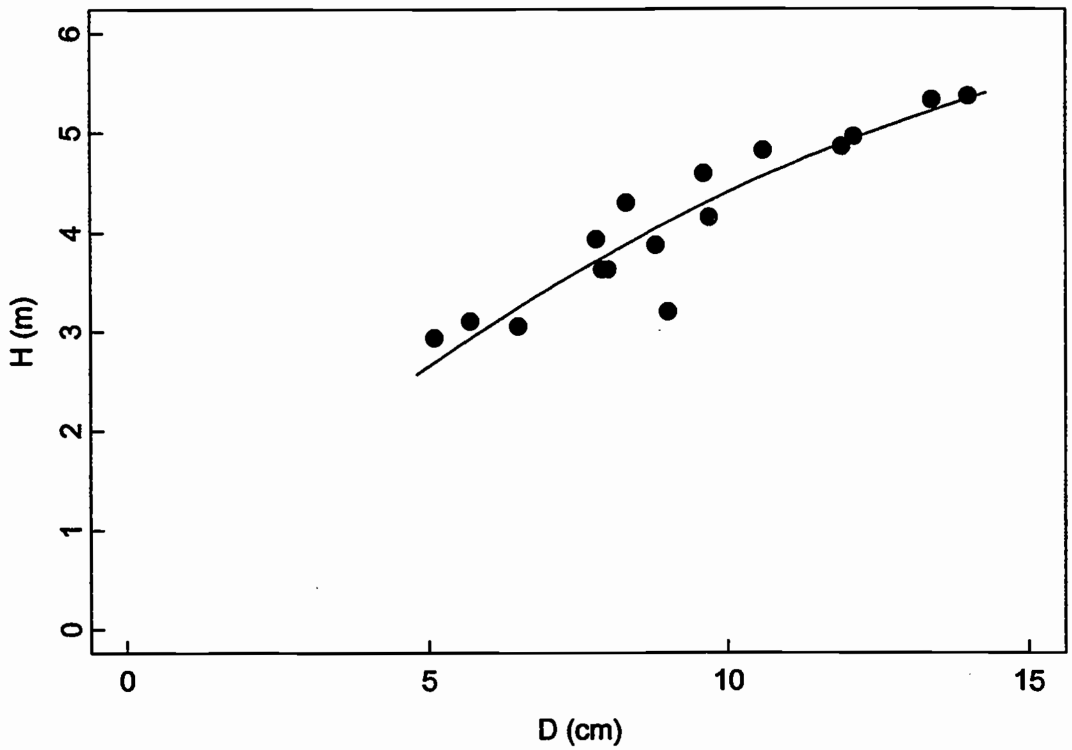

Figure II.7. Height (H)-diameter at breast height (D) data and regression line based on equation 3 for the plot with the smallest number of trees (16).

Table II.5. Parameters and selected weights for equations 3 and 4 fitted to the whole data set using English units.

Equation 3			Equation 4			
β_0	β_1	weight	β_0	β_1	β_2	weight
4.3437	-9 .3981	$1/D^2$	.0159	5.1987	.1689	$1/D^2$

where the mean D would seldom be allowed to exceed 50 cm, the upper diameter of our data set.

Equations 1 and 2 have to be adjusted for bias associated with logarithmic transformation of the response variable. This represents extra work and performing any one of several possible corrections will not necessarily eliminate all bias (Bell et al. 1981, Flewelling and Pienaar 1981). However, for foresters who do not have access to statistical packages with nonlinear estimation capabilities, models 1 or 2 can produce satisfactory results. Equation 2 is preferable for this data set because it tends to have slightly lower maximum Furnival index values (Appendix 1).

In most plots the D range of the trees was narrow because sample stands were young. Hence, H was basically directly proportional to D and a straight or a slightly curved line would have produced a good fit (Figure II.7). Nevertheless, the temptation to apply a quadratic model was and should almost always be avoided because it would not behave well in plots with wider D ranges where higher flexibility is required (Figure II.6). Extrapolation of quadratic functions also tends to lead to unrealistic height predictions (Huang et al. 1992).

The most effective application of these height-diameter equations is achieved by computing parameter estimates with height-diameter data from the stand where the models will be applied. In the case of equation 3, the coefficients given above can be helpful as the initial estimates. The height-diameter data should be collected throughout the whole range of stand Ds, making sure to sample the smallest and largest trees, in order to estimate the parameters of the equation most accurately (Figures II.6, II.7). The minimum number of sample trees required for an accurate estimation of the equation coefficients will depend on the variability of H.

For the southern range of the ponderosa pine plantations in Patagonia (Río Negro and Chubut provinces) (Figure II.2), the coefficients of the equation $H = \beta_0 + \beta_1 \log D$, may be properly estimated by fitting the model to as few as 12 or even four trees per stand (Andenmatten and Letourneau 1996). These individuals should be sampled across the whole range of Ds, including the tallest and shortest trees.

Individual Versus All Stand Analysis

A plot showing the regression lines for individual plots and the regression line for all plots pooled (comprehensive line) clearly shows that the slope of the latter equation is steeper, and a lack of fit at small Ds suggests that this function may be insufficiently flexible for region-wide curves (Figure II.8). The differences in slope tend to be larger for stands with trees of small D. The coefficients of the comprehensive line are more extreme than the ones of the individual stands (Table II.6). Hence, significant estimation errors would have resulted if the data were pooled to fit one region-wide equation, especially since most of the stands have young small trees (Figure II.8).

Table II.6. Coefficients for equation 3 fitted to pooled data and individual stand data.

Coefficients	Pooled data	Individual stand data		
		Mean	Minimum	Maximum
β_0	2.88839	2.47223	1.63331	3.52815
β_1	-17.90739	-11.81193	-19.86992	-3.80778

In the western United States, some of the published height-diameter functions for ponderosa pine that are based on pooled regional data do not include explanatory variables to account for site and basal area differences. Therefore, the potential exists to produce estimates of tree H that are biased on a stand level when such regional curves are used to estimate missing heights on individual stands, if the coefficients are not recalculated with local height-diameter data. For the northern Patagonia data set, the smaller the trees, the stronger the bias (Figure II.8).

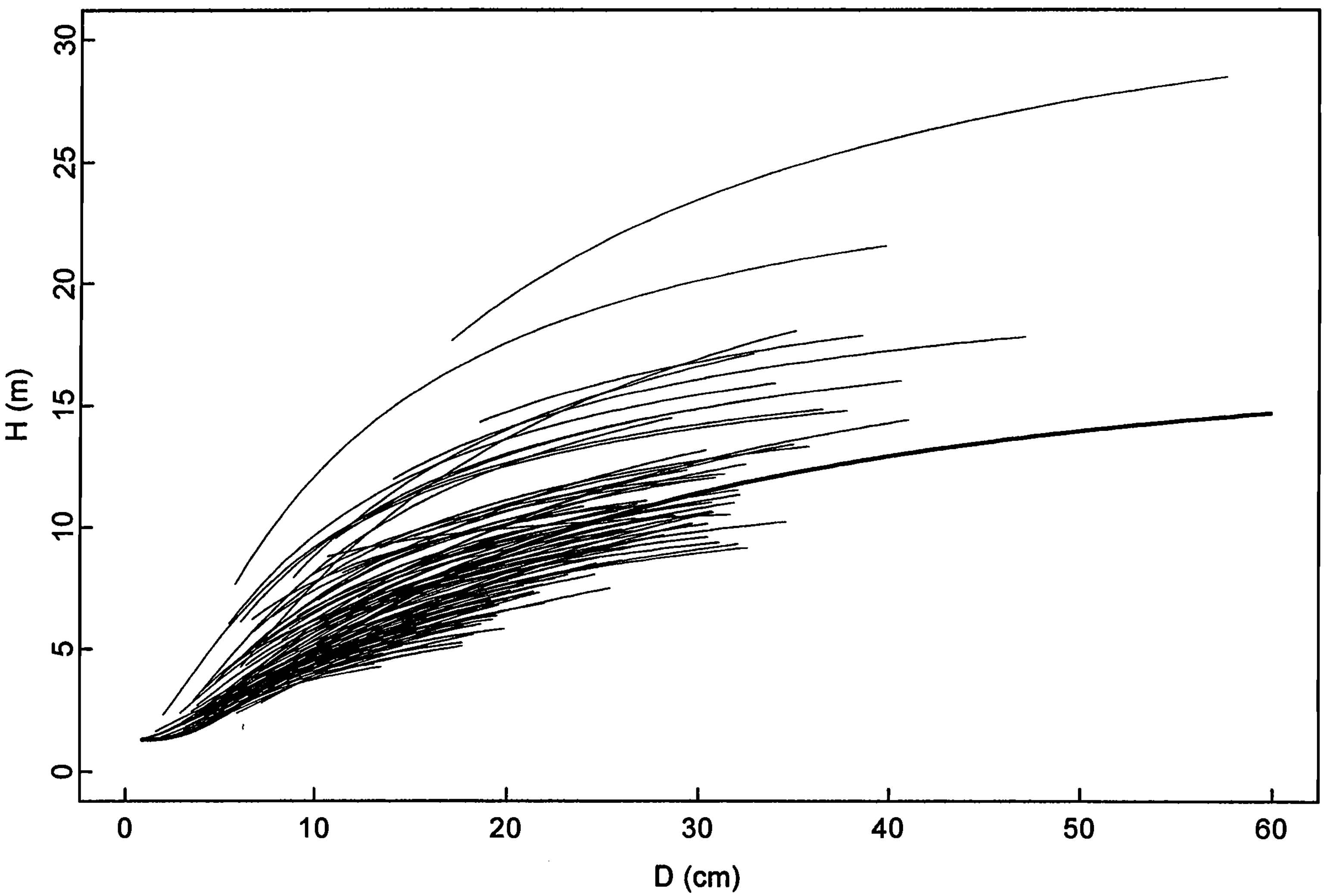

Figure II.8. Regression lines for equation 3 fitted to height(H)-diameter at breast height(D) data from individual plots (thin lines) and a regression line for the same equation fitted to the whole H-D data set (thick line).

Regional Nonlinear Functions in the Western United States

Applying H-D equations to data pooled from different stands proved not to be an appropriate procedure for the ponderosa pine plantations in Neuquén (Figure II.8). Nevertheless, both nonlinear models (equations 3 and 4) were fitted to the whole data set, with the sole purpose of comparing their parameters with those based on ponderosa pine data from the western United States.

The parameters that Moore and others (1996) estimated by fitting equation 3 to ponderosa pine trees in northeastern California were different from those we estimated for Neuquén data (Table II.7). Their taller H predictions are the result of a much wider range of data that includes larger trees (Table II.2), since the shape of the curves is almost the same (Figure II.9).

Table II.7. Coefficients and selected weights of equations 3 and 4 when fitted to ponderosa pine data in English units in northern Patagonia (Gonda et al. 1997), northeastern California (Dolph et al. 1995), southwest Oregon (Larsen and Hann 1987), eastern Washington and Oregon (Moore et al. 1996), and the Willamette Valley (Wang and Hann 1988).

	Equation 3			Equation 4			
	β_0	β_1	weight	β_0	β_1	β_2	weight
Gonda et al.	4.3437	- 9.3981	$1/D^2$	.0159	5.1987	.1689	$1/D^2$
Moore et al.	5.1094	-11.9354	1	1769.17 * *	-5.7742	-.2197	1
Dolph et al.	----	----	----	666.8066	-6.1361	-.3410	1/D
Larsen & Hann	----	----	----	3591.9841	-6.6532	-.2035	1/D
Wang & Hann	----	----	----	446.6744	-4.4854	-.3000	1/D

* = Decimal place not reported by the authors.

The coefficients for equation 4 fitted to ponderosa pine trees in southwest Oregon (Larsen and Hann 1987), and northern Idaho, eastern Oregon and Washington (Moore et al. 1996) overestimate the H of Neuquén trees (Table II.7, Figure II.10). Coefficients of the same equation fitted to the same species in the

Willamette Valley (Wang and Hann 1988) and northeastern California (Dolph et al. 1995) overestimate the H of Neuquén trees with a D below 6 cm, and underestimate the H of trees with larger D (Table II.7, Figure II.10). These differences in the coefficients for equation 4 can be caused by numerous factors such as size of the sample trees, site quality, stand density, etc., and confirm that height-diameter equations, especially those with only one-parameter, should not be extrapolated to different regions.

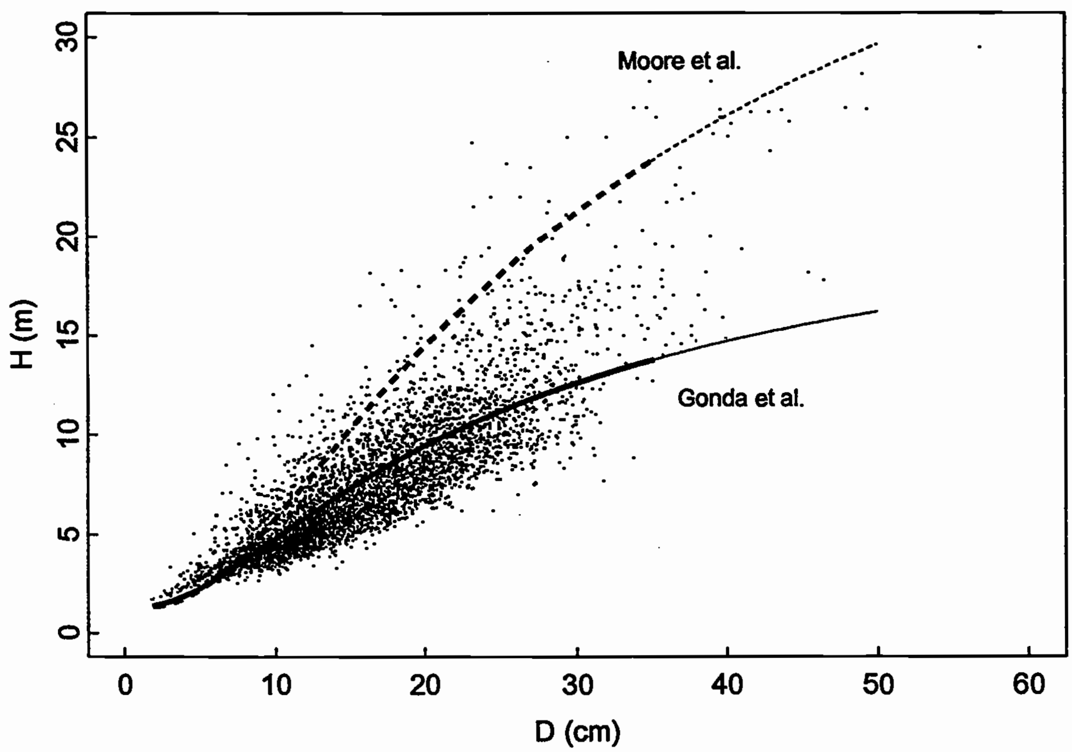

Figure II.9. Neuquén height (H)-diameter at breast height (D) data, and two regression lines based on equation 3: one fitted to Neuquén pooled data (Gonda et al. 1997) and the other one fitted to regional ponderosa pine data in northeastern California (Moore et al. 1996). The thicker portion of the lines correspond to the D range for which the model was more intensively tested. Moore and others (1996) fitted model 3 to a much wider range of Ds than this figure represents.

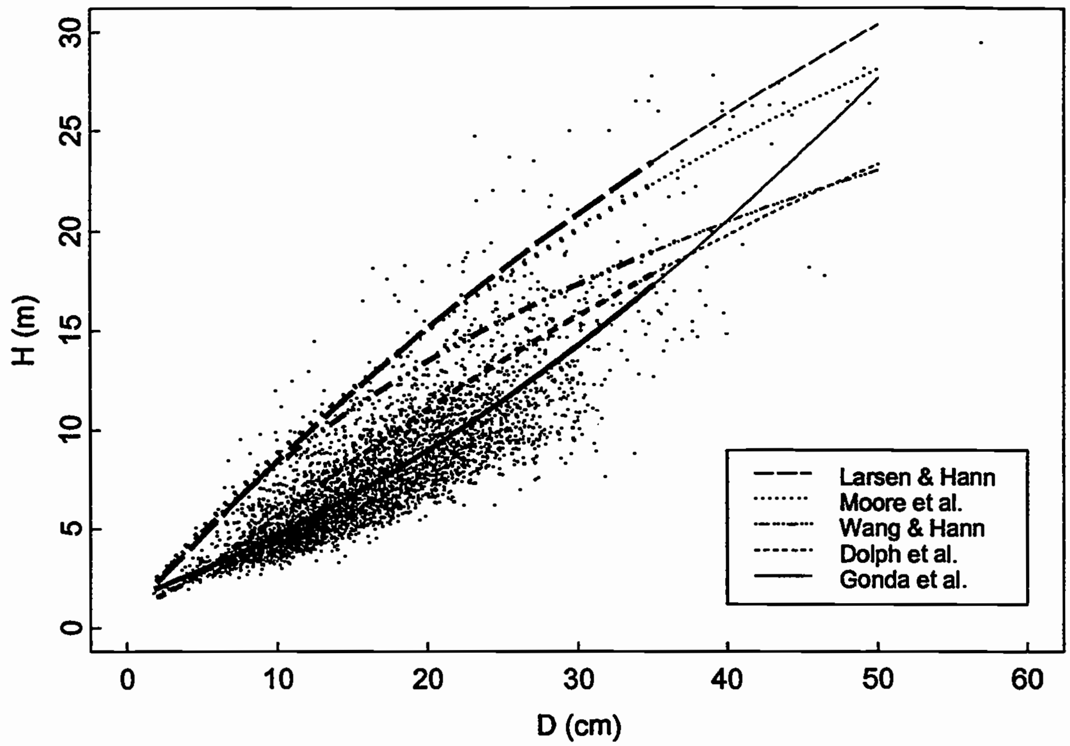

Figure II.10. Neuquén height (H)-diameter at breast height (D) data, and regression lines for equation 4 fitted to Neuquén pooled data (Gonda et al. 1997), northeastern California data (Dolph et al. 1995), northern Idaho, eastern Oregon and Washington data (Moore et al. 1996), southwest Oregon data (Larsen and Hann 1987), and Willamette Valley data (Wang and Hann 1988). The thicker portion of the lines correspond to the D range for which the model was more intensively tested. Except for Wang and Hann (1988), the other authors fitted model 4 to a much wider range of Ds than this figure represents.

If H-D equations based on pooled data were ever to be used in Neuquén, within the inferential range of our data set (2-50 cm), equation 4 would behave better than equation 3 because the latter model tends to underestimate the H of trees with larger Ds (Figures II.9 and II.10).

CONCLUSIONS

The nonlinear equation developed by Wykoff et al. (1982) (equation 3) is the recommended model form for fitting height-diameter equations in Neuquén ponderosa pine stands on which heights have been subsampled. It converged much more efficiently than the other nonlinear equation (equation 3), and it was more flexible than the two linear models tested (equations 1 and 2). The selected equation will accurately predict the H of trees when fitted to stands with Ds between 2 and 35 cm. In stands where the Ds of the largest trees are between 35 and 50 cm, H predictions should be still satisfactory as suggested by the few sample plots with the largest Ds. This research provides no information on how well the recommended model would perform in stands with tree Ds beyond 50 cm.

Because the sample trees were obtained throughout the current range of ponderosa pine plantations in Neuquén province, this province is the primary geographical region for application of the equation. Hence, the results are valid for stands within the same latitude, longitude, elevation, annual precipitation, soil depth, age, and density ranges, and with the same current health conditions. However, if a pest, heavy snow, or other agent ever significantly affects tree shape, the recommended models should be revised.

The recommended equation could be made "regional", that is applicable to any plot in Neuquén with the same coefficients, if tree form differences related to site, or site and density, are accounted for by including some explanatory variables in the equation, as it was demonstrated by Larsen and Hann (1987), Garman et al. (1995), and Wang and Hann (1988) in ponderosa pine forests of the Western United States. When the results from additional ongoing yield and site quality studies for the ponderosa pine plantations of Neuquén become available this will be a main topic for further research.

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APPENDIX

Furnival Index of fit for the Four Tested Models by Plot

Model 1: $\log(H-1.3) = \beta_0 + \beta_1 \log D + \varepsilon$
Model 2: $\log(H-1.3) = \beta_0 + \beta_1 D^c + \varepsilon$
Model 3: $H = 1.3 + \exp(\beta_0 + (\beta_1 / (D+1))) + \varepsilon$
Model 4: $H = 1.3 + \beta_0 * \exp(\beta_1 * D^{\beta_2}) + \varepsilon$

Where: H = total tree height
D = diameter at breast height
β_0, β_1, and β_2 = coefficients

C = exponent of Model 2

Plot	Model 1	Model 2	C	Model 3	Model 4
1	1.34	1.27	1.2	1.33	1.24
2	1.55	1.48	-4.0	1.36	0.89
3	0.45	0.44	-0.8	0.44	0.44
4	1.55	1.05	-1.2	1.09	1.07
5	0.87	0.79	-0.9	0.78	0.81
6	2.01	1.60	-3.5	1.74	1.83
7	1.45	1.42	0.7	1.36	1.26
8	0.37	0.37	-0.2	0.39	0.38
9	0.31	0.30	-1.2	0.31	0.30
10	0.76	0.74	-0.4	0.69	0.69
11	0.62	0.62	0.1	0.69	0.66
12	0.57	0.54	-1.5	0.51	0.50
13	1.89	1.28	-0.9	0.99	0.98
14	0.43	0.43	-0.1	0.45	0.45
15	1.11	0.99	-0.9	1.01	1.02
16	0.37	0.37	0.3	0.76	0.76
17	0.82	0.79	-0.4	0.74	0.72
18	0.56	0.53	-1.6	0.52	0.55
19	0.63	0.62	0.5	0.62	0.60
20	0.83	0.81	-0.9	0.83	0.83
21	1.01	1.01	-0.7	0.92	0.92
22	0.71	0.68	-0.7	0.70	0.70
23	0.85	0.85	0.2	0.86	0.84
24	1.21	1.21	1.4	1.18	1.22
25	0.71	0.70	0.4	0.69	0.70
26	1.33	1.11	-1.1	0.94	0.93
27	0.68	0.68	1.6	0.69	0.68
28	0.29	0.29	0.3	0.28	0.28
29	0.35	0.35	-0.9	0.38	0.38
30	1.06	0.90	-0.8	0.91	0.91
31	1.02	0.89	-2.3	0.94	0.91
32	0.35	0.35	0.1	0.38	0.37
33	0.61	0.60	-0.1	0.63	0.62
34	0.61	0.60	1.2	0.64	0.65
35	0.49	0.48	-0.5	0.47	0.46
36	0.39	0.39	-0.5	0.39	0.39
37	0.64	0.64	-0.1	0.65	0.77
38	0.39	0.39	-0.1	0.39	0.39
39	0.32	0.32	-0.3	0.32	0.32

40	0.67	0.61	-1.3	0.62	0.61	continued
41	0.53	0.52	1.2	0.57	0.56*	
42	0.30	0.29	-0.7	0.32	0.33	
43	0.43	0.43	-0.5	0.43	0.43	
44	0.56	0.56	-0.2	0.57	0.57	
45	0.47	0.47	-0.3	0.44	0.45	
46	0.34	0.34	0.1	0.56	0.58	
47	0.34	0.33	-1.4	0.34	0.33	
48	0.33	0.31	-1.1	0.32	0.32	
49	0.58	0.58	-0.1	0.60	0.60	
50	0.95	0.88	-2.1	0.90	0.90	
51	0.18	0.18	0.1	0.23	0.21	
52	0.21	0.21	-0.3	0.22	0.22	
53	0.35	0.35	-0.1	0.36	0.37	
54	0.32	0.29	-1.4	0.31	0.29	
55	0.36	0.36	-0.2	0.37	0.36	
56	0.51	0.45	-0.7	0.48	0.48	
57	0.86	0.84	-0.2	0.93	0.85	
58	0.33	0.33	-0.2	0.35	0.36	
59	0.81	0.81	0.4	0.86	0.80	
60	1.56	1.49	-0.5	1.53	1.49	
61	0.88	0.86	-1.4	0.84	0.84	
62	0.34	0.27	-1.0	0.25	0.25	
63	0.64	0.64	0.5	0.64	0.64	
64	0.44	0.43	0.7	0.46	0.43	
65	0.50	0.50	0.6	0.55	0.54	
66	0.33	0.33	-0.2	0.38	0.36	
67	0.54	0.53	-0.6	0.61	0.63	
68	0.66	0.64	0.9	0.77	0.69	
69	0.41	0.41	0.1	0.43	0.43	
70	0.37	0.36	-0.8	0.34	0.34	
71	0.76	0.73	-0.8	0.75	0.75	
72	0.32	0.31	-0.8	0.31	0.30	
73	0.47	0.45	-0.9	0.41	0.41	
74	0.70	0.68	1.4	0.79	0.77	
75	0.29	0.29	0.2	0.32	0.31	
76	0.48	0.48	0.1	0.55	0.54	
77	0.65	0.62	0.8	0.66	0.64	
78	0.72	0.67	-1.6	0.73	0.71	
79	0.65	0.58	-2.0	0.52	0.50	
80	0.40	0.40	0.6	0.44	0.43	
81	0.43	0.43	0.1	0.46	0.46	
82	0.30	0.27	0.7	0.31	0.34	
83	0.44	0.44	0.4	0.49	0.47*	
84	0.38	0.38	0.2	0.38	0.37	
85	0.48	0.47	1.0	0.52	0.50	
86	0.43	0.42	-0.5	0.43	0.43	
87	0.62	0.62	-0.1	0.65	0.63	
88	1.05	1.04	-0.4	0.81	0.80	
89	0.65	0.60	1.4	0.74	0.69	
90	0.84	0.81	-0.6	0.78	0.79	
91	0.17	0.16	-0.5	0.16	0.16	
92	1.13	1.11	-2.2	1.11	1.12	
93	0.53	0.52	0.6	0.57	0.55	
94	0.90	0.90	0.9	0.89	0.89	
95	0.76	0.75	-1.1	0.75	0.75	
96	0.68	0.63	-0.7	0.68	0.69	
97	0.40	0.40	-0.1	0.40	0.41	
98	0.40	0.40	-0.1	0.39	0.40	
99	0.66	0.66	-0.5	0.62	0.62	
100	1.11	1.06	-1.4	1.12	1.15	
101	0.69	0.65	-1.8	0.65	0.68	
102	0.90	0.90	0.2	0.95	0.96	
103	0.73	0.71	0.8	0.75	0.72	
104	0.41	0.41	-0.3	0.43	0.45	
105	0.37	0.34	-2.2	0.34	0.37	
106	0.63	0.62	-0.5	0.55	0.55	

107	0.70	0.70	-0.2	0.70	0.70	continued
108	1.09	1.07	1.4	1.09	1.09	
109	0.76	0.76	-0.1	0.80	0.77	
110	0.74	0.73	-1.1	0.76	0.77	
111	0.47	0.46	-0.6	0.44	0.46	
112	0.47	0.47	-0.1	0.51	0.50	
113	0.36	0.36	-0.1	0.39	0.39	
114	0.36	0.36	0.4	0.39	0.39	
115	0.63	0.63	0.1	0.59	0.59	
116	0.65	0.63	-0.9	0.64	0.64	
117	1.19	1.17	-2.6	1.16	1.18	
118	0.96	0.96	0.3	0.94	0.92	
119	0.88	0.79	-1.6	0.83	0.82	
120	0.91	0.90	-0.5	0.90	0.91	
121	0.71	0.69	-1.7	0.71	0.71	
122	0.34	0.34	0.2	0.33	0.32	
123	0.39	0.39	-0.2	0.42	0.39*	
124	0.43	0.42	-0.8	0.43	0.44	
125	0.40	0.39	-1.9	0.39	0.39	
126	0.68	0.57	-1.7	0.63	0.63	
127	0.65	0.64	-0.2	0.67	0.67	

* equation did not converge.

III. TREE VOLUME EQUATIONS FOR UNTHINNED YOUNG-GROWTH PONDEROSA PINE PLANTATIONS IN NEUQUÉN, PATAGONIA, ARGENTINA. A COMPARISON WITH EQUATIONS DEVELOPED IN THE WESTERN UNITED STATES

Héctor E. Gonda, David D. Marshall, Gustavo O. Cortés,

and Steven D. Tesch

ABSTRACT

Two 3-variable models (total height (H), diameter at breast height (D), and crown ratio (CR)), twelve 2-variable equations (H and D), and seven 1-variable functions (D) were examined to identify models capable of accurately predicting total inside bark volume (V) of trees in the young ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) plantations of Neuquén, northern Patagonia, Argentina. Equations $V = a + b D^2H + c D + \varepsilon$ and $V = a + b D + c D^2 + \varepsilon$ were chosen as the final 2- and 1- variable models respectively, based on Furnival's (1961) index of fit. Crown ratio proved to be not significant. Several two-variable models developed in the western United States underestimated the volume of Neuquén trees, suggesting that in northern Patagonia, the boles of ponderosa pine trees are less tapered.

INTRODUCTION

Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) is the most widely planted species in the Patagonian Andes region of Argentina, where it grows vigorously and without any serious pest problems. Preliminary studies suggest that the average yield of these stands could be similar to or even higher than those growing on the more productive regions of the western United States (Gonda and Lomagno 1995, Urzúa 1991). The environmental conditions in northern Patagonia are similar to those where ponderosa pine (variety ponderosa) forests grow naturally in the western United States. The piedmont of the northern Patagonian Andes and the interior Pacific Northwest share the following main characteristics:

1. The latitudinal ranges are similar in the respective hemispheres (Figure III.1)
2. Moisture is provided by humid winds blowing from the Pacific Ocean.

3. A rain shadow effect is produced by the Andes as well as by the Cascades and the northern Sierra Nevada ranges.
4. A Mediterranean climate prevails, imposing a well-defined dry season.
5. A high proportion of the soils are of volcanic origin.

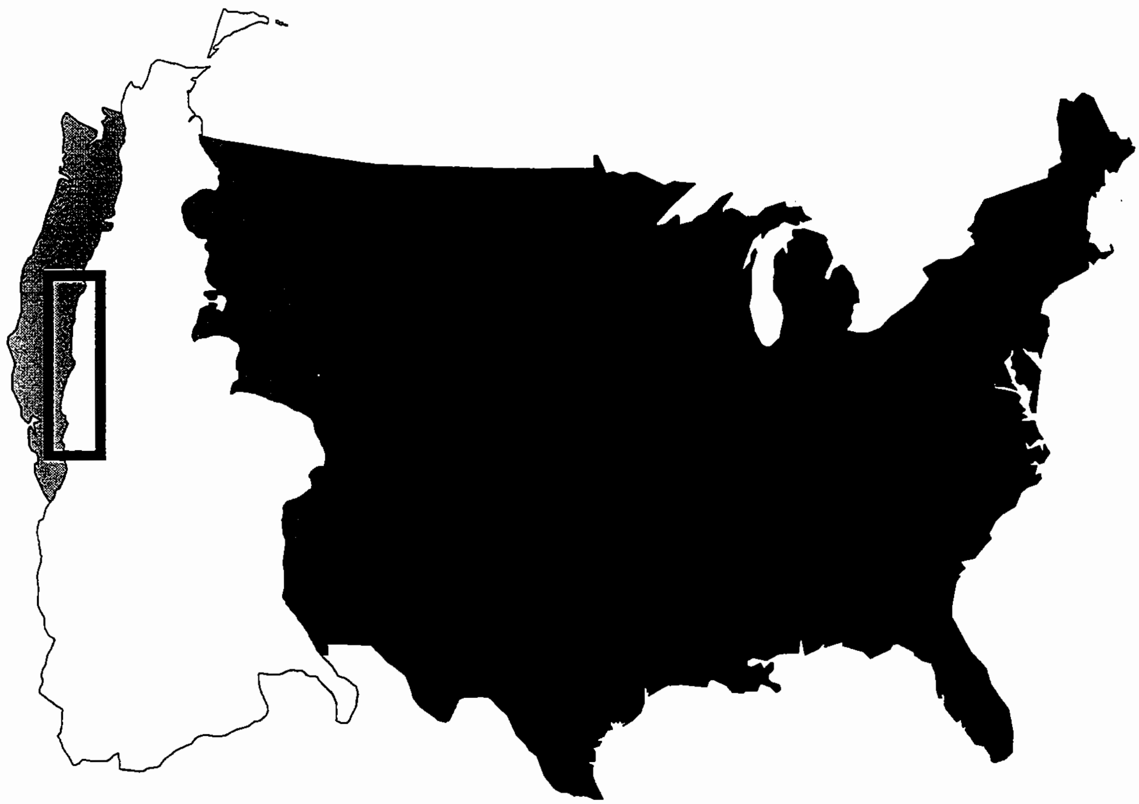

Figure III.1. A map superimposing the Patagonian Andes (Argentina) over the Cascades and northern Sierra Nevada (United States). The rectangle includes the current distribution area of the ponderosa pine plantations in Patagonia. The latitude of both countries match, and they are drawn at the same scale.

The area planted annually with ponderosa pine in Argentina is rapidly increasing due to the subsidies and credits that the Patagonian provinces and the federal government provide for planting fast-growing species. The primary objective of this support is to promote afforestation as a means to improve the socioeconomic conditions of the region. Currently there are about 30,000 hectares of ponderosa pine forests (Urzúa 1991), with about a million hectares of grasslands suitable for commercial afforestation throughout the piedmont of the Patagonian Andes (Enricci 1993).

Information on site quality and growth of ponderosa pine in Patagonia is limited. This incomplete knowledge can dissuade potential investors from planting trees and frustrate efforts to develop sound management plans. Because species that are grown outside their native range typically exhibit growth and developmental patterns that differ significantly from those of the species within its native environment, it is also risky to extrapolate growth predictions to new geographic areas (Zobel et al. 1987).

To ameliorate these problems the Patagonian Andes Forest Research and Extension Center (CIEFAP), along with the University of Comahue Forest Technical School and the government of Neuquén, have started quantitative silvicultural studies on ponderosa pine plantations throughout Neuquén province, covering an area that includes about 80% of the present plantation forests of this species in Patagonia (Figure III.2). These studies constitute the Neuquén Ponderosa Pine Site Quality and Yield (NPPSQY) project.

Volume Equations

Two- and 3- Variable Equations

Two- variable or standard volume functions include diameter at breast height (D) and total height (H) as explanatory variables, and sometimes also their powers and cross products. Other stand characteristics such as site class, age, number of trees per unit area, or basal area, are usually not included because they do not improve predictive ability (e.g. Burkhart 1977, MacLean and Berger 1976). An exception to that is crown ratio (CR), which was found to be highly significant when estimating stem volume (V) of Douglas-fir (*Pseudotsuga*

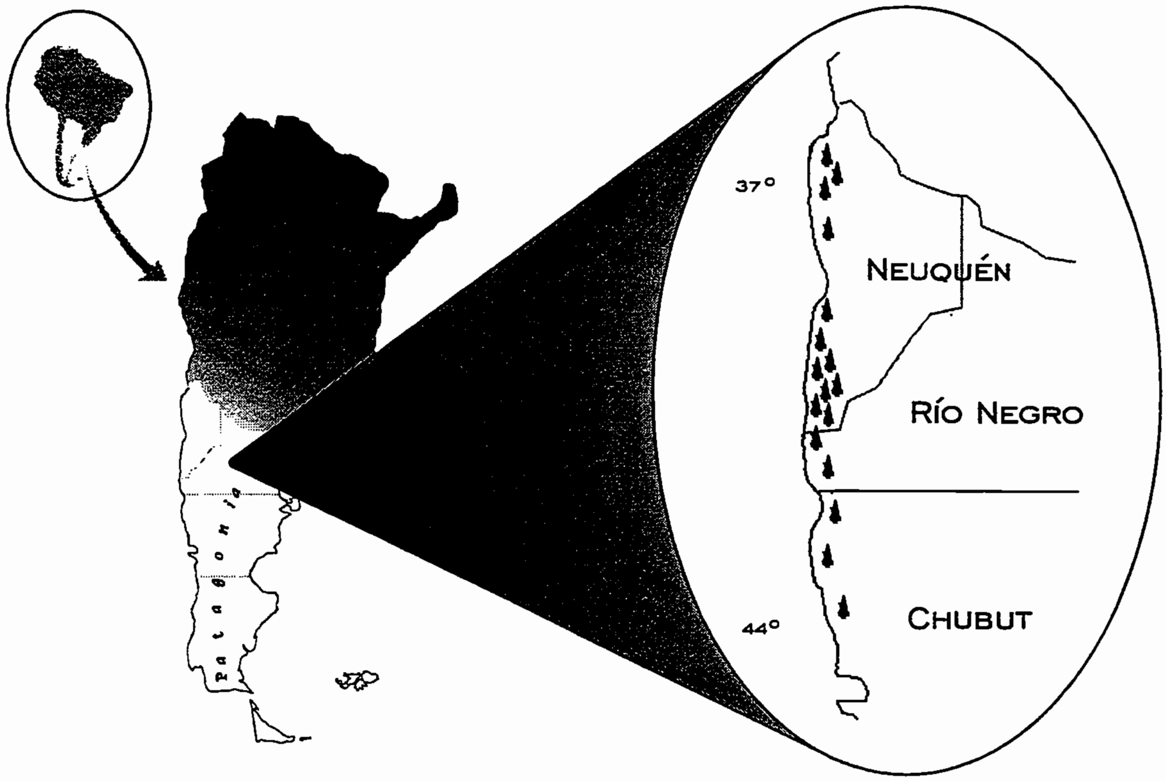

Figure III.2. From left to right: maps showing the position of Argentina in South America, Patagonia within Argentina, and the current distribution of the ponderosa pine plantations in the provinces of Neuquén, Río Negro, and Chubut. The number of pine trees is proportional to the plantation area.

menziessi (Mirb.) Franco) (Hann et al. 1986), and Douglas-fir and white fir in southwest Oregon (Walters et al. 1985, Walters and Hann 1986). However, CR was not significant when estimating the volume of ponderosa pine in the same region (Walters et al. 1985, Walters and Hann 1986).

We selected 10 2- variable and two 3-variable volume models most commonly used in the Western United States that have the potential to give accurate volume predictions when fitted to Neuquén data (Table III.1). One of these models was also fitted to predict outside bark volume of ponderosa pine trees in Río Negro and Chubut (Andenmatten et al. 1995).

Table III.1. Two- and three-variable volume equations selected and names of the coniferous species to which they were fitted by previous authors. Abbreviations: diameter at breast height (D), height (H), and volume (V).

Model Form	Authors and species
Linear logarithmic (ln=natural logarithm)	
[1] $LnV = \beta_0 + \beta_1 \ln D + \beta_2 \ln H$	Browne 1962 (ponderosa pine and 15 other commercial tree species of British Columbia), Cochran 1985 (ponderosa pine, western white pine (*Pinus monticola* Dougl.), lodgepole pine (*Pinus contorta* Dougl.), western larch (*Larix occidentalis* Nutt.), Douglas-fir, white fir (*Abies concolor* (Gordon. & Glend.) Lindl.), grand fir (*Abies grandis* (Dougl.) Lindl.), engelmann spruce (*Picea engelmannii* Parry)), Wensel 1977 (ponderosa pine).
[2] $LnV = \beta_0 + \beta_1 \ln D + \beta_2 \ln H + \beta_3 D$	Bell et al. 1981 (mountain hemlock (Tsuga mertensiana (Bong,) Carr.))
Linear nonlogarithmic	
[3] $V = \beta_0 + \beta_1 D^2H$	Chapman et al. 1982 (ponderosa pine, lodgepole pine, western larch, Douglas-fir), MacLean and Berger 1976, (ponderosa pine, jeffrey pine (*Pinus jeffreyi* Grev. & Balf) , sugar pine (*Pinus lambertiana* Dougl.), lodgepole pine, Douglas-fir, white fir, California red fir (*Abies magnifica* A. Murr.), incense cedar (*Libocedrus decurrens* Torr.)), Oliver and Powers 1978 (ponderosa pine), Burkhart 1977(loblolly pine (*Pinus taeda* L.)), Cao et al. 1980 (loblolly pine), (Andenmatten et al. 1995 (ponderosa pine)
[4] $V = \beta_0 + \beta_1 D^2H + \beta_2 D$	Bell et al. 1981 (mountain hemlock)
[5] $V = \beta_0 + \beta_1 D^2H + \beta_2 D + \beta_3 H$	Bell et al. 1981 (mountain hemlock)
[6] $V = \beta_0 + \beta_1 D^2H + \beta_2 D^2 + \beta_3 H$	Bell et al. 1981 (mountain hemlock)
Nonlinear	
[7] $V = \beta_0 + \beta_1 (H/D)^{\beta 2} (D^2H)$	Hann et al. 1986 (Douglas-fir)
[8] $V = 10^{\beta 0} D^{\beta 1} H^{\beta 2}$	Bell et al. 1981 (mountain hemlock)
[9] $V = \beta_0 + 10^{\beta 1} D^{\beta 2} (H^{\beta 3})^{\beta 4}$	Bell et al. 1981 (mountain hemlock)
[10] $V = \beta_0 (H/D)^{\beta 1} (D^2H)$*	Walters et al. 1985 (ponderosa pine, sugar pine, incense-cedar, Douglas-fir, grand fir, white fir)
Crown ratio (ln=natural logarithm)	
[11] $LnV = \beta_0 + \beta_1 \ln D + \beta_2 \ln H + \beta_3 CR$	Hann et al. 1986 (Douglas-fir)
[12] $V = \beta_0 + \beta_1 \exp(\beta_2 CR) (D^2H)$	Hann et al. 1986 (Douglas-fir)

*Equation originally developed to calculate volume above breast height.

One- Variable Equations

One- variable or local volume equations are typically applied to small forest areas. When applied to a wide range of site conditions, equations containing D as the only explanatory variable are not as accurate as those containing D and H. This was demonstrated for young ponderosa pine stands in northern California (Chapman et al. 1982). In Neuquén, ponderosa pine plantations are located throughout a latitudinal transect 500 km long that includes a relatively wide range of site conditions. However, volume equation users often do not have H information, so we selected seven models that could predict stem volume based solely on D data (Table III.2). Two of these equations had been fitted for young ponderosa pine trees in Western United States by Chapman and others (1982) and McDonald and Skinner (1989).

Table III.2. One-variable volume equations selected for the study. Two of them have been fitted by previous authors to several species. Abbreviations: diameter at breast height (D), height (H), volume (V), and natural logarithm (ln).

Model Form	Authors and species
[13] $\ln V = \beta_0 + \beta_1 \ln D$	McDonald and Skinner 1989 (ponderosa pine)
[14] $\ln V = \beta_0 + \beta_1 \ln D + D$	-
[15] $\ln V = \beta_0 + \beta_1 \ln D^2$	-
[16] $V = \beta_0 + \beta_1 D$	-
[17] $V = \beta_0 + \beta_1 D^2$	-
[18] $V = \beta_0 + \beta_1 D + \beta_2 D^2$	-
[19] $V = \beta_0 D^{2\ \beta_1}$	Chapman et al. 1982 (ponderosa pine, Douglas-fir, lodgepole pine, and western larch)

Linear and Nonlinear Equations

Errors associated with tree volume prediction tend to be heteroscedastic and the variance tends to increase with tree size (Furnival 1961, Cunia 1964). Thus, linear volume equations are often fitted by logarithmic least-square regression. However, models with a logarithmically transformed response variable introduce some log bias that should be corrected (Baskerville 1972, Payandeh 1981). Yet, this correction theoretically cannot be performed if the residuals are not normally distributed (Baskerville 1972), and the choice of alternative correction factors is not always easy and does not necessarily eliminate all bias (Flewelling and Pienaar 1981).

Nonlinear models do not require a log bias correction, but they need to be weighted in order to correct for departures from homoscedasticity. The main advantage of the nonlinear models is that their flexibility allows biologically reasonable shapes. This feature is highly desirable since users often extrapolate them (Vanclay 1994).

Objectives

The first objective of this paper is to identify models capable of accurately estimating total-stem cubic volume based upon D or D and H, for ponderosa pine plantations in Neuquén province. The second objective is to determine whether incorporating CR into selected models would improve their predictive ability. The third objective is to compare predictions from our selected models with predictions from the same models fitted by previous authors to ponderosa pine trees in the Western United States.

The equations developed will have two main applications. First, they will contribute to the development of yield tables in the NPPSQY project, by making it possible to estimate tree volumes. Second, they will provide local users with models that will allow them to calculate standing wood volume of ponderosa pine stands either for commercial or research goals.

METHODS

Data Source

The data consisted of stem analysis measurements from 156 sample trees from 78 stands growing under a wide range of site conditions throughout Neuquén province (Table III.3). Sample trees were measured in unthinned plantations which had negligible insect, disease, or storm damage. Seventy two sample trees came from individuals that had been pruned, in most cases within the last 5-10 years.

Table III.3. Minimum (min), maximum (max), and mean values of latitude, longitude, elevation (elev), slope, aspect, annual precipitation (precip), soil depth (soil d), age, and density (tr/ha) ranges of the 78 stands where the sample trees were taken throughout Neuquén province.

	Latitude	Longitude	Elev (m)	Slope (degr)	Aspect (degr)	Precip (mm/yr)	Soil D (m)	Age	Tr/ha
Min	36°30'00"	70°36'31"	650	0	0	400	0.4	10	538
Mean	38°47'37"	71°04'53"	1121	8.6	130	967	1.0	17	1466
Max	41°05'15"	71°33'15"	1700	28.0	337	2229	1.8	35	2500

Sample trees were felled adjacent to 78 permanent plots established for the NPPSQY project, from June to September 1997 (Figure III.3). Each plot was located in a different stand. These were spread out along Neuquén province, except for the three southernmost stands that were located in Río Negro province, only a few kilometers from the Neuquén border; because there were no

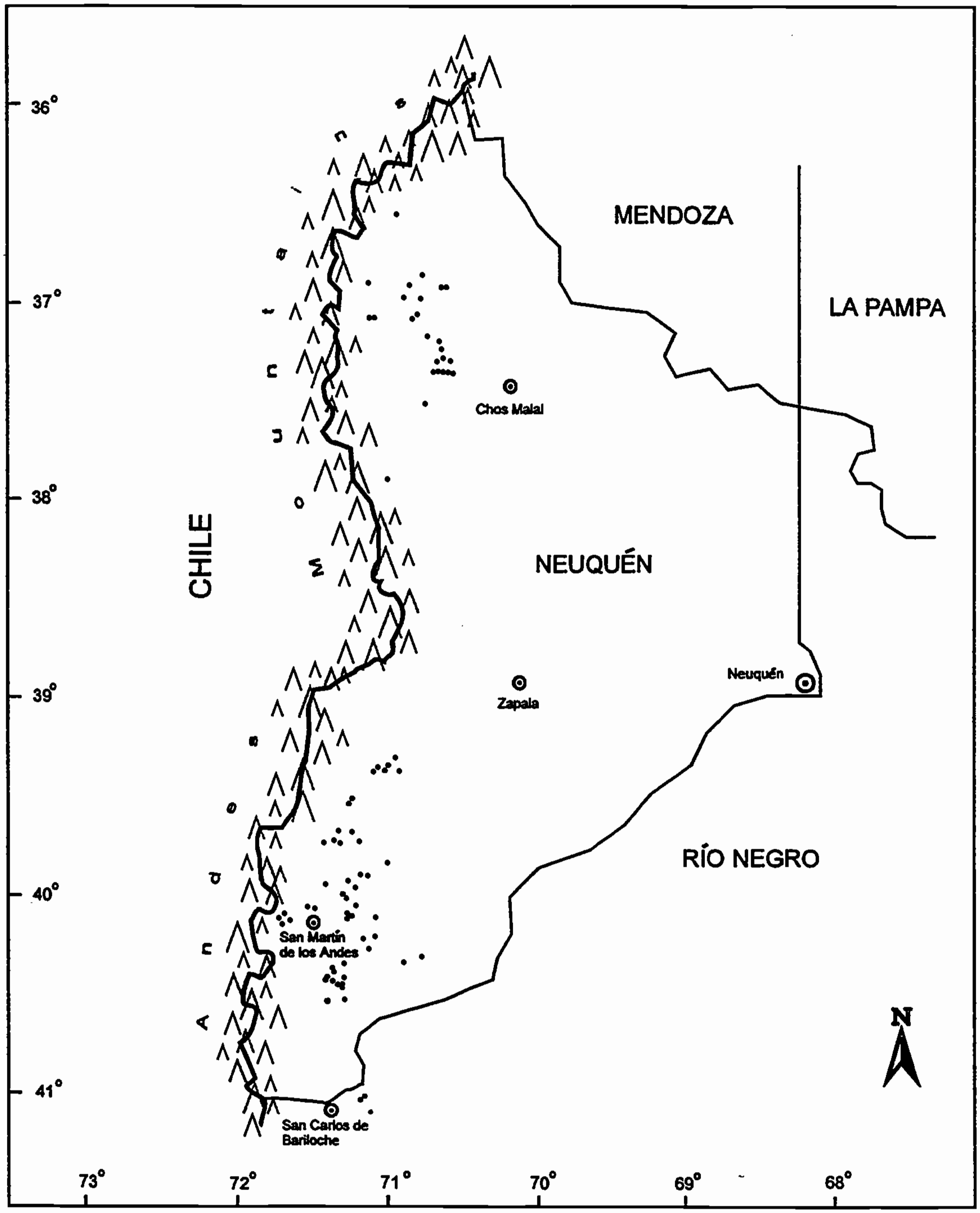

Figure III.3. Location of the 78 plots near which the 156 sample trees were felled.

ponderosa pine plantations on the Neuquén side (Figure III.3). All 78 plots were circular, but with different diameter in order to incorporate at least 40 trees.

Two sample trees were felled in the proximity of each plot, one with the diameter of the tree of mean basal area and mean plot height, and the other one with the mean D and H of the 300 largest trees per hectare in the plot (Figure III.4). As a result of this selection process, all sample trees were among the three superior crown classes. Sample trees did not include open-grown individuals, those in stands having a wide variety of densities due to poor planting survival, or those curved, forked, unhealthy, or with broken tops.

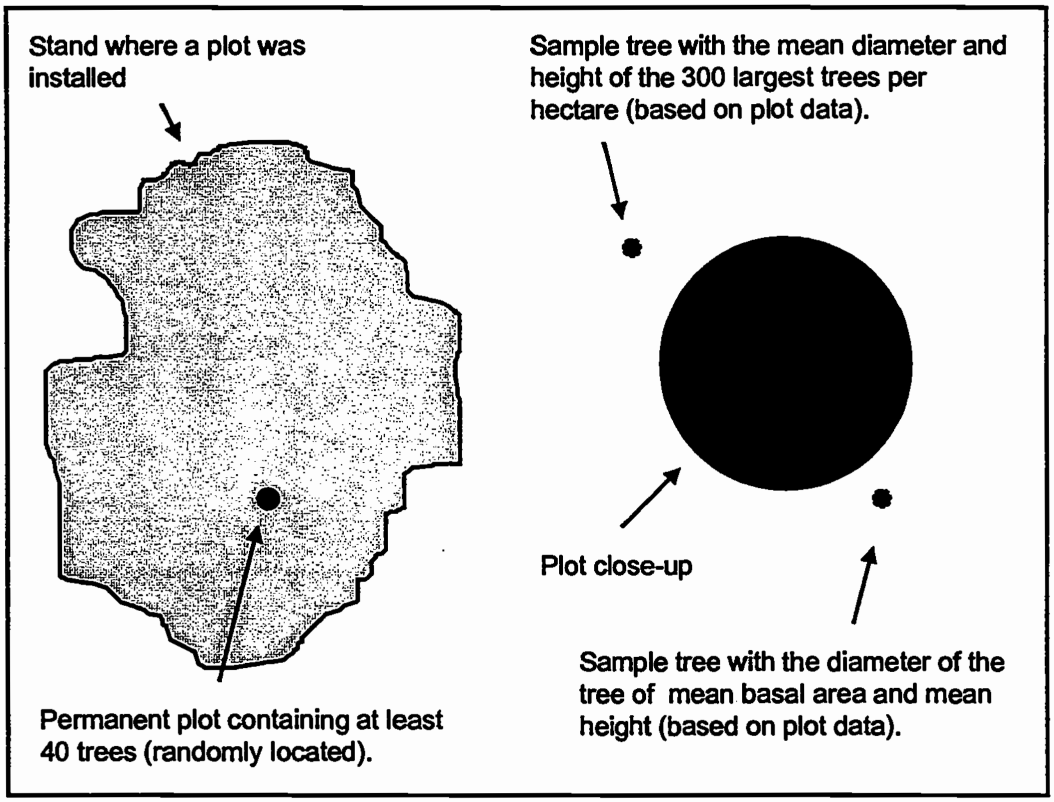

Figure III.4. Representation of how two sample trees were selected in each of the 78 sample stands.

Tree Measurements

Total tree volume was determined from a 5 cm stump height to tree top. Total H and D were measured on the sample trees prior to felling. After felling, trees were sectioned in 13 pieces. Logs were sectioned at .30, .80 and 1.30 m, and the remaining part of the bole was cut in 10 pieces of equal length (Figure III.5). The diameters outside and inside the bark at both ends of each section were measured for the longest and shortest axes, and the average diameter of the two axes was recorded. Diameters were measured with a ruler to the nearest millimeter. The volume of each of the lower 12 sections was calculated with the Smalian's formula. The volume of the tip section was calculated with the formula for volume of a cone. Volumes of the 13 individual sections were then summed to obtain the calculated total stem inside bark volume for each tree.

Height-to-live crown was measured on all sample trees upon felling in order to calculate CR. Only data from the 87 trees that had not been pruned reflected the natural crown recession process. On most pruned tress, natural crown recession had not occurred, so that height-to-live crown was the result of artificial pruning. The distance from the sample tree to the closest 4 neighbors was measured with a tape to the nearest cm. This measurement provided an estimate of the spacing for each sample tree.

Analysis

Two- and 3- Variable Volume Equations

Ten 2- and three 3- variable equations were examined in search for a suitable model to predict total underbark stem volume of ponderosa pine trees in Neuquén province. The 2- variable equations were grouped into four different types, i.e. linear logarithmic, linear nonlogarithmic, nonlinear (Table III.1).

Equations 1, 2, and 11 were fitted by logarithmic least-squares regression, and multiplicative errors were assumed to follow a log-normal distribution. The rest of the models were fitted using weighted least-squares regression for estimating their parameters; the following weights were tested: 1, $1/D$, $1/D^2$, $1/D^3$,

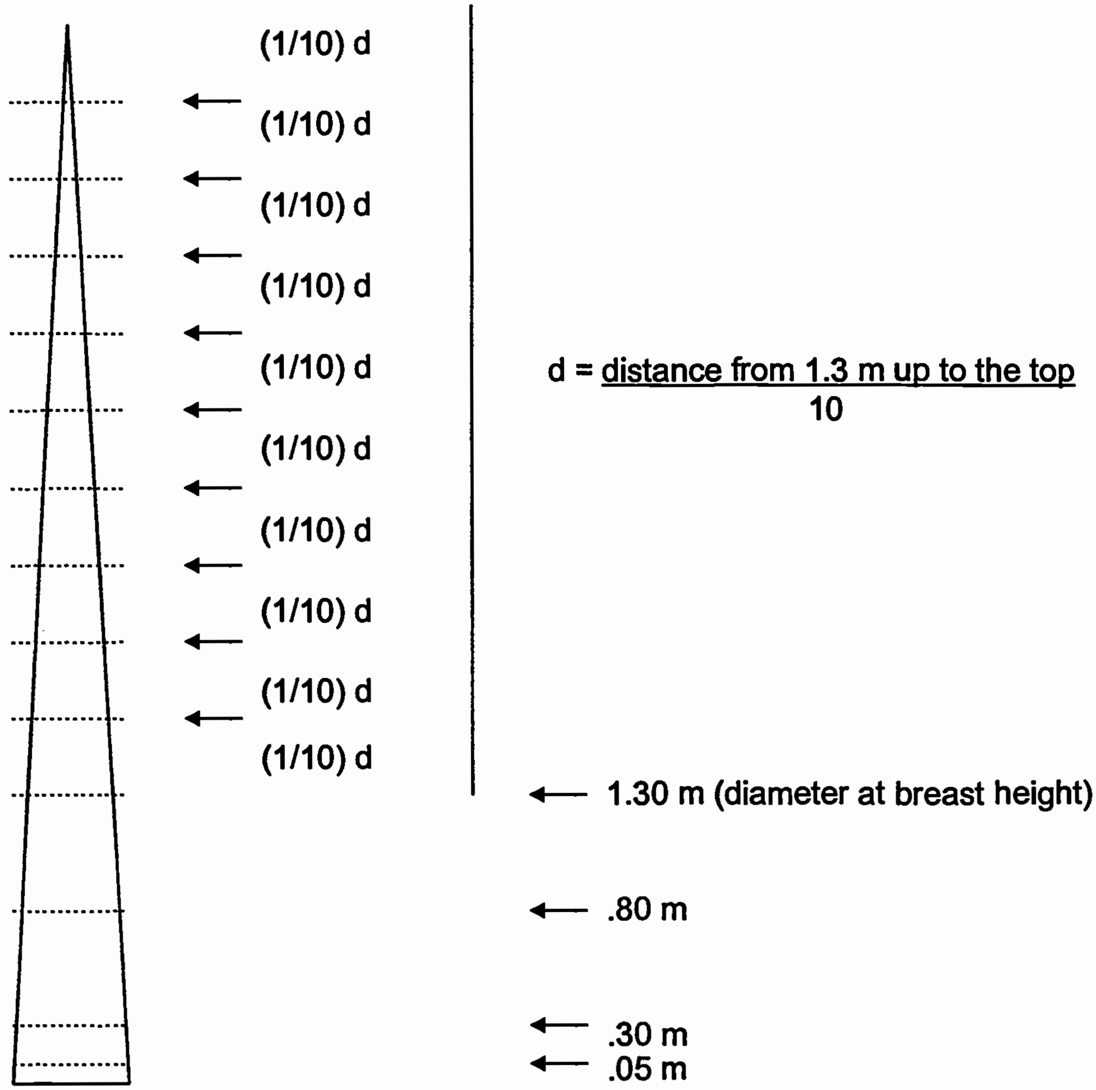

Figure III.5. Positions at which felled trees were cross sectioned.

$1/D^4$, $1/D^2 H$, and $1/(D^2 H)^2$. The best weight for each function was chosen by computing Furnival's (1961) index of fit. This index has the advantage of reflecting both the size of the residuals and possible departures from linearity, normality, and homoscedasticity (Furnival 1961). Then, all the equations were compared on the basis of the same index.

To test the effect of CR, an exponential transformation was added as a multiplier in equations 1 and 3 to produce equations 11 and 12 (Table III.1). This procedure was the same applied on stem volume functions developed for ponderosa pine (Walters et al. 1985) and Douglas-fir (Hann et al. 1986); the term β_3 (CR), implies that small crowned trees have more volume than large-crowned trees. The *t*-test was used to check equations 11 and 12 for significance of the CR parameters using the data from the 87 trees on which crown recession due to natural causes was not masked by pruning.

One- Variable Volume Equations

Neuquén volume equation users often do not have H information, so seven equations were examined in order to select a model that could predict stem volume based solely on D data (Table III.2). Equations 13, 14, and 15 were fitted by logarithmic least-squares regression. Equations 16, 17, 18, and 19 were fitted using weighted least-squares regression for estimating their parameters; weights tested were: 1, 1/D, $1/D^2$, $1/D^3$, $1/D^4$, $1/D^5$, $1/D^6$, $1/D^7$, $1/D^8$. The best weight for each equation was chosen by computing Furnival's (1961) index of fit. Then, the seven equations were compared using the same index to select the final model.

A Comparison with Volume Equations Developed for Ponderosa Pine Trees in the Western United States

The predictions of the 1- and 2- variable volume equations most widely used to compute the volume of ponderosa trees in the western United States, namely equations 1, 3, 13, and 19, were compared with the predictions of the same models fitted to Neuquén data. Because American authors reported the coefficients of the equations only in English units, the four models where refitted to Neuquén data in English units to make the comparison of the coefficients meaningful.

RESULTS

Two- and 3-Variable Volume Equations

Most equations produced similar Furnival's index of fit, between .0063 and .0070 (Table III.4), except for equations 7, 8, and 10 that showed larger values: .0075, .0080, and .0101, respectively. The weight $1/(D^2H)^2$ was most appropriate for equations 3, 4, 5, 6, 8, and 9, and $1/D^4$ was the best for equations 7 and 10. In equation 5 (once weighted) the parameter for H was not significant, thus equation 5 was assumed to be the same as function 4. The intercept was not significant in weighted equations 4, 6, and 9. The variable CR was not significant in either model, 11 or 12.

One- Variable Volume Equations

The weight $1/D^8$ was the most appropriate for all nonlogarithmic functions, except for model 19 ($1/D^7$). Models 16 and 17 produced higher Furnival's indices than the rest of the equations, .029 and 0.20 respectively (Table III.5).

DISCUSSION

Characteristics of the Data

Most plantations in Neuquén are younger than 25 years of age, thus the trees (Figure III.6) are smaller than those used to fit most volume functions for ponderosa pine stands in the Western United States (e.g. Faurot 1977, MacLean & Berger 1976, Oliver and Powers 1978, Walters et al. 1985) (Table III.6).

Table III.4. Furnival's index (Fur. index), weight, coefficients, and mean square error (MSE) for the two-variable equations with an index of fit below .0071. Equation 5 is not included because it was equivalent to equation 4; H was not a significant parameter.

	Equation types and numbers					
	Linear					Nonlinear
	Logarithmic		Nonlogarithmic			
	[1]	[2]	[3]	[4]	[6]	[9]
Fur. Index	.0070	.0064	.0067	.0063	.0064	.0068
Weight	1	1	$\frac{1}{(D^2H)^2}$	$\frac{1}{(D^2H)^2}$	$\frac{1}{(D^2H)^2}$	$\frac{1}{(D^2H)^2}$
Coefficient						
β_0	-9.382945	-8.625554	.004248	.000214*	.001053*	.002419*
β_1	1.678522	1.285985	.000032	.000030	.000028	-4.178613
β_2	1.020303	.970827		.000538	.000023	1.691697
β_3		.025254			.000602*	2.930213
β_3						.370000
MSE	.007626	.00642	8.684281 E-12	7.711851 E-12	7.845787 E-12	9.044205 E-12

* Parameter not significant at a probability level of .01.

Table III.5. Furnival's index, weights, coefficients, and mean square error (MSE) for the one- variable equations with an index below .016.

	Equation types and numbers				
	Linear				Nonlinear
	Logarithmic			Nonlogarithmic	
	[13]	[14]	[15]	[18]	[19]
Furnival's index	.015	.013	.014	.014	.016
Weight	1	1	1	$1/D^8$	$1/D^7$
Coefficient					
β_0	-10.487060	-8.940183	-10.487060	.025821	.000054
β_1	2.807196	1.954019	1.403598	-.006303	1.278030
β_2		.048172		.000556	
MSE	.03306	.02853	.03306	2.973752 E-14	6.043570 E-13

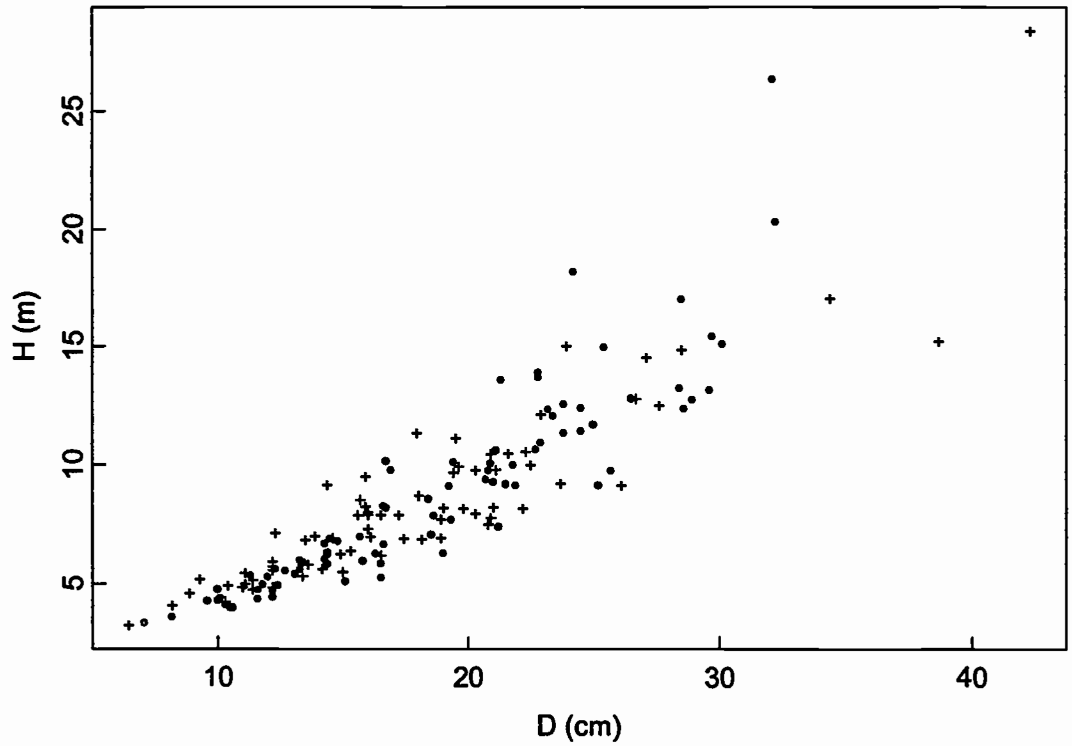

Figure III.6. Scatterplot of height (H) vs. diameter at breast height (D) for each of the 156 sample trees. Pruned sample trees are shown as "+".

Table III.6. Ranges of (height) H and diameter at breast height (D) measurements of the sample trees for the present study and four others carried out for ponderosa pine in the Western United States by Faurot (1977), MacLean & Berger (1976), Oliver and Powers (1978), and Walters et al. (1985).

	Patagonia			Inland Northwest									Coast Range		
	Neuquén			N. California			Interior California			W. Montana			W. Oregon		
	Gonda et al.			Oliver & Powers			MacLean & Berger			Faurot			Walters et al.		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
D (cm)	6.5	18.1	42.3	2.5	-	61.0	30.5	-	172.7	5.1	-	58.4	3.3	6.8	90.4
H (m)	3.2	8.6	29.5	1.5	-	28.9	12.2	-	70.1	3.0	-	33.5	4.6	24.8	58.8

Two- and 3-Variable Volume Equations

Final model

Equation 4 ($V = \beta_0 + \beta_1 D^2H + \beta_2 D$) was chosen as the final model among the 2- variable functions because it had the lowest Furnival's index of fit (Table III.4). Equation 4 explained most of the variability associated with inside bark volume. The residuals showed no trends when plotted against the environmental variables: latitude, longitude, elevation, slope, aspect, annual precipitation, soil depth, number of trees per ha in the plot and mean spacing between the sample tree and its nearest neighbors. Also, residuals from the pruned trees were not different from those corresponding to unpruned individuals; this is also illustrated in Figure III.6.

Equation 6, and even equations 3 and 9, were considered valid alternatives since their indices of fit were only slightly higher (Table III.4). Model 2 had also a low index of fit, but being logarithmic it required a log bias correction (Baskerville 1972) that can not be performed if the residuals are not normally distributed. Yet, even if they are normally distributed the choice of alternative correction factors is not always easy (Flewelling and Piennar 1981). In Patagonia, Andenmatten and others (1995) fitted equation 3 to predict the volume of ponderosa pine trees in the provinces of Río Negro and Chubut. Their results are not comparable because they estimated outside-bark volume.

Crown ratio was not significant because it was relatively high for most sample trees, even for those with the closest spacings. The minimum, mean and, maximum CRs were 42, 78 and 100% respectively.

A Comparison with Models Developed in the Western United States

Equation 1 ($\ln V = \beta_0 + \beta_1 \ln D + \beta_2 \ln H$) was fitted to larger ponderosa pine trees in even-aged stands of eastern Washington and Oregon (Cochran 1985) and in the mixed-conifer stands of the mid-Sierra region of California (Wensel 1977). Equation 3 ($V = \beta_0 + \beta_1 D^2H$) was fitted to larger ponderosa pine trees in northern California plantations (Oliver and Powers 1978) and to trees of similar size to the ones used for this study in northeastern Washington (Chapman et al. 1982) (Table III.7). The volumes that the coefficients of models 1 and 3 predicted when fitted to our data set were compared with the volumes these functions predicted with the coefficients calculated by these authors for ponderosa pine trees growing in western United States.

Table III.7. Coefficients of 2-variable equations 1 and 3, fitted to ponderosa pine tree data in English units in Neuquén (Gonda et al. 1979), northeastern Washington (Chapman et al. 1982), eastern Oregon and Washington (Cochran 1985), and northern California (Oliver and Powers 1978, Wensel 1977).

	Equation 1* ($\ln V = \beta_0 + \beta_1 \ln D + \beta_2 \ln H$)			Equation 3 ($V = \beta_0 + \beta_1 D^2H$)		
	Gonda et al.	Cochran	Wensel	Gonda et al. weight: $1/(D^2H)^2$	Chapman et al. weight: $1/D^2H$	Oliver & Powers weight: $1/D^2H$
β_0	-5.466215	-6.0336	-6.5819	.150020	.16831	.02484
β_1	1.678522	1.8715	2.0022	.002240	.00177	.00176
β_2	1.020303	1.0166	1.0598			

* None of the authors corrected for the log bias of equation 1.

The volume predictions of both equations for the different regions were compared for the D range of our data set, 6 to 40 cm. Height was held constant by computing it with the H-D equation developed by Wykoff et al. (1982). The coefficients of this equation were calculated by fitting it to H-D data collected from the ponderosa pine plantations of Neuquén province: $H = 1.3 + e^{(2.88839 - (17.90739 / (D+1)))} + \varepsilon$ (see Chapter 2). The regression lines showing the volume predictions for the different regions were drawn on a graph with only two dimensions: D and volume (Figure III.7).

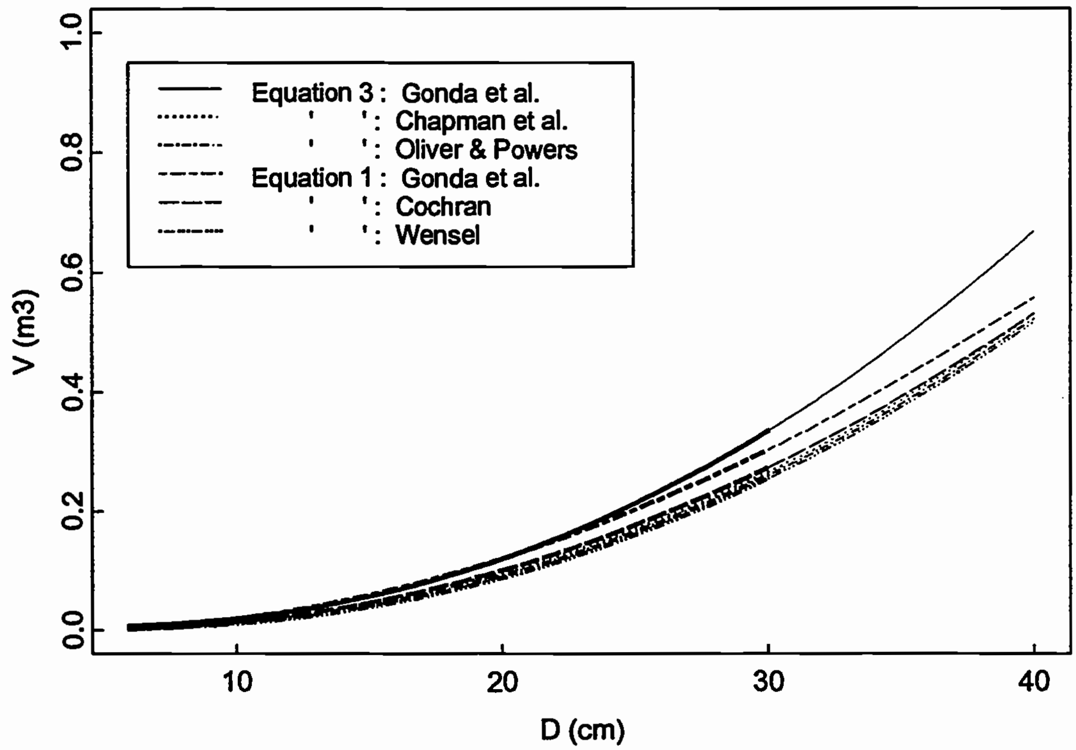

Figure III.7. Regression lines for equation 1, fitted to Neuquén, eastern Washington and Oregon (Cochran 1985), and the mid-Sierra region of California data (Wensel 1977), and equation 3 fitted to Neuquén, northeastern Washington (Chapman et al. 1982), and northern California data (Oliver and Powers 1978). Height was maintained constant by computing it with a H-D equation. Comparisons are most meaningful within the 6-30 cm D range (thick portion of lines).

Both equations predicted more volume for ponderosa pine trees growing in Neuquén than for individuals of the same species growing in the western United States (Figure III.7). Comparisons were most meaningful for trees with Ds between 6 and 30 cm. Within this range, equations 1 and 3 predicted an average of 20 and 25% more stem volume for Neuquén trees than for those in eastern Oregon and Washington and northern California respectively.

Second-growth natural stands, as well as planted ponderosa pine trees in the western United States, compete with herbaceous and woody vegetation on most areas, e.g. central Washington (Stewart and Beebe 1974), central Oregon (Barret 1982, Busse et al. 1996), north central Oregon (Van Sickle and Hickman 1959), northeastern Oregon (Riegel et al. 1992), southcentral Oregon (Crouch 1979), and northern California (Bentley et al. 1971, Oliver 1979, Oliver 1984). In planted stands, the understory consumes important amounts of water and nutrients that often reduce the early H and D growth of trees significantly, not only upon outplanting (Bentley et al. 1971, Eckert 1979, Lanini and Radosevich 1986, Powers and Jackson 1978), but also for as long as 20 years (Oliver 1990, Tappeiner and Radosevich 1982). Even the growth of 60-year-old second-growth stands can be reduced by the presence of lower vegetation (Barret 1982, Busse et al. 1996, Oren et al. 1987). Conversely, ponderosa pine plantations in Neuquén compete only with bunch grasses, which are often sparse after intensive grazing. Woody vegetation is typically absent, and pine needles decay so slowly that they function as a mulch that helps the pines overtop the grasses at early ages.

We speculate that the presence of more and much taller competing vegetation can affect the diameter growth of ponderosa pine trees in the western United States. The slower D and H growth, due to the reduced availability of resources from competition, results in ponderosa pine trees in the western United States that are more slender than individuals with the same D and H growing in Neuquén. Stems of older trees would tend to be smaller in diameter because they have been competing with the understory and among themselves for a longer period of time. Shrubs significantly affect the crown ratio of ponderosa pine trees growing in the western United States (Barrett 1973, Oliver 1990). Natural pruning in the lower parts of the stem occurs more rapidly, inducing the formation of smaller diameter stems.

Crown recession due to inter-tree competition seems to be slower for Neuquén trees. Even in highly stocked stands the crown ratios of individuals in the middle and upper diameter classes is over 40%. The foliage of Neuquén trees also tends to be more dense, supporting a higher number of needles for a longer time. The fact that the other authors measured DBH at 1.37 m (4.5 ft) from the ground instead of 1.30 m could have made a slight contribution for the prediction of higher volumes of Neuquén trees.

One-Variable Volume Equations

Final Model

Among 1-variable functions, equation 18 ($V = \beta_0 + \beta_1 D + \beta_2 D^2$) was chosen as the final model. Logarithmic equations 14 and 15 had slightly lower indices of fit (Table III.6), but they require a cumbersome log bias correction. Equation 18 has a good index of fit and behaves reasonably well, even beyond the range of the data; it does not reach a maximum even when the D is 2.0 m. However, its residuals do not spread as evenly as those from the selected two-variable model when plotted against the environmental variables. Slight trends in residuals were observed against latitude, longitude, soil depth, number of trees per ha in the plot, and mean spacing of the sample trees. This was not surprising since 1-variable equations usually can not explain as much of the variability associated with volume as 2-variable equations. Residuals from pruned trees were no different from those shown by unpruned individuals. The regression lines of the five models whose indices of fit were below .017 showed that only equation 19 behaved almost the same as the selected final model (Figure III.8). Thus, equation 19 was considered an alternative final model; it is nonlinear and thus capable of assuming biologically reasonable shapes.

By applying the weighted least squares procedure, observations with large variances had a smaller influence on the estimated parameters. This was illustrated by comparing the weighted regression line for the final model (18), with the regression line for its unweighted version (Figure III.9).

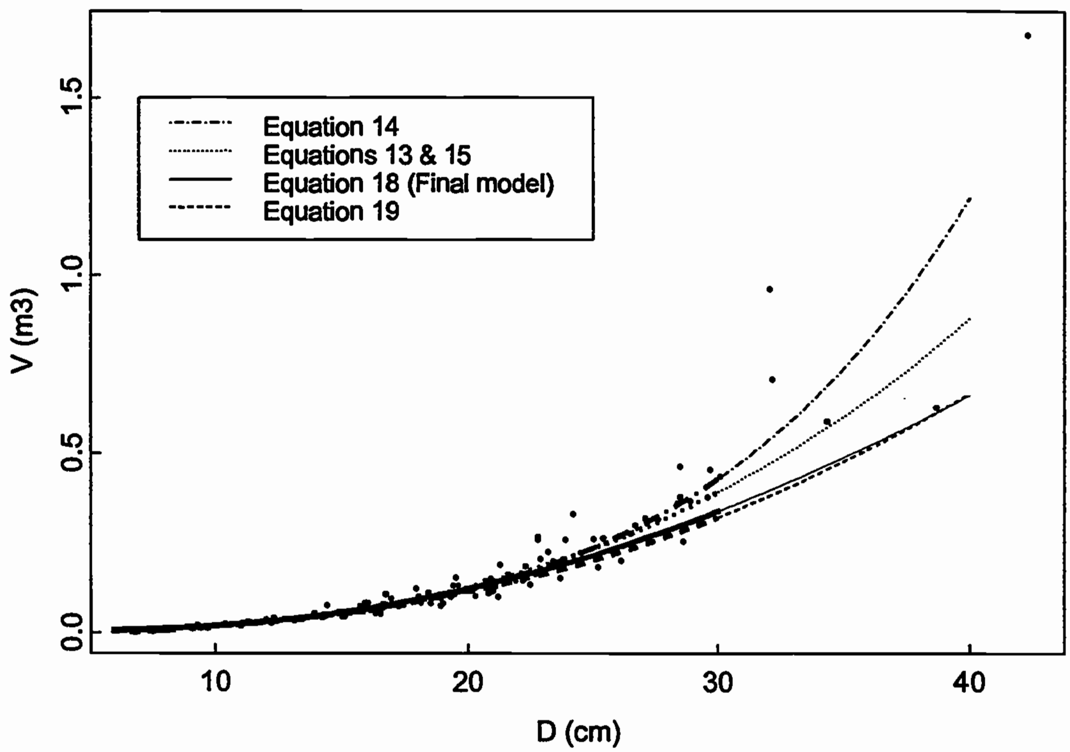

Figure III.8. Neuquén diameter(D)-volume(V) data and regression lines for equations 13, 14, 15, 18, and 19. All equations had an index of fit below .017. Comparisons are most meaningful within the 6-30 cm D range (thick portion of lines).

A Comparison with Models Developed in the Western United States

McDonald and Skinner (1989) used equation 13 ($\ln V = \beta_0 + \beta_1 \ln D$) to calculate cubic volume of young ponderosa pine trees growing on highly productive sites on westside northern Sierra Nevada mixed-conifer forests (Table III.8). They sampled larger trees with Ds ranging between 8 and 102 cm. Chapman and others (1982) applied model 19 ($V = \beta_0 D^{2\,\beta_1}$) to estimate volumes of ponderosa pine trees in northern Washington (Table III.8). They sampled individuals with a mean and maximum D of 19.3 and 30.5 cm, much more similar to the mean and maximum D of Neuquén sample trees, 18.1 and 42.3 cm.

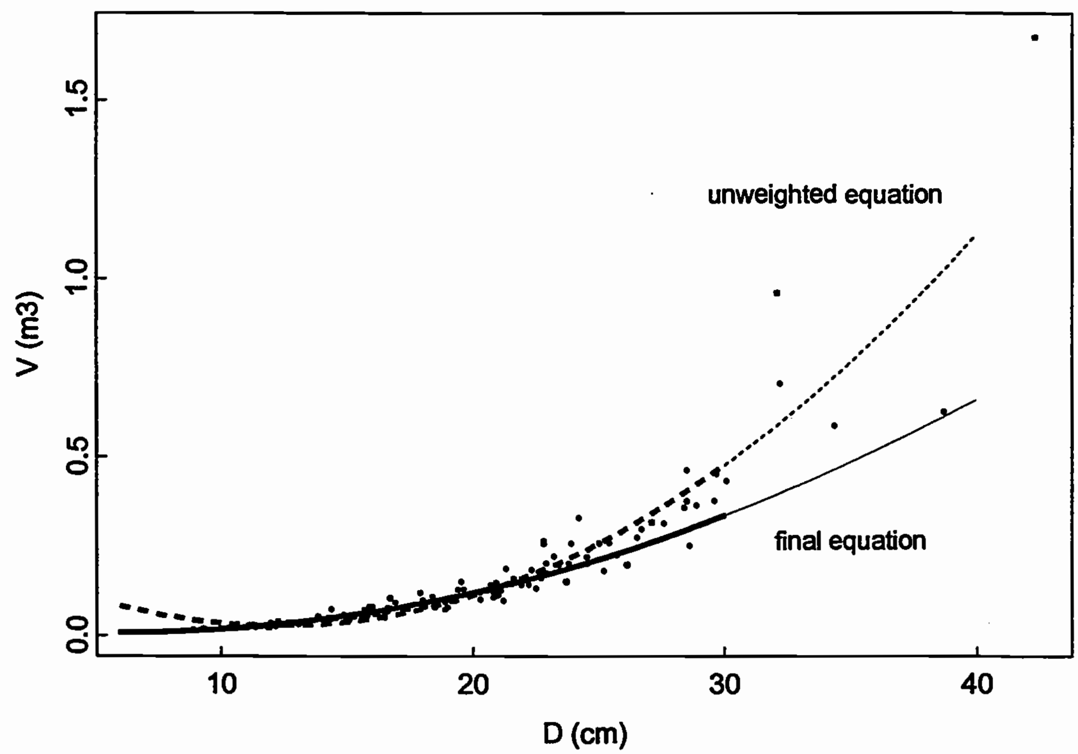

Figure III.9. Neuquén diameter(D)-volume(V) data and the regression line for the selected one-variable model, equation 18. The unweighted version of equation 18 is also shown for comparison. Final model predictions will be most accurate within the 6-30 cm D range (thick portion of the line).

Table III.8. Coefficients of one-variable equations 13 and 19, fitted to ponderosa pine data in English units in Neuquén (Gonda et al. 1979), northeastern Washington (Chapman et al. 1982), and the westside of Sierra Nevada (McDonald and Skinner 1989).

	Equation 13 ($\ln V = \beta_0 + \beta_1 \ln D$)		Equation 19 ($V = \beta_0\ D^{2\,\beta_1}$)	
	Gonda et al. not corrected	McDonald & Skinner corrected for log bias	Gonda et al. weight: $1/D^7$	Chapman et al. unweighted
β_0	-4.305999	-4.0865	.019724	.02149
β_1	2.807196	2.7826	1.293126	1.33525

The volume predictions of both equations for the different regions were compared for the D range of our data set, 6 to 40 cm (Figure III.10). Comparisons were most meaningful for trees with Ds between 6 and 30 cm. Within this range, equations 13 and 19 predicted an average of 15 and 25% more stem volume for northern California and Washington trees than for those in Neuquén respectively. An important proportion of these volume differences could be due to fitting procedures. The log bias of equation 13 was corrected for California trees but not for Neuquén individuals. Equation 19 was weighted for Neuquén trees but not for individuals growing in northeast Washington. However, it seemed reasonable that ponderosa pine trees of the same D would have the same or little less volume in Neuquén than those growing in United States. Yield studies (Gonda, unpublished data) demonstrated that Neuquén trees grow faster than those in most regions of the United States, thus trees of the same D would tend to be younger and thus shorter in Neuquén. We speculate that the difference in age between trees of the same D in the United States and Neuquén is large enough for trees in United States to be significantly taller, despite the potential detrimental effect of competing vegetation on early H growth. The fact that northern California sample trees were much larger than those sampled in Neuquén could also contribute to an overestimation of the volume of individuals between 6 and 40 cm when applying the coefficients from the former region.

Further Studies

To estimate stem volume of trees with Ds larger than 40 cm, data should be collected from trees with larger diameters and the equations refitted. In order to produce high value timber, the mean D of the ponderosa pine plantations of Neuquén will be allowed to reach approximately 50 cm. Thus, an extension of the proposed models should be developed within the next 15 years, when many of the stands start approaching rotation age.

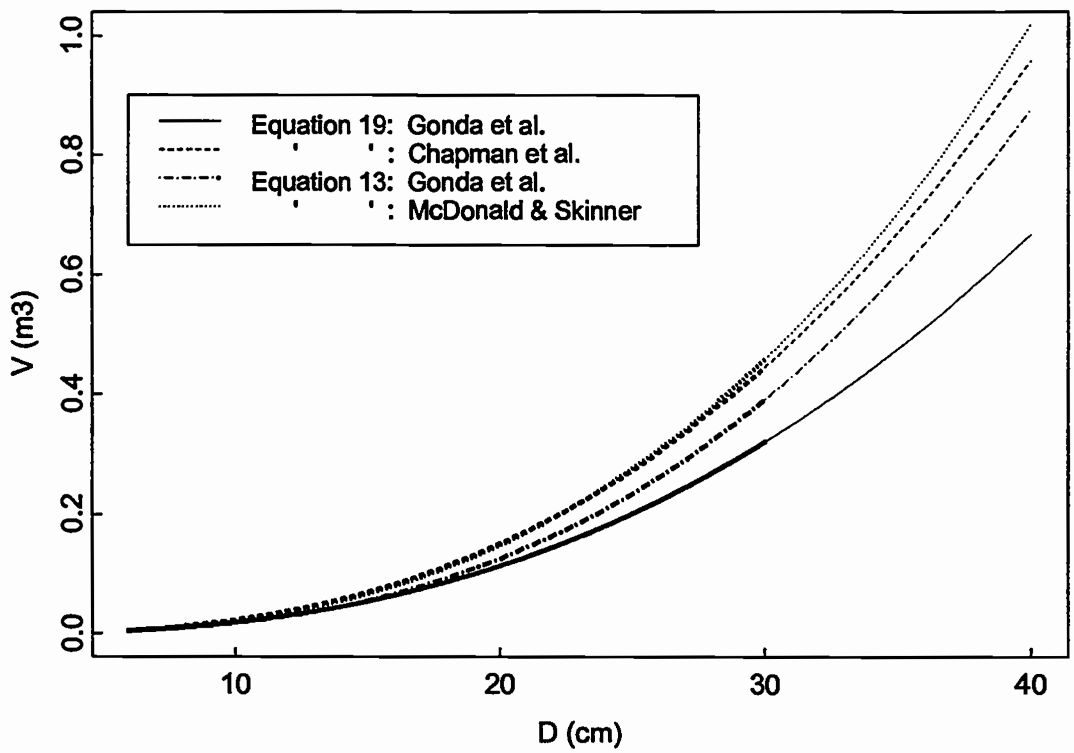

Figure III.10. Neuquén diameter(D)-volume(V) data and regression lines for equation 13, fitted to Neuquén (Gonda et al. 1997) and northern Sierra Nevada data (McDonald and Skinner 1989), and equation 19 fitted to Neuquén (Gonda et al. 1997) and Northern Washington data (Chapman and others 1982). Comparisons are most meaningful within the 6-30 cm D range (thick lines).

Neuquén foresters will also need to calculate inside bark volume of standing ponderosa pine trees to different top diameters in the near future because merchantability standards change rapidly. This can be achieved by developing different types of models such as volume ratio functions that predict the ratio of merchantable to total volume (Burkhart 1977, Cao et al. 1980, Faurot 1977), or taper equations (Amidon 1984, Biging 1984, Cao et al 1980, Czaplewski et al. 1989, Max and Burkhart 1976). Any of these procedures can be carried out with the data collected for the present study. Letourneau (1996) has already developed stem profile equations to predict outside bark diameters for ponderosa pine trees in the provinces of Río Negro and Chubut, Patagonia.

Equations to estimate diameter inside bark, double bark thickness, and past diameter outside bark from measurements of current diameter outside bark at breast height can also be useful, as Dolph (1984) demonstrated for young-growth ponderosa pine in Northern California.

CONCLUSIONS

On the basis of Furnival's index of fit and model behavior, a linear function containing D^2H and D as explanatory variables (equation 4) should yield the most accurate stem volume predictions. A linear model of the form $V = \beta_0 D + \beta_1 D^2 + \varepsilon$ (equation 18) would give the best volume prediction when H data is not available. Crown ratio was not a significant variable when added to D and H. This was not surprising because CR was over 50% for most sample trees, even for older individuals at close spacings. Both final models are most appropriate for trees with Ds between 10 and 30 cm, which is the D range of 96% of the sample trees used for the study (Figure III.5) and most of the ponderosa pine plantations in Neuquén province. Volume predictions for trees with diameters between 30 and 40 cm may not be as accurate, and extrapolations beyond 40 cm are not recommended.

Two-variable functions developed for ponderosa pine in the Western United States underestimate the volume of trees of the same species in Neuquén province. Trees of the same D and H appear to have more volume in northern Patagonia. Trees of the same D however, would have approximately the same volume in both countries because they would be older and thus taller in western United States. All functions developed in the western United States predicted similar volumes for different regions and for different tree sizes. This indicates that tree shape differences between the two countries is not likely due to chance. We speculate volume differences can be attributed mainly to the detrimental effect competing vegetation produces on the growth of ponderosa pine trees in western United States, and the faster D growth of Neuquén trees.

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IV. A GROWTH INTERCEPT INDEX FOR UNTHINNED YOUNG-GROWTH PONDEROSA PINE PLANTATIONS IN NEUQUÉN, PATAGONIA, ARGENTINA

Héctor E. Gonda, Steven D. Tesch, David D. Marshall,

and Gustavo O. Cortés

ABSTRACT

Growth intercept (GI) is commonly regarded as a more suitable indicator of site potential than site index for young plantations. Growth intercept typically assesses site quality by measuring the length of a specific number of successive annual internodes starting at a defined point on the stem. The ability of several GIs to predict top height (TH) and crop height (CH) from ages 12 to 20, was evaluated on data collected from standing trees in 104 unthinned ponderosa pine plantations in Neuquén, Patagonia, Argentina. Top height and CH were defined as the mean total height of the 100 and 300 trees per hectare with the largest diameter at breast height (BH), respectively. A GI index was developed to predict the site quality of stands based on the length of the five internodes beginning at or above BH. This index can accurately predict TH at a base age of 20 years and it can be applied as early as age 10 on most sites. In a companion analysis, the use of the GI concept in predicting the height of selected dominant trees from ages 10 to 25 was tested on felled tree data from 77 stands. These results supported standing-tree data trends up to age 20, and based on a small sample size suggested that several GI indexes can predict the height of dominant trees up to at least age 25.

INTRODUCTION

The Importance of Ponderosa Pine in Patagonia

Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) is the most widely planted species in the Patagonian Andes region of Argentina, where it grows vigorously and without any serious pest problems. Preliminary studies suggest that the average yield of these stands could be similar to or even higher than those growing on highly productive regions of the United States, such as northern California (Gonda and Lomagno 1995, Urzúa 1991). The environmental conditions in northern Patagonia are similar to those where ponderosa pine (variety ponderosa) forests grow naturally in the western United States. The piedmont of the northern Patagonian Andes and the interior Pacific Northwest share the following main characteristics:

1. The latitudinal ranges are similar in the respective hemispheres (Figure IV.1)
2. Moisture is provided by humid winds blowing from the Pacific Ocean.
3. A rain shadow effect is produced by the Andes as well as by the Cascades and the northern Sierra Nevada ranges.
4. A Mediterranean climate prevails, imposing a well-defined dry season.

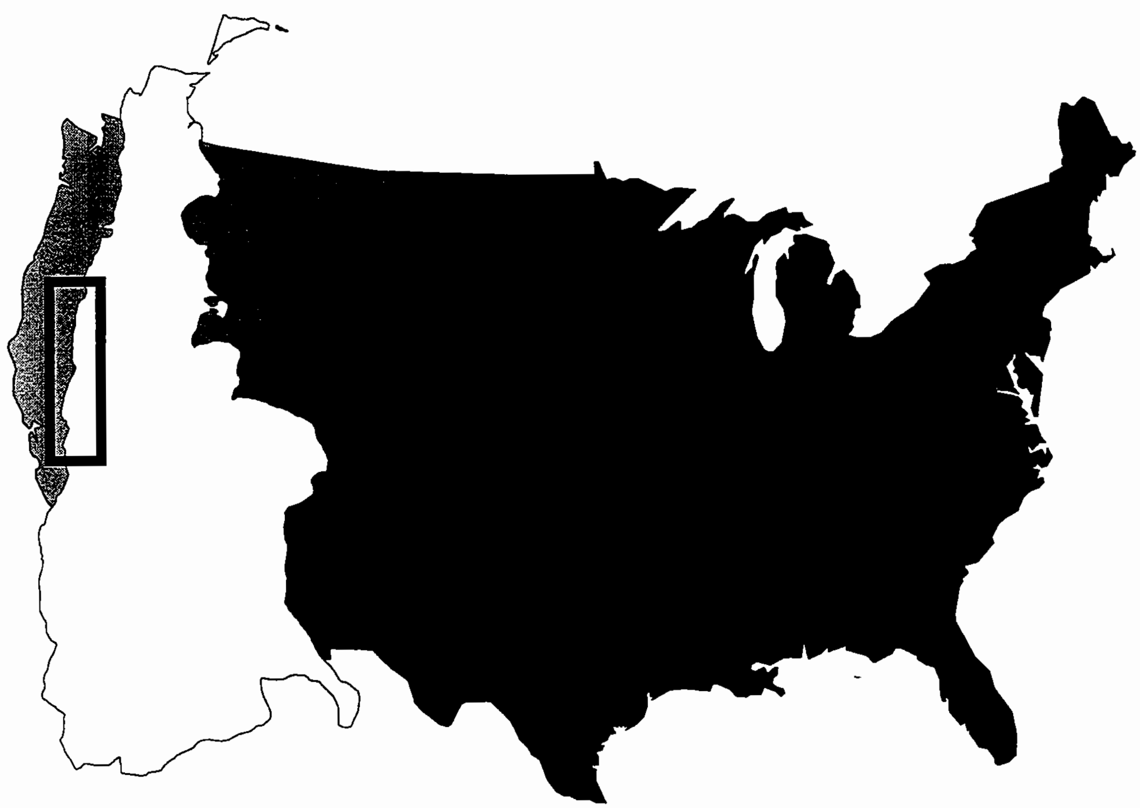


Figure IV.1. A map superimposing the Patagonian Andes (Argentina) over the Cascades and northern Sierra Nevada (United States). The rectangle includes the current distribution area of the ponderosa pine plantations in Patagonia. The latitude of both countries match, and they are drawn at the same scale.

5. A high proportion of the soils are of volcanic origin.

The area planted annually with ponderosa pine in Argentina is rapidly increasing due to the subsidies and credits that the Patagonian provinces and the federal government provide for planting fast-growing species. The primary objective of this support is to promote afforestation as a means to improve the socioeconomic conditions of the region. Even though currently there are only about 30,000 hectares of ponderosa pine forests (Urzúa 1991), there are about a million hectares of grasslands suitable for commercial afforestation throughout the piedmont of the Patagonian Andes (Enricci 1993).

Information on site quality and growth of ponderosa pine in Patagonia is limited. This incomplete knowledge can dissuade potential investors from planting trees and frustrate efforts to develop sound management plans. Because species that are grown outside their native range typically exhibit growth and developmental patterns that differ significantly from those of the species within its native environment, it is also risky to extrapolate growth predictions to new geographic areas (Zobel et al. 1987).

To ameliorate these problems the Patagonian Andes Forest Research and Extension Center (CIEFAP), along with the University of Comahue Forest Technical School and the government of Neuquén, have started quantitative silvicultural studies on ponderosa pine plantations throughout Neuquén province, covering an area that includes about 80% of the present plantation forests of this species in Patagonia (Figure IV.2). These studies constitute the Neuquén Ponderosa Pine Site Quality and Yield (NPPSQY) project.

Why Growth Intercept ?

Site index, the most frequently used indicator of site potential (Clutter et al. 1983, Smith et al. 1997), is usually not suitable for young plantations below 15 or 20 years of age. Site index requires knowledge of the total height and age of the

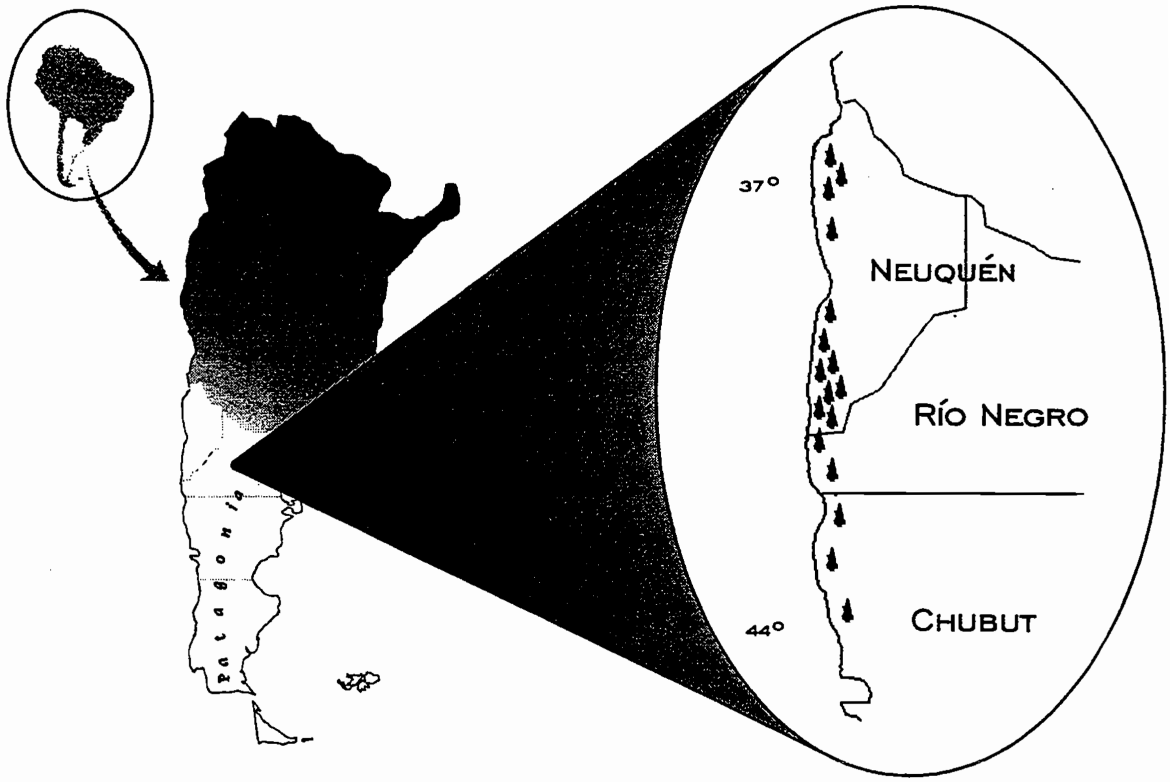


Figure IV.2. From left to right: maps showing the position of Argentina in South America, Patagonia within Argentina, and the current distribution of the ponderosa pine plantations in the provinces of Neuquén, Río Negro, and Chubut. The number of pine trees is proportional to the plantation area.

stands. In young stands, total height can be strongly influenced by competition or other factors and small miscalculations of the plantation age can result in a large site index error; only one or two years represent a large proportion of the total tree height. In young plantations, the growth intercept (GI) method has been demonstrated to be a more accurate indicator of site quality than site index (Alban 1972, Alban 1979, Beck 1971, Carmean 1975, Day et al. 1960, Ferree et al. 1958, Gregory 1960, Oliver 1972, Powers and Oliver 1978, Richards et al. 1962, Wakeley 1954, Wakeley and Marrero 1958, Warrack and Fraser 1955). Growth intercept typically consists of evaluating site quality by using information on stand height growth for some relatively short period of time.

Most GI methods involve the length measurement of a specified number of successive annual internodes or GI, beginning at a defined point on the stem. The starting point is usually near or above breast height (BH), in order to avoid the often erratic height growth during the seedling establishment period. More recently, some variations of the traditional method have been explored. Nigh (1996) designed a GI model that, based on all the growth above BH, can be applied to species without distinctive branch whorls. Brown and Stires (1981) demonstrated that by including some topographic and/or soil factors into GI functions, the accuracy of the site quality prediction can be significantly increased.

Numerous factors can cause the irregularities during the establishment period such as competitive vegetation (Powers and Oliver 1978, Wilde 1964), diseases and pests that exert their effects at early ages (Wakeley and Marrero 1958), nursery stock, planting technique, mishandling of seedlings (Wakeley and Marrero 1958), rabbit damage (Wakeley 1954), etc. The effect of the erratic early growth on site index was recognized as early as 1956 in two separated papers by Hush (1956) and McCormack (1956), who indicated that age above breast height was preferable to total age as the variable in height-age curves.

The GI method is most useful in short rotations where height growth is only projected a few years beyond the GI measurements (Alban 1979, Carmean 1975). Later height growth may not be adequately predicted, particularly in areas where site factors are much different from the area where the study was performed (Carmean 1975). In red pine (*Pinus resinosa* Ait.) stands of the Lake States, GI gives a more accurate estimate of site quality than site index up to age 25 (Alban 1979, Day et al. 1960, Ferree et al. 1958). From ages 25 to 30 the two methods work similarly well and beyond 30 years site index usually gives the best results (Alban 1979). For northern California ponderosa pine GI works well up to slightly over 20 years (Oliver 1972). In the southern Appalachians, estimates of eastern white pine (*Pinus strobus* L.) site index from GI are about as accurate as estimates from site index curves up to age 15 (Beck 1971). In British Columbia Douglas-fir (*Pseudotsuga menziessi* (Mirb.) Franco) stands, the mean length of four or five internodes above BH showed low potential to predict total height at ages 50 and 100 (Smith et al. 1960).

Most GI studies conducted for commercial tree species in North America and Europe related GI to site index, expecting that GI may eventually serve for a more rapid and accurate determination of the site index of young plantations. This relationship was examined for eastern white pine in the southern Appalachians (Beck 1971), and Ohio (Brown and Stires 1981), ponderosa pine in northern California (Oliver 1972), Douglas-fir in British Columbia, Canada (Smith and Ker 1956, Smith et al. 1960, Warrack and Fraser 1955), red pine in Minnesota (Alban 1972, Schallau and Miller 1966), Michigan (Day et al. 1960,Gunter 1968), Wisconsin (Wilde 1964), and New York (Richards et al. 1962), mixed stands of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Alaska (Gregory 1960), and black pine (*Pinus nigra* var. *pallasiana*) in Greece (Economou 1990).

Only two studies considered the relationship between GI and total height, proposing GI as an independent measure of site quality. Wakeley (1954) and Wakeley and Marrero (1958), who were the first to use the GI approach, proposed a five-year intercept index for young southern pine plantations, i.e. loblolly pine (*Pinus taeda* L.), slash pine (*Pinus elliottii* Engelm.), shortleaf pine (*Pinus echinata* Mill.), and longleaf pine (*Pinus palustris* Mill.). Ferre and others (1958) developed a similar index for red pine plantations in New York.

Three papers explored the potential of the average annual height growth, instead of the successive lengths of internodes, as the site quality estimator of young plantations. Hansen and McComb (1958) applied this criterion on plantations of several species growing on submarginal farmland in Iowa, paying special attention to green ash (*Fraxinus pennsylvanica* Marsch.) and black walnut (*Juglas nigra* L.). Stoate and Crossin (1959) developed an increment-height site index for young Douglas-fir stands in British Columbia. Schallau and Miller (1966) utilized the mean yearly growth of 1 to 4 internodes to predict site index of red pine plantations damaged by the European pine shoot moth.

Ponderosa pine is a suitable species for the application of the GI approach, because height growth is unimodal; it forms a single whorl of branches each year (Oliver 1972), and height growth differences caused by site tend to appear early when stands reach BH (Oliver and Powers 1971). Using the site index method, site quality is best estimated when volume production potential and height growth are highly correlated (Clutter et al. 1983). This is also the case for GI, because we will examine the ability of different GIs to predict site quality based on their ability to predict height. In the ponderosa pine plantations of Neuquén, among the 127 plots established for the NPPSQY project, the correlation coefficient between total volume and either mean or dominant height was .93, regardless of age, spacing, or any other factors (Gonda, unpublished data).

Most ponderosa pine plantations in Neuquén are young, less than 2/3 of the rotation age which is estimated to be between ages 30 and 40 (Urzúa 1991). Information from the few older stands is of limited utility for yield studies because they have been recently thinned, or because they are so small in area that it is not possible to obtain data without observing a severe edge effect. Stand age information is often not available, and determining it in the field can result in an error when the total number of internodes in the lower portion of the stem cannot be counted accurately.

Literature on site quality determination of the ponderosa pine plantations in Patagonia is limited. Colmet Daage (1989), Ferrer et al. (1990), and Mendía and Irisarri (1986) presented classification systems to determine the capacity of large areas to grow ponderosa pine trees based mainly on soil characteristics. Girarden and Broquen (1995) studied height and volume growth in plantations from 2 to 16 years of age on three transects running east-west in northern, central, and southern Neuquén. They defined site quality based on the dominant height of the stands at age 14.

For the southern range of the ponderosa pine plantations located in the provinces of Río Negro and Chubut (Figure IV.2), Andenmatten and Letourneau (1996b) developed a site index equation to predict TH up to age 35 from age at breast height based on the stem analysis of 57 trees collected in 22 plots. They also examined the ability of different GIs to predict site index on data collected from 22 dominant trees (Andenmatten and Letourneau 1996a).

The intrinsic characteristics of the GI method make it potentially the most appropriate indicator of site productivity for the young-growth ponderosa pine plantations in Neuquén: 1) age needs not be measured, this saves time and reduces error; 2) measuring internodes is more rapid and accurate than measuring total tree heights, especially in dense stands; and 3) measuring internodes above BH eliminates the period of erratic early height growth, avoiding errors that are often associated with site index curves based on total age. The main disadvantage of the GI method is that site quality estimation is only based on early height growth which may not be related to height growth in later years (Carmean 1975, Wilde 1964).

Objectives

The first objective of this study is to evaluate different GI methods involving the length of varying numbers of internodes starting at different points on the stem for the ponderosa pine plantations in Neuquén. The evaluation consists of determining which method is not only a reliable predictor of height growth, but also feasible to apply in the field at early ages. The second objective is to develop a site quality index based on the selected GI method.

METHODS

The ability of several GIs to predict stand height was examined from ages 10 to 25. From here on, stand or tree age will be referred to as age from planting; the two or three years seedlings spent in the nursery are not taken into consideration. Since few stands older than 20 years were available for measurement, the inferential model or GI index was developed to predict height at age 20.

The study was carried out by performing a similar type of analysis on two different sets of data collected during the winter of 1996: 1) Information was collected from standing trees in 104 plots, in almost the same fashion as is recommended for applying the proposed GI index. Plots provided information related to a single point in time, the stand's current age. The model for the GI index was based on this data set. 2) Data were also obtained from a single dominant tree felled in 77 plots. Measuring the length of the internodes made it possible to calculate the stand height in past years. Despite coming from fewer plots, this data set contained more observations per age class that could be used to test the predictive ability of several GIs.

Data from Standing Trees

Plots Location and Age Classes

Thirteen GIs were evaluated to test their ability to predict the top height (TH) and crop height (CH) of stands between ages 12 and 20. Data were collected in 104 plots scattered throughout the current range of the ponderosa pine plantations in Neuquén province. The three southernmost plots were located in Río Negro province, only a few kilometers from the Neuquén border; because there were no ponderosa pine plantations on the Neuquén side (Figure IV.3). Top height and CH were defined as the mean total height of the 100 and 300

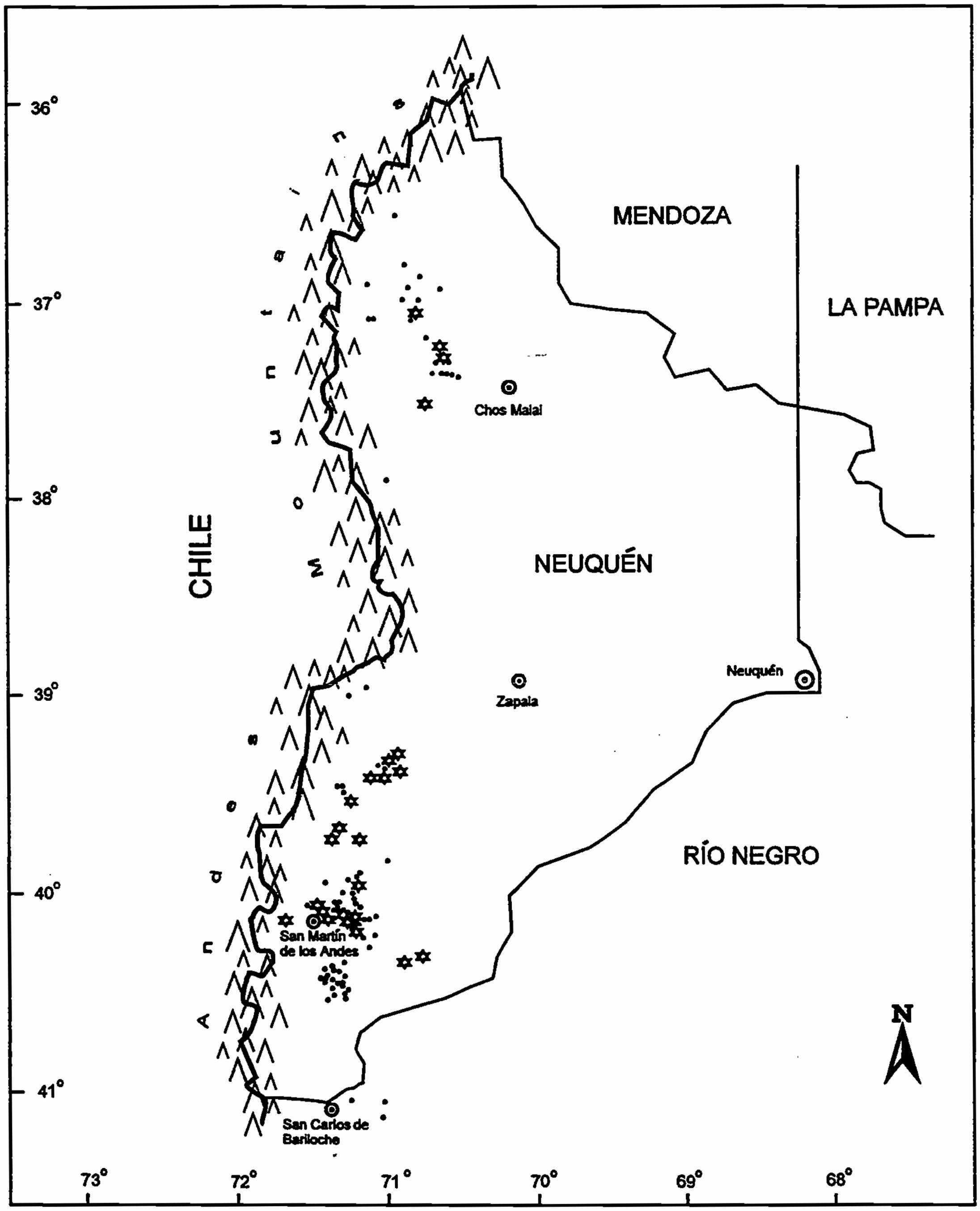


Figure IV.3. Location of the 104 standing-tree sample plots . The stars correspond to the 24 plots whose information was used to build the final model.

trees per ha with the largest diameter at breast height (D), respectively. Top height was the preferred parameter for the GI index because it requires measuring fewer trees, and it tends to be a more accurate site quality indicator than CH because larger trees are usually less affected by dense stocking or thinning (Assman 1970, Clutter et al. 1983). Crop height provided informationabout the average height of the most valuable trees of the stand, the ones that would be part of the last thinning and the final harvest.

To increase the number of observations available for the models that predict stand height at age 20, THs and CHs from 19- and 21-year-old plots were extrapolated to age 20 (Table IV.1). The length of the extrapolated internode was calculated by dividing TH and CH by the age of the respective plot minus a certain number of years. The subtraction was intended to account for the slow height growth period after outplanting. The felled-tree data were used as a basis for determining how many years to subtract, resulting in a more accurate extrapolation. Subtractions of 0 to 5 years from the stand current age were tested, and the respective height predictions were evaluated by performing a paired t-test between them and the observed height at age 20. A sample of 17 felled trees was used to evaluate the five values for the extrapolation of the H of the 21-year-old plots and, 24 felled sample trees were used for the same evaluation for the extrapolation of the H of 19-year-old plots. The result was to subtract three and four years from the 21- and 19-year-old plots respectively.

Table IV.1 Number of standing-tree sample plots available between ages 12 and 21, and number of observations available to analyze the relationship of the GIs with TH and CH at age 20, after extrapolating TH and CH from 19- and 21- year-old plots ($extrapolation_{20}$).

Age	12	13	14	15	16	17	18	19	20	21
Plots	14	13	13	11	11	8	10	11	8	5
$Extrapolation_{20}$									24	

Geographical and Environmental Ranges

The 104 standing-tree sample stands covered most of the geographic distribution of the ponderosa pine plantations in Neuquén province (Figure IV.3), as well as much of the range of factors that can be associated with tree growth and form, i.e. latitude, longitude, elevation, slope, aspect, precipitation, soil depth, age, and density (Table IV.2). The number of plots available for measurement in each of the age classes was limited (Table IV.1) and the full range of factors was not available in each age class. However, the 24 plantations used to develop the GI index at age 20 sampled most of the geographical and environmental variability (Table IV.2, Figure IV.3).

Table IV.2. Minimum (min), maximum (max), and mean values of latitude, longitude, elevation (elev), slope, aspect, annual precipitation (precip), soil depth (soil d), and density (tr/ha) ranges covered by the 104 standing-tree sample plots scattered throughout Neuquén province, and by the 24 plots used to predict TH at age 20.

Plot age		Latitude	Longitude	Elev (m)	Slope (degr)	Aspect (degr)	Precip (mm/yr)	Soil D (m)	Tr/ha
12-21	Min	36°30'00"	70°35'22"	745	0	0	400	0.4	307
	Mean	38°47'58"	71°04'18"	1076	8.5	140	912	1.1	1323
	Max	41°05'57"	71°33'15"	1715	28.0	350	2229	1.8	2500
20	Min	36°59'06'	70°36'47"	750	0	0	400	0.4	671
	Mean	38°38'26"	71°05'01"	1041	11.4	185	946	1.0	1401
	Max	40°17'46"	71°33'15"	1360	25.0	350	2229	1.3	2100

Plot Characteristics

The 104 sample plots used in this study were selected from 127 permanent plots established for the NPPSQY project. The plots not used were younger than age 12 and older than 20; they were rejected because we wanted a minimum of eight plots per age class for the analysis and these age classes did not meet that criterion. The 21-year-old plots were only used for extrapolation purposes. A maximum of one plot was sampled per stand; plots were circular in shape, and were large enough to include at least 40 trees.

In 67 of the plots, D and total height (H) were measured on each tree. In the other 37 plots, the Ds of all trees were recorded but, due to time constraints, the Hs of 2/3 of the individuals were typically measured. Heights were always measured across the range of diameter classes, paying special attention to include the tallest and shortest individuals. Missing Hs were computed by fitting Wykoff's height-diameter function (Wykoff et al. 1982) to each of the 37 plots: $H = 1.3 + e^{(\beta 0 + (\beta 1 / (D + 1)))} + \varepsilon$.

The heights to the first six whorls of branches, beginning at or above breast height, were measured on the five tallest trees in each of the 104 plots. These measurements were used to calculate the length of each of the five internodes starting at or above breast height.

The vast majority of the 5084 sample trees were healthy and undamaged. Only 56 individuals, scattered among 31 plots, showed some degree of abnormality; 26 were forked, 20 bent by the snow, 10 had broken tops, and six shared the same stem below breast height. The H of trees bent by the snow or with broken tops were computed with Wykoff's H-D equation. None of the plots contained more than five abnormal trees. One of the plots contained 43 ponderosa pine and 10 Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) trees. The Jeffrey pines were retained because these trees exhibit similar growth characteristics (Hallin 1957). Some of the sample trees had been pruned, but it was assumed not to affect tree growth significantly because the standard pruning practice eliminates no more than 1/3 to 1/2 of the live crown, and pruning had been done recently.

The age of the plots was determined by counting the total number of internodes on several dominant trees. The H of trees less than 12 meters tall as well as the height to the first six whorl of branches starting at or above breast height, were measured directly with a telescopic fiberglass pole to the nearest cm. Taller trees were measured indirectly with clinometer (either *Blume-Leiss* or *Suunto*) to the nearest 5 cm. The D was measured to the nearest 0.1 cm with diameter tape at 1.3 m from the ground.

Analysis

Growth Intercepts

Each of the 13 GIs studied included one or more of the first five internodes beginning at or above BH. Five GIs contained the cumulative lengths of one to five of those internodes going from the bottom up ($GI_{1\text{-}BH}$, $GI_{2\text{-}BH}$, $GI_{3\text{-}BH}$, $GI_{4\text{-}BH}$, and $GI_{5\text{-}BH}$). Four GIs comprised the cumulative length of one to four of those internodes going from the top of the five measured internodes down ($GI_{1\text{-}BHT}$, $GI_{2\text{-}BHT}$, $GI_{3\text{-}BHT}$, and $GI_{4\text{-}BHT}$) (Figure IV.4). The other four GIs, included the length of the four ($GI_{4\text{-}2m}$), three ($GI_{3\text{-}2.5m}$), two ($GI_{2\text{-}3m}$), and one ($GI_{1\text{-}3.5m}$) internodes, beginning at or above 2.0, 2.5, 3.0, and 3.5 m respectively (Figure IV.4). On most sites, the intercepts $GI_{1\text{-}BHT}$, $GI_{2\text{-}BHT}$, $GI_{3\text{-}BHT}$, and $GI_{4\text{-}BHT}$ included the same internodes as $GI_{1\text{-}3.5m}$, $GI_{2\text{-}3m}$, $GI_{3\text{-}2.5m}$, and $GI_{4\text{-}2m}$, respectively. However, they differ in that the latter intercepts are easier to measure because they start from a fixed height on the stem.

For slower growing sample trees on the poorer sites, some of the growth intercepts starting at 2 m or higher, required measurements of the length of the sixth or the sixth and seventh internodes beginning at or above BH. Since these two internodes were not measured, complete data were unavailable for some sample trees. Hence, the length of $GI_{1\text{-}3.5m}$, $GI_{2\text{-}3m}$, $GI_{3\text{-}2.5m}$, and $GI_{4\text{-}2m}$, in 10, 20, 30

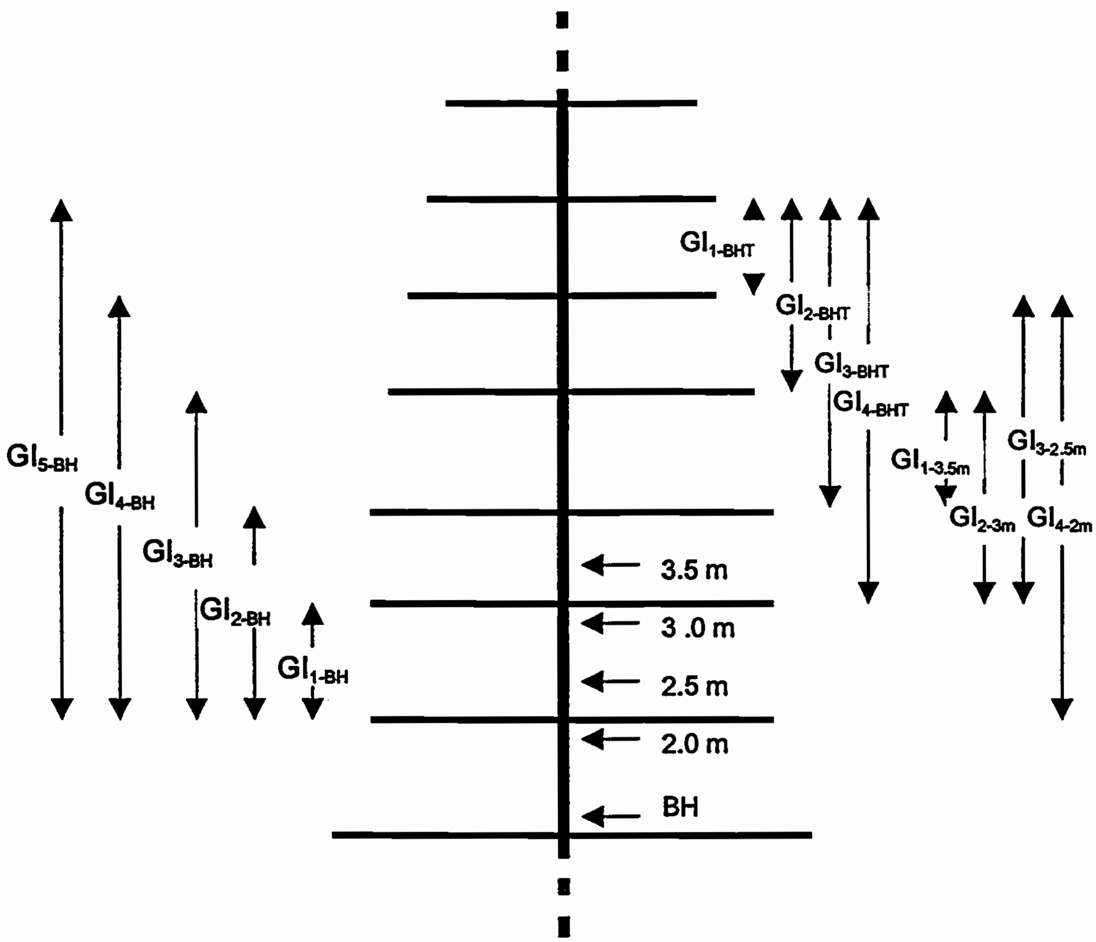


Figure IV.4. Lower part of a stem showing the 13 different GIs measured on the five tallest standing trees in 104 plots. The BH intercepts include the cumulative length of one to five internodes starting at or above BH going from the bottom up. The BHT (breast height top) intercepts include the cumulative length of one to four internodes above BH, but starting from the top of the five internodes measured down. The GIs named GI_{4-2m}, $GI_{3-2.5m}$, GI_{2-3m}, and $GI_{1-3.5m}$, include the length of four, three, two, and one internodes beginning at or above 2, 2.5, 3, and 3.5 meters respectively. On most sites they include the same internodes as the BHT intercepts that contain the same number of internodes; though it is not illustrated in this diagram.

and 50% of the plots, respectively, were based on the mean from the 2-4 tallest trees per plot, instead of the desired five per plot.

Equations

Three linear functions were fitted relating each of the 13 GIs as explanatory variable and TH and CH as response variables, for each of the age classes studied. The first function contained a linear and a squared term, the second only a linear term, and the third only a squared term. The function with the lowest mean square error (MSE) and with significant explanatory variables (at the 95% level) was selected for comparison. The significance of a squared term wasexamined because scatterplots of the GI-TH and GI-CH data suggested that some of the relationships tended to be slightly curved. The ability of the different growth intercept methods to predict TH and CH was then evaluated by comparing the adjusted coefficients of determination (R^2) of the respective linear regressions.

Data from Felled Trees

A second data set that had been collected to develop tree volume equations was used to test the ability of 35 different GIs to predict the total height of selected dominant trees. This data set was obtained by felling a single dominant tree in 77 stands, on which the length of all internodes was measured. The 35 GIs studied were the result of the combination of the cumulative length of one to seven internodes with five starting points on the stem: at or above BH, 2.0, 2.5, 3.0, and 3.5 m. The D of the felled trees was intended to be as similar as possible to the mean D of the 300 trees per ha with the largest D, and their H as similar as possible to the stand CH. However, since most stands were young, the difference between TH and CH was small, and the felled trees are representative of both TH and CH of standing trees for practical purposes.

The main goal of this analysis was to study the predictive ability of a larger number of GIs on selected dominant trees, in order to double check the trends found in the standing tree data. The results were not used to develop predictive functions because the height of a single dominant tree is not an objective parameter, such as stand TH or CH. Felled trees were selected based on data collected from a single plot in each of the 77 stands (Figure IV.5). These 77 plots were part of the 127 plots established for the NPPSQY project, and thus they were installed in the same manner as those included in the standing-tree set of data. Sixty-four plots provided information for both data sets. Sample trees did not include those curved, forked, unhealthy or with broken tops. Total H and D were measured on the sample trees before felling. After felling, the length of all internodes were measured with a fiberglass or metal tape.

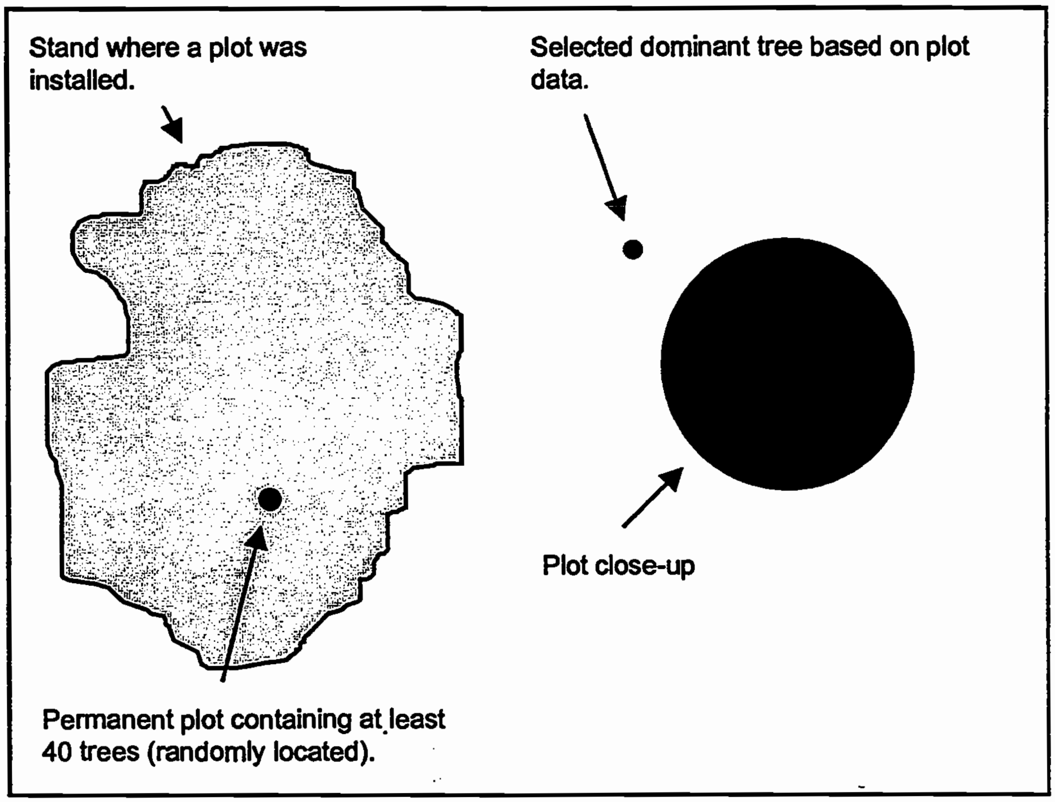


Figure IV.5. Representation of how dominant trees were selected in each of the 77 stands for the felled tree data set.

The 77 sample stands covered most of the geographic distribution as well as the ranges of the environmental factors with the highest potential to influence tree growth. Twenty four felled trees were 20 years old or older, so we did not extrapolate H information to study the relationship between tree H and GI at age20, as we did for the standing-tree data. The 24 plots that had reached age 20 covered a high proportion of the geographic and environmental ranges (Table IV.3). The relationship between each of the 35 different GIs and tree H was evaluated by fitting simple linear regressions with GI as the explanatory variable. Similarly to the standing tree data, some of the relationships showed a slight curvature, therefore the significance of a square term was also evaluated in all cases. Three functions were fitted: 1) containing a linear and a square term, 2) containing only a linear term, and 3) containing only a square term. The function with the lowest MSE and with significant explanatory variables at the 95% level was the one selected. Then, the ability of the different GI methods to predict tree H was evaluated by comparing the adjusted R^2 values of the respective linear regressions.

Table IV.3. Minimum (min), maximum (max), and mean values of latitude, longitude, elevation (elev), slope, aspect, annual precipitation (precip), soil depth (soil d), and density (tr/ha) ranges of the 77 plots sampled throughout Neuquén province, on which the GI methods were studied on felled trees. All plots had reached age 10, but only 24 plots had reached age 20, covering slightly reduced ranges.

Plot age		Latitude	Longitude	Elev (m)	Slope (degr)	Aspect (degr)	Precip (mm/yr)	Soil D (m)	Tr/ha
10-25	Min	36°30'00"	70°36'31"	650	0	0	400	0.4	538
	Mean	38°47'39"	70°57'27"	1121	8.6	130	967	1.0	1466
	Max	41°05'19"	71°18'24"	1700	28.0	337	2229	1.8	2500
20	Min	37°07'08"	70°36'48"	650	0	0	500	0.4	889
	Mean	39°06'13"	70°57'36"	996	11.2	154	1138	1.0	1621
	Max	41°05'19"	71°18'24"	1345	22.0	337	2229	1.5	2280

RESULTS AND DISCUSSION

Data from Standing Trees

A paired t-test indicated that differences between TH and CH were significant at a 95% confidence level at all ages, except for 16-, 19-, and 20-year-old stands. However, at age 20 this difference became significant, when information from the 19- and 21-year-old plots was extrapolated in order to have 24 observations. Even though for practical purposes the difference between TH and CH was not large, we decided to analyze the relationship between the GIs and TH separately from the relationship between the GIs and CH.

The 13 GIs showed a similar ability in predicting TH and CH, at any of the age classes (Table IV.4). This was not surprising since TH and CH were highly correlated. Most of the BH and BHT growth intercepts predicted TH and CH well after stands reached age 12 (R^2>.60), and this ability increased with time up to age 15, when it seemed to reach a plateau by remaining fairly constant until age 20 (Table IV.4). Over 50% of the final regression equations fitted between the GIs and TH and CH called for the inclusion of a significant squared term (Table IV.4), suggesting that these relationships tend to be curvilinear. Moreover, when the straight line function had the smallest MSE, the MSE of the function including only a squared term was often less than 5% larger, suggesting that the latter function had almost the same predictive ability as the straight line equation, plus the capability of behaving better.

Between ages 15 and 20, the upper four, three, or two internodes starting at or above BH, namely $GI_{4\text{-}BHT}$, $GI_{3\text{-}BHT}$, and $GI_{2\text{-}BHT}$, had the same or even a slightly higher predictive ability than the five internodes all together ($GI_{5\text{-}BH}$) (Table IV.4). Even $GI_{1\text{-}BHT}$, the single upper internode, did not have a much lower R^2 value than $GI_{5\text{-}BH}$ (Table IV.4). This indicated that the first few internodes above breast height are of limited usefulness in estimating TH. This has also been observed

Table IV.4. Adjusted coefficients of determination (R^2) for simple linear regressions with different growth intercepts (GIs) as the explanatory variable and top height (TH) or crop height (CH) as the response variable, at nine age classes. Nine different GIs, based on the cumulative length of various numbers of the first five internodes starting at or above breast height (BH), are included. The R^2 values of the four GIs starting at higher points of the stem are not presented because they basically were the same as the R^2 values for the respective BHT internodes. Data were collected from standing trees in 99 plots, between ages 12 and 20; data from the five 21-year-old plots were only used for extrapolation purposes. All R^2 values were significant (.95 confidence level). The boxes include the higher R^2 values, which are > .80 in most cases.

Age	Number of plots	R^2 values for regressions between C H and cumulative length of internodes starting at or above BH									R^2 values for regressions between T H and cumulative length of internodes starting at or above BH								
		1, 2, 3, 4, and 5 internodes starting from the bottom up					1, 2, 3, and 4 internodes starting from the top down				1, 2, 3, 4, and 5 internodes starting from the bottom up					1, 2, 3, and 4 internodes starting from the top down			
		$GI_{1\cdot BH}$	$GI_{2\cdot BH}$	$GI_{3\cdot BH}$	$GI_{4\cdot BH}$	$GI_{5\cdot BH}$	$GI_{1\cdot BHT}$	$GI_{2\cdot BHT}$	$GI_{3\cdot BHT}$	$GI_{4\cdot BHT}$	$GI_{1\cdot BH}$	$GI_{2\cdot BH}$	$GI_{3\cdot BH}$	$GI_{4\cdot BH}$	$GI_{5\cdot BH}$	$GI_{1\cdot BHT}$	$GI_{2\cdot BHT}$	$GI_{3\cdot BHT}$	$GI_{4\cdot BHT}$
20	8	.46	***.58***	.61	***.71***	***.78***	.66	***.92***	***.84***	***.83***	.52	***.64***	***.66***	***.73***	***.81***	***.71***	***.91***	***.85***	***.85***
19	11	ns	.28	.50	.77	.83	.83	.94	.91	.88	ns	.27	.49	.64	.80	***.81***	.90	.89	.85
18	10	ns	ns	.45	.62	.74	***.70***	***.82***	***.82***	***.78***	***.38***	***.42***	***.62***	***.75***	***.84***	***.61***	***.78***	***.82***	***.83***
17	8	ns	.67	***.78***	.76	***.85***	***.76***	***.80***	.70	.83	.57	.61	.78	***.80***	***.87***	***.75***	.84	.76	.86
16	11	.47	.61	.78	.90	.92	.77	.83	.89	.92	.36	.53	.71	.83	***.87***	***.77***	***.81***	***.87***	***.91***
15	11	***.91***	***.96***	***.97***	***.97***	***.96***	.89	.92	***.95***	***.96***	.82	.90	.92	.93	.94	.88	.92	.93	.94
14	13	.52	.84	.79	.73	.77	.74	.69	.66	.75	.46	.78	.76	.71	***.75***	.70	.66	***.66***	***.74***
13	13	***.60***	***.66***	***.66***	***.65***	***.68***	***.37***	***.49***	.65	***.62***	***.64***	***.71***	***.74***	***.75***	***.78***	***.39***	***.59***	.78	.80
12	14	***.30***	***.56***	***.72***	***.68***	.65	.21	.43	.60	.63	***.37***	***.66***	***.76***	***.75***	***.74***	***.31***	.55	.67	***.70***

The R^2 values of equations that include an intercept and a linear term are presented in regular fonts.
The R^2 values of equations that include an intercept and a square term are shown in bold face italics.
The R^2 values of equations that include an intercept, a linear term, and a square term are underlined.
ns : model not significant at the .95 level.

in red pine plantations and natural stands in the lake states (Alban 1979). These results did not change among age 20 data containing extrapolations (Table IV.5).

Data from Felled Trees

The results from felled trees confirmed the main trends found in the standing-tree data. Among the GIs that start at or above BH, those that contained three or more internodes began to be strongly associated with the H of dominant trees ($R^2 > .60$) at age 12, and their predictive ability did not improve significantly between age 15 and 20 (Table IV.6). The GIs that start at higher points on the stem, did not show a strong association with H until age 13, 14, or 15, and their predictive ability kept improving slowly, but steadily, until age 19 or 20 (Table IV.6).

Data from felled trees corroborated that the higher the starting point on the tree, the better the predictive ability of the internodes, and thus fewer of them need to be measured to estimate the stand dominant H with the same accuracy (Table IV.6). At age 20, the GIs starting at or above 1.3 and 2.0 m above the ground provide maximum accuracy when seven internodes are measured; growth intercepts starting at 2.5, 3.0, and 3.5 m would be most accurate by including only six, five, and four internodes respectively. The high R^2 values associated with the few plots that were available for measurement between ages 21 and 25 suggested that GI methods could possibly predict the height of dominant trees at least up to age 25 in the ponderosa pine plantations of Neuquén (Table IV.6). Only 20% of the functions called for the inclusion of a significant square term. Nevertheless, most straight line equations had a MSE that was only 5% lower than the MSE of a function containing only the squared term as explanatory variable.

Table IV.5. Adjusted coefficients of determination (R^2) for simple linear regressions with 13 different growth intercepts (GIs) as the explanatory variable and crop height (CH) or top height (TH) as the response variable, for combined 20-year-old data. Data were obtained from eight 20-year-old plots, and extrapolated TH and CH information from 11 19-year-old plots, and 5 19-year-old plots. All R^2 values were significant at the .95 confidence level.

R^2 values for regressions between CH and									R^2 values for regressions between TH and								
cumulative length of internodes starting at or above BH									cumulative length of internodes starting at or above BH								
1, 2, 3, 4, and 5 internodes starting from the bottom up					1, 2, 3, and 4 internodes starting from the top down				1, 2, 3, 4, and 5 internodes starting from the bottom up					1, 2, 3, and 4 internodes starting from the top down			
$GI_{1\text{-}BH}$	$GI_{2\text{-}BH}$	$GI_{3\text{-}BH}$	$GI_{4\text{-}BH}$	$GI_{5\text{-}BH}$	$GI_{1\text{-}BHT}$	$GI_{2\text{-}BHT}$	$GI_{3\text{-}BHT}$	$GI_{4\text{-}BHT}$	$GI_{1\text{-}BH}$	$GI_{2\text{-}BH}$	$GI_{3\text{-}BH}$	$GI_{4\text{-}BH}$	$GI_{5\text{-}BH}$	$GI_{1\text{-}BHT}$	$GI_{2\text{-}BHT}$	$GI_{3\text{-}BHT}$	$GI_{4\text{-}BHT}$
.42	***.62***	***.68***	***.78***	***.85***	.77	***.90***	***.86***	***.86***	***.44***	***.63***	***.71***	***.80***	***.88***	***.80***	***.92***	***.89***	***.89***

R^2s for regressions between CH and			
Cumulative length of 1, 2, 3 & 4 internodes starting at or above 3.5, 3.0, 2.5 & 2.0 m respectively			
$GI_{1\text{-}3.5m}$	$GI_{2\text{-}3m}$	$GI_{3\text{-}2.5m}$	$GI_{4\text{-}2m}$
.84	***.87***	***.82***	***.87***

R^2s for regressions between TH and			
Cumulative length of 1, 2, 3 & 4 internodes starting at or above 3.5, 3.0, 2.5 & 2.0 m respectively			
$GI_{1\text{-}3.5m}$	$GI_{2\text{-}3m}$	$GI_{3\text{-}2.5m}$	$GI_{4\text{-}2m}$
.80	***.87***	***.84***	***.89***

The R^2 value of the equation that includes an intercept and a linear term is presented in regular fonts.
The R^2 values of equations that include an intercept and a square term are shown in bold face italics.

Table IV.6. Adjusted coefficients of determination (R^2) for simple linear regressions with the total height (H) of a dominant tree as response variable, and the cumulative length of one to seven internodes starting at or above five different points on the stem as the explanatory variable, at 16 age classes. Data were collected from a single felled tree in 77 plots, between ages 10 and 25. Boxes include R^2 values equal to or larger than .80 up to age 20.

		R^2 values for regressions between the H of dominant trees and the cumulative length of internodes																						
Age	Plots	Starting at or above BH							Plots	Starting at or above 2 m							Plots	Starting at or above 2.5 m						
		1	2	3	4	5	6	7		1	2	3	4	5	6	7		1	2	3	4	5	6	7
25	7	.50	ns	***.46***	.49	***.80***	.84	.88	7	ns	ns	ns	.85	.86	***.89***	.93	7	ns	.50	.65	***.66***	.78	.75	***.82***
24	8	ns	ns	***.40***	.46	***.80***	.84	.89	8	ns	ns	.44	.87	.87	***.91***	.93	8	ns	.52	.69	.72	.80	.78	.83
23	9	ns	**ns**	***.49***	.53	.85	.86	.89	9	ns	***.38***	.53	.89	.86	.87	.89	9	ns	.60	.73	.74	.79	.78	.83
22	11	.40	ns	.32	.41	.65	.72	.79	11	ns	***.29***	.44	.73	.75	.80	.86	11	ns	.49	.64	.67	.74	.75	.80
21	17	.19	.28	.46	.70	.78	.75	.80	17	ns	.43	.57	.80	.75	.80	.86	17	.30	.56	.69	.69	.73	.77	.81
20	24	.56	.40	.65	.76	.83	.83	.87	24	***.19***	***.49***	.69	.85	.85	.89	.92	24	.44	.64	.77	.80	.85	.89	.90
19	28	.45	.30	.47	.68	.80	.86	.90	28	***.17***	***.45***	.73	.84	.88	.91	.92	28	.40	.71	.81	.85	.88	.89	.89
18	36	.21	.30	.47	.67	.79	.85	.87	36	***.25***	***.52***	.76	.84	.87	.88	.90	36	.42	.67	.79	.83	.84	.86	.86
17	38	.30	.34	.51	.69	.80	.86	.87	38	***.30***	***.57***	***.78***	.85	.88	.88	.89	38	.46	.70	.78	.83	.84	.84	.84
16	43	.31	.35	.57	.72	.82	.85	.84	43	***.33***	***.63***	.78	.83	.86	.84	.85	43	.52	***.70***	***.77***	.80	.80	.80	.80
15	51	.36	.47	.66	.77	.83	.85	.83	49	***.45***	***.71***	.80	.82	.83	.80	.79	47	.55	***.69***	.73	.74	.71	.71	.70
14	57	.40	.49	.65	.74	.78	.80	.77	51	***.47***	***.69***	.76	.77	.78	.73	.70	47	.53	.64	.67	.68	.63	.63	.63
13	62	.36	.46	.60	.68	.72	.73	.68	51	***.41***	***.64***	.69	.71	.71	.65	***.60***	47	.48	.58	.59	.59	.54	.53	.53
12	62	***.35***	.46	.58	.63	.64	.63	.55	51	***.43***	***.61***	.62	.61	.57	.51	***.44***	47	.44	.50	.49	.46	.39	.37	.38
11	62	***.36***	.47	.57	.59	.56	.54	.44	51	***.41***	***.58***	.56	.51	***.45***	.39	.32	47	.41	.43	.40	.35	.27	.25	.26
10	62	***.34***	***.46***	.53	.49	.43	.40	.30	51	***.41***	***.52***	.41	.36	.31	.25	***.19***	47	.32	.30	.25	21	.15	.13	.13

The R^2 values of equations that include an intercept and a linear term are presented in regular fonts.
The R^2 values of equations that include an intercept and a square term are shown in bold face italics.
The R^2 values of equations that include an intercept, a linear term, and a square term are underlined.
ns : model not significant at the .95 level.

continued

Table IV.6. Continued.

Age	Plots	Starting at or above 3 m							Plots	Starting at or above 3.5 m						
		1	2	3	4	5	6	7		1	2	3	4	5	6	7
25	7	.75	***.69***	.72	***.77***	***.83***	***.82***	***.82***	7	.38	***.83***	***.88***	***.87***	***.91***	***.83***	.78
24	8	.79	***.74***	.75	***.80***	***.84***	***.83***	.82	8	.48	.82	.86	.85	.87	.81	.79
23	9	.80	***.78***	.77	.80	.82	.83	.83	9	.51	.82	.84	.80	.85	.81	.80
22	11	.75	.67	.71	.75	.79	.80	.81	11	.41	.67	.75	.74	.80	.77	.74
21	17	.75	.68	.67	.72	.78	.81	.82	17	.48	.66	.75	.79	.79	.80	.79
20	24	.69	.76	.80	.85	.87	.88	.88	24	.59	.76	.83	.87	.89	.88	.86
19	28	.71	.82	.85	.88	.88	.89	.88	28	.69	.79	.86	.85	.87	.86	.85
18	36	.61	.79	.82	.84	.84	.85	.85	35	.68	.76	.81	.80	.82	.81	.81
17	37	.60	.78	.82	.83	.82	.83	.81	36	.66	.74	.79	.78	.80	.77	.76
16	42	.60	.70	.75	.77	.76	.76	.75	40	.59	.66	.71	.70	.72	.71	.69
15	46	.57	.67	.68	.67	.66	.66	.63	42	.56	.59	.60	.60	.60	.58	.57
14	46	.52	.59	.60	.58	.57	.57	.54	42	.49	.52	.51	.51	.52	.49	.48
13	46	.48	51	.53	.50	.48	.47	.43	42	.40	.44	.44	.43	.42	.38	.37
12	46	.41	.42	.40	.36	.32	.33	.29	42	.33	.33	.30	.27	.29	.24	.23
11	46	.31	.33	.30	.24	.21	.21	.18	42	.23	.22	.19	.16	.17	.14	.12
10	46	.18	.19	.16	.12	.10	.10	.08	42	.14	.01	.01	.07	.07	ns	ns

Table heading: R^2 values for regressions between the H of dominant trees and the cumulative length of internodes

Selected Model

Our goal was to develop a model to predict TH at the oldest possible age class. Given the available data we chose age 20, and extrapolated information from 19- and 21- year old plots to improve the number of observations. The explanatory variable for the selected model was chosen among the GIs that best predicted TH at age 20 (Table IV.5). The GIs that could be measured without the need of a ladder were given preference to make site determination practical. Since growth intercept length can be read at its lower end by using a telescopic pole or a tape hooked to the upper whorl of the intercept, the GIs that start at or above BH are more convenient. Selecting a GI starting at a higher point on the stem would require measuring the length of fewer internodes, but it would be necessary to climb a ladder to read the GI length.

Among the GIs that start at or above BH, the one that includes five internodes ($GI_{5\text{-}BH}$) has the potential to be the most accurate (Table IV.5). The growth intercepts that include four ($GI_{4\text{-}BH}$) and three ($GI_{3\text{-}BH}$) internodes at or above BH would make field measurements easier and could be measured at a lower minimum age . However, 20-year-old data showed that the predictive ability of $GI_{3\text{-}BH}$ and $GI_{4\text{-}BH}$ was about 20 and 10% lower than that of $GI_{5\text{-}BH}$ respectively (Table IV.5). More importantly, the MSE of $GI_{3\text{-}BH}$ and $GI_{4\text{-}BH}$ was 58 and 39% higher than that of $GI_{5\text{-}BH}$. This is clearly illustrated by the respective prediction intervals (Figure IV.6). For our data set, 95% of the THs predicted by $GI_{5\text{-}BH}$ were within 15 % of those observed, whereas 95% of the $GI_{4\text{-}BH}$ and $GI_{3\text{-}BH}$ predictions were within 25% of the observed values (Table IV.7). The $GI_{5\text{-}BH}$ has a better predictive ability than $GI_{4\text{-}BH}$ because the upper internode in the former intercept can explain by itself 80% of the variation of TH at age 20 (Table IV.5).

Felled-tree data suggested that measuring six or seven internodes starting at or above BH would not significantly improve the predicting ability of the first five (Table IV.6). Hence, $GI_{5\text{-}BH}$ was selected as the explanatory variable for the inferential model to predict TH at age 20. This function includes an intercept and and a squared term, both significant at the 95% level. Preferred model:

$$TH_{age\,20} = 3.873597 + .5212258\ (GI_{5\text{-}BH})^2 + \varepsilon \qquad \text{[selected model]}$$

Where:

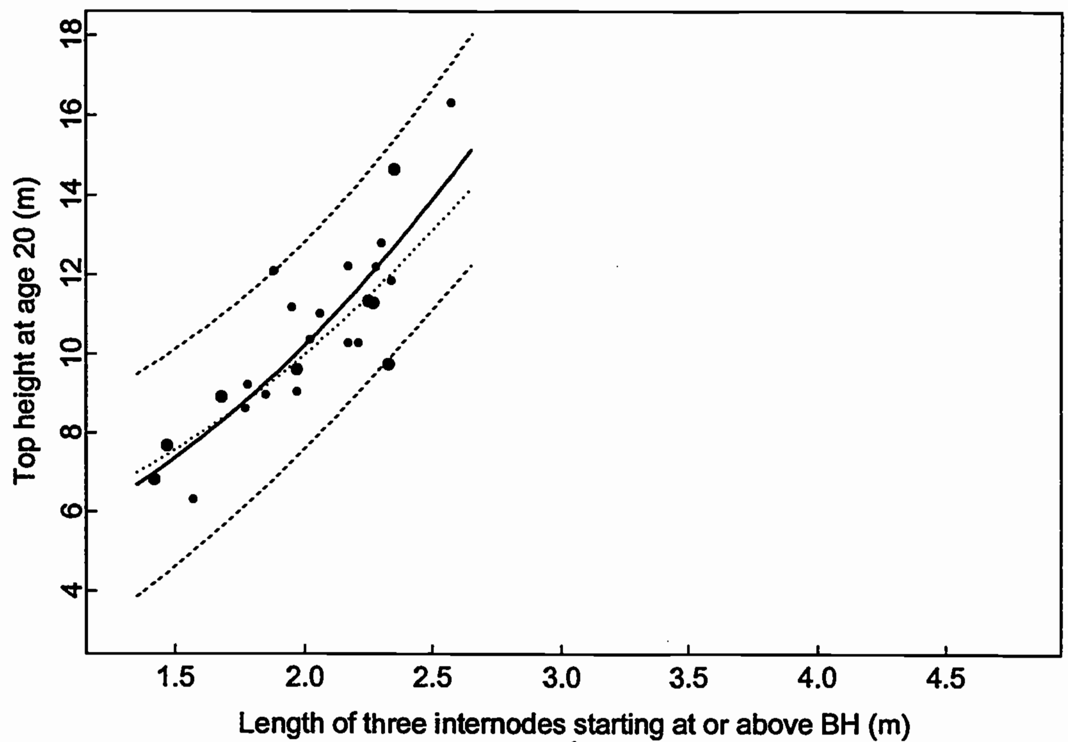
MSE: .6334823 *Adjusted* R^2: .88
TH $_{age\,20}$*: top height of the stand in meters at age 20*
$GI_{5\text{-}BH}$ *: length of the five internodes beginning at or above breast height in meters*

Table IV.7. Difference at age 20 between the observed top height (TH) and the TH predicted by the three growth intercepts (GI) that included the length of three ($GI_{3\text{-}BH}$), four ($GI_{4\text{-}BH}$), and five($GI_{5\text{-}BH}$) internodes starting at or above breast height. The data set included the 20-year-old plots and extrapolated height information from 19- and 21-year-old plots. The TH differences are presented as the percentage of plots that shared the same maximum error. The maximum differences (max dif %) are also shown for comparison.

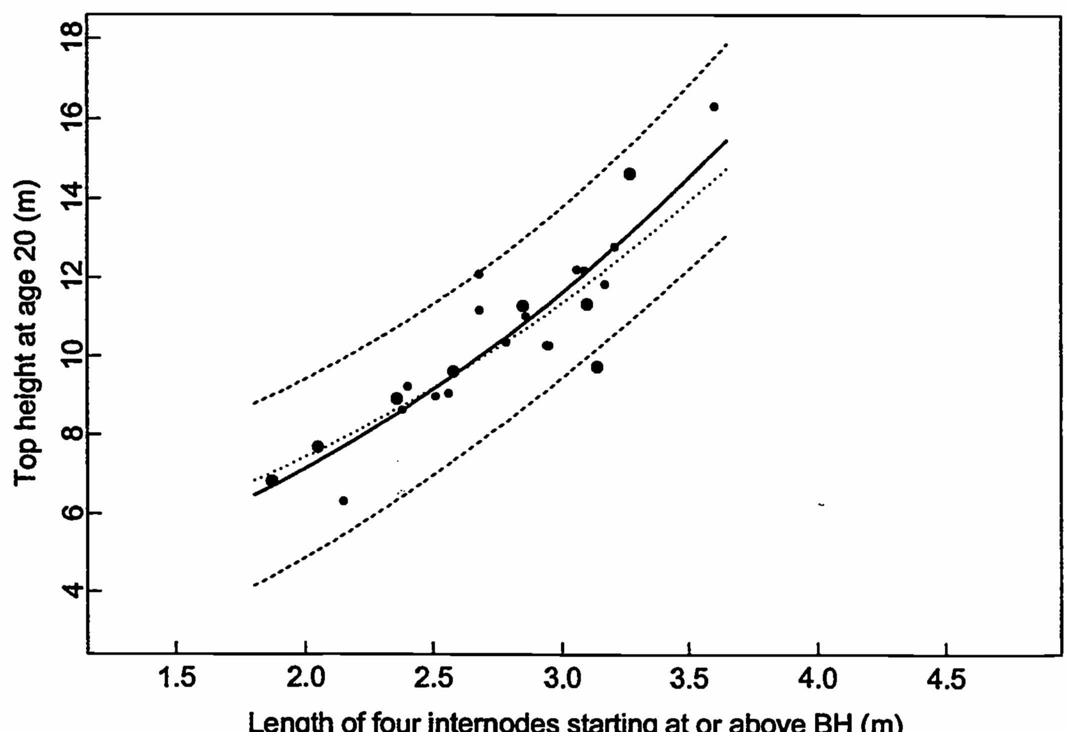
GI	Percent of plots with the observed TH estimated within						max
	± 5%	± 10%	± 15%	± 20%	± 25%	± 30%	dif (%)
$GI_{5\text{-}BH}$	54	87	96	100			20
$GI_{4\text{-}BH}$	54	75	87	92	96	100	27
$GI_{3\text{-}BH}$	37	62	87	87	96	100	29

Based on our data, dominant trees reach BH between four and eight years from planting, on high and low quality sites respectively. Thus, the youngest age from planting at which the inferential model can be applied varies from nine to 13. Since most plantations are and will be established among medium and high quality sites, the minimum age at which $GI_{5\text{-}BH}$ can be measured will usually be between nine and eleven.

We know of no previous studies examining the ability of GI methods to predict stand height in ponderosa pine plantations. However, Oliver (1972) developed a



A



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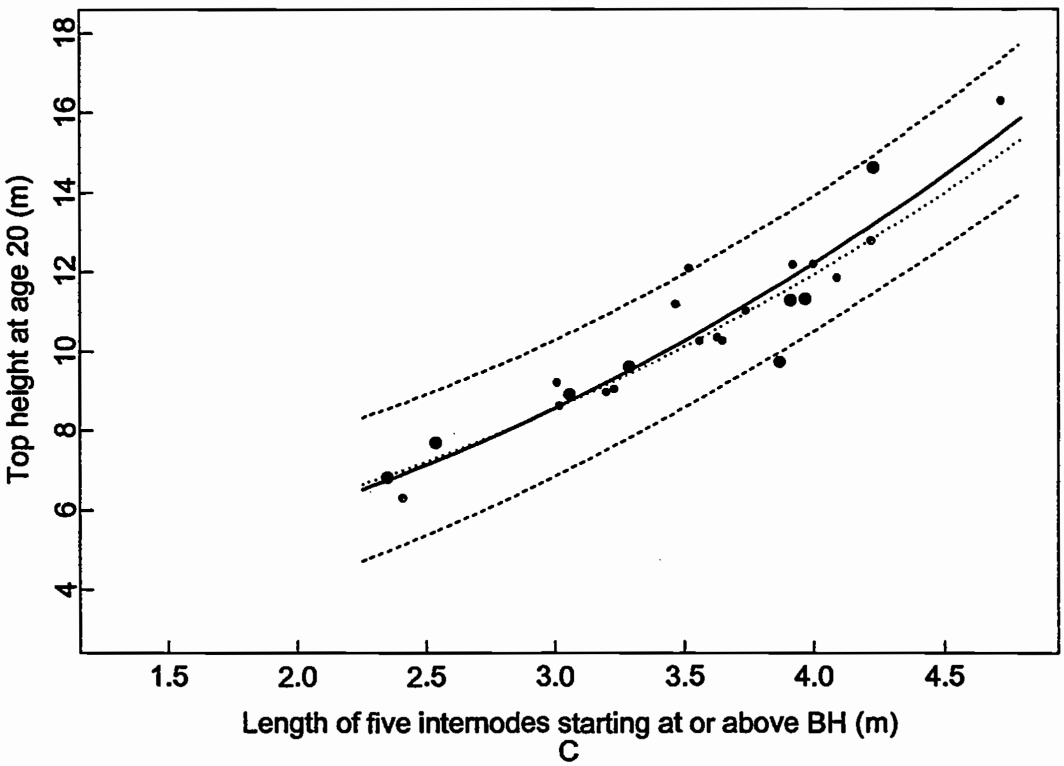

Figure IV.6. Regression line (solid), and prediction intervals (dashed line) at the 95% level for the models that best predicted top height at age 20 from the cumulative length of three (A), four (B), and five (C) internodes beginning at or above breast height (BH). The data includes information from eight 20-year-old plots (large dots) and extrapolated information from 11 19-year-old plots and five 21-year-old plots (small dots). The regression lines corresponding to the models that include only information from the 20-year-old plots are presented as dotted lines.

linear equation to predict site index based on the length of four internodes starting at or above BH, in young ponderosa pine plantations and natural stands in northern California. He selected four internodes instead of five because his data suggested that little improvement could be expected when more internodes were considered. The R^2 value of his inferential function was .79, and increased to only .80 and .81 if five or six internodes were considered.

The height-growth curves developed by Girarden and Broquen (1995) for the ponderosa pine plantations in Neuquén, predict a dominant H for the best sites at age 16 that is almost the same as the TH predicted by our model for best sites at age 20. Girarden and Broquen's (1995) curves predict taller trees because they defined dominant H as the H of the single tallest tree in each of the sample stands, while we based TH on the mean H of the 100 trees per ha with the largest D.

The height-growth curves developed by Andenmatten and Letourneau (1996b) for the ponderosa pine plantations in Río Negro and Chubut at age 20, predict almost the same range in THs as those predicted by our final model for Neuquén stands of the same age. This suggests that ponderosa pine plantations in Patagonia share the same productivity span in the northern and southern ranges of their current distribution area (Figure IV.2).

On the best sites in Rio Negro and Chubut, Andenmatten and Letourneau (1996a) measured higher $GI_{5\text{-}BH}$ values (i.e., 5.5 m) than the ones we determined on Neuquén top sites (i.e., 4.8 m). This difference is again due to the fact that for their model $GI_{5\text{-}BH}$ data come from single trees, whereas in our model each data point is the mean of the $GI_{5\text{-}BH}$ measured on the five tallest trees per plot.

Growth Intercept Index

The GI that best predicted TH at age 20, i.e. $GI_{5\text{-}BH}$, will serve as an index to determine the quality of the ponderosa pine plantations in Neuquén. Yield functions for unthinned plantations will be developed to predict stand volume based on this GI index, age, and number of trees per unit area or basal area.

The lowest and highest $GI_{5\text{-}BH}$ values among the 127 plots in the NPPSQY data set were 1.56 and 4.72 m respectively. We believed this $GI_{5\text{-}BH}$ range includes most of the site quality variation within the sampled geographical area because special attention was dedicated to include stands located on both extremes of the productivity spectrum. The range of $GI_{5\text{-}BH}$ was only slightly extended (1.50-4.80 m) in order to round off the observed extreme values (Table

IV.8). Plantations growing on the lowest site qualities are scarce; we could find only five stands with $GI_{5\text{-}BH}$ values below 2.50 m, and only one with a $GI_{5\text{-}BH}$ below 2.0 m among the 127 plots established for the NPPSQY project.

Table IV.8. Top height (TH) at age 20 predicted by 12 values of the growth intercept (GI) index, i.e. the length of the five internodes beginning at or above breast height ($GI_{5\text{-}BH}$). The mean annual increment (MAI) of TH is also presented to further illustrate the growth rate associated to each GI index value.

GI index based on $GI_{5\text{-}BH}$ (m)	TH at age 20 (m)	MAI of TH at age 20 (m)
4.8	15.90	.79
4.5	14.40	.72
4.2	13.10	.65
3.9	11.80	.59
3.6	10.60	.53
3.3	09.50	.48
3.0	08.60	.43
2.7	07.70	.38
2.4	06.90	.34
2.1	06.20	.31
1.8	05.60	.28
1.5	05.00	.25

Field Application

To determine the GI index of ponderosa pine stands in Neuquén, the following procedure, consistent with the methodology applied in the study, is recommended. Determine the approximate shape and size of the stand and randomly locate the center of single plot. Relocate it, only if it happens to fall in an area where trees present unusual characteristics in relation to the rest of the stand in terms of density, disease, etc. Establish a circular or square plot large enough to include at least 40 trees. Select the tallest five trees within the plot, and on each of them measure the cumulative length of the five internodes beginning at or above BH, and calculate the average.

Selecting the five tallest individuals is important, since measuring $GI_{5\text{-}BH}$ on shorter trees can result in an underestimation of the site quality. In tall and dense stands finding the tallest individuals may be difficult because it may not be possible to see the top of the trees from the ground. In this case we recommend that one person climb the tallest possible tree near the plot center, in order to spot the tallest individuals and point them out to other member of the crew on the ground. Be aware that in dense stands the tallest trees may not be among the ones with the largest Ds.

To predict the TH of the stand at age 20 using the mean $GI_{5\text{-}BH}$ value, read the TH of the stand at age 20 from Table IV.8, or compute TH using the selected model for a more refined estimation.

CONCLUSIONS

Site index is not likely to reliably estimate site quality in young stands of ponderosa pine in Neuquén. The erratic early growth period, as well as the field determination of either total or breast height age could introduce relatively large errors. The results from this study suggested that several growth intercepts can accurately predict top height at age 20, as a way of estimating site quality. The length of five internodes starting at or above five meters was selected as the growth intercept index because it produces accurate predictions and is also practical to apply in the field. The minimum age after planting at which it can be measured on most commercial sites is estimated to vary between nine and 11.

The selected model was developed with data from unthinned stands that have not received any site preparation. Hence, the application of effective site preparation techniques or any other treatments that can significantly accelerate the height growth of young stands would require a revision of the function.

ACKNOWLEDGMENTS

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V. NEEDLE LENGTH AS SITE QUALITY PREDICTOR IN UNTHINNED YOUNG-GROWTH PONDEROSA PINE PLANTATIONS IN NEUQUÉN, PATAGONIA, ARGENTINA

Héctor E. Gonda, Steven D. Tesch, and Gustavo O. Cortés

ABSTRACT

The ability of lateral branch needle length (LNL) and terminal leader needle length (TNL) to predict stand top height (TH) from ages 14 to 21 was evaluated for unthinned ponderosa pine plantations in Neuquén province. Top height was defined as the mean total height of the 100 trees per hectare with the largest diameter at breast height. Terminal leader needle length was defined as the mean length of 10 fascicles clustered around the terminal bud on the leader, and LNL as the mean length of 10 fascicles located around the terminal bud of two or three first order branches, located in the upper half of the crown. Data were collected from standing trees in 56 plantations. A model that predicts TH at age 20 based on LNL, was used as a basis to develop a LNL index. In a companion analysis, the use of LNL and TNL in predicting the height of selected dominant trees from ages 10 to 25 was evaluated on felled tree data from 74 sample stands. These results supported the standing tree data results up to age 20, and based on a small sample size, suggested that LNL index can predict the height of dominant trees up to at least age 25.

INTRODUCTION

Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) is the most widely planted species in the Patagonian Andes region of Argentina, where it grows vigorously and without any serious pest problems. Preliminary studies suggest that the average yield of these stands could be similar to or even higher than those growing on the more productive regions of the western United States (Gonda and Lomagno 1995, Urzúa 1991). The environmental conditions in northern Patagonia are similar to those where ponderosa pine (variety ponderosa) forests grow naturally in the western United States. The piedmont of the northern Patagonian Andes and the interior Pacific Northwest share the following main characteristics:

1. The latitudinal ranges are similar in the respective hemispheres (Figure V.1)
2. Moisture is provided by humid winds blowing from the Pacific Ocean.
3. A rain shadow effect is produced by the Andes as well as by the Cascades and the northern Sierra Nevada ranges.
4. A Mediterranean climate prevails, imposing a well-defined dry season.
5. A high proportion of the soils are of volcanic origin.

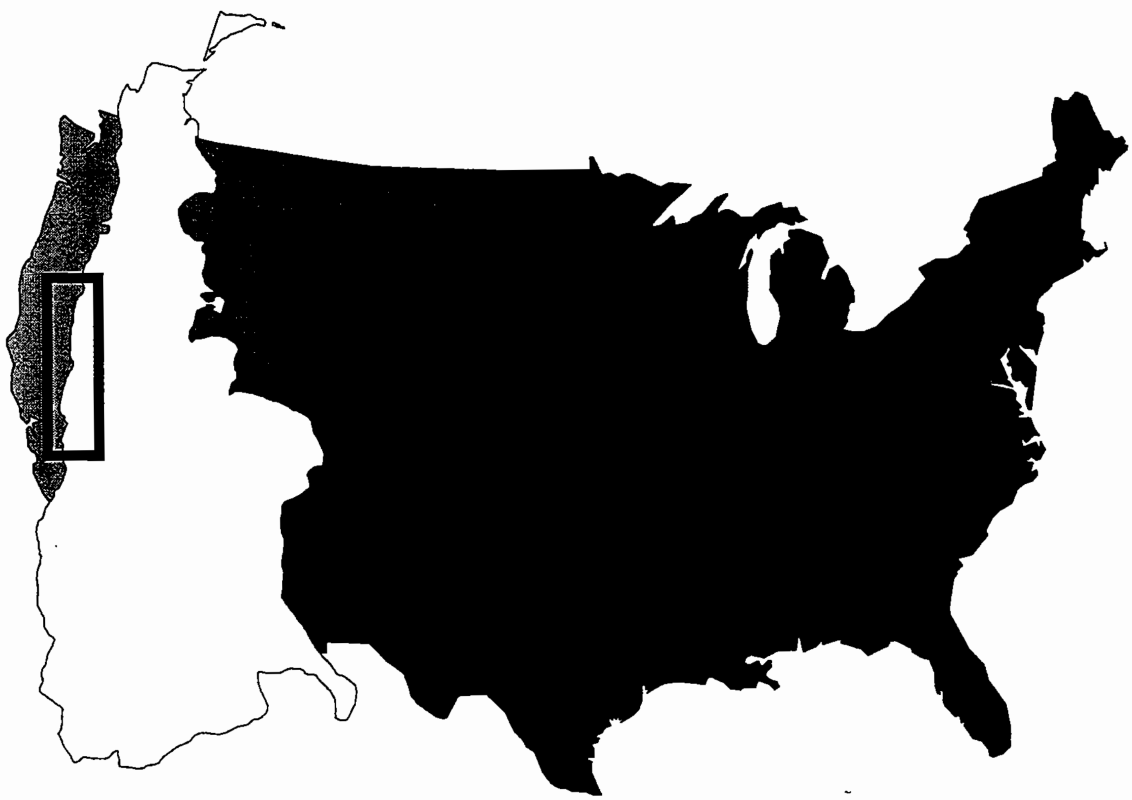

Figure V.1. A map superimposing the Patagonian Andes (Argentina) over the Cascades and northern Sierra Nevada (United States). The rectangle includes the current distribution area of the ponderosa pine plantations in Patagonia. The latitude of both countries match, and they are drawn at the same scale.

The area planted annually with ponderosa pine in Argentina is rapidly increasing due to the subsidies and credits that the Patagonian provinces and the federal government provide for planting fast-growing species. The primary objective of this support is to promote afforestation as a means to improve the socioeconomic conditions of the region. Currently there are about 30,000 hectares of ponderosa pine forests (Urzúa 1991), with about a million hectares of grasslands suitable for commercial afforestation throughout the piedmont of the Patagonian Andes (Enricci 1993).

Information on site quality and growth of ponderosa pine in Patagonia is limited. This incomplete knowledge can dissuade potential investors from planting trees and frustrate efforts to develop sound management plans. Because species that are grown outside their native range typically exhibit growth and developmental patterns that differ significantly from those of the species within its native environment, it is also risky to extrapolate growth predictions to new geographic areas (Zobel et al. 1987).

To ameliorate these problems the Patagonian Andes Forest Research and Extension Center (CIEFAP), along with the University of Comahue Forest Technical School and the government of Neuquén, have started quantitative silvicultural studies on ponderosa pine plantations throughout Neuquén province, covering an area that includes about 80% of the present plantation forests of this species in Patagonia (Figure V.2). These studies constitute the Neuquén Ponderosa Pine Site Quality and Yield (NPPSQY) project.

Needle Length and Site Quality

Using even the growth intercept index (GII) approach to site quality estimation, the site quality of ponderosa pine stands in Neuquén can not be determined until they are about 11 years old, and it requires the measurement of internode lengths on the taller trees in the stand (Chapter IV). The traditional application of site index (SI) requires older stands and height measurements that

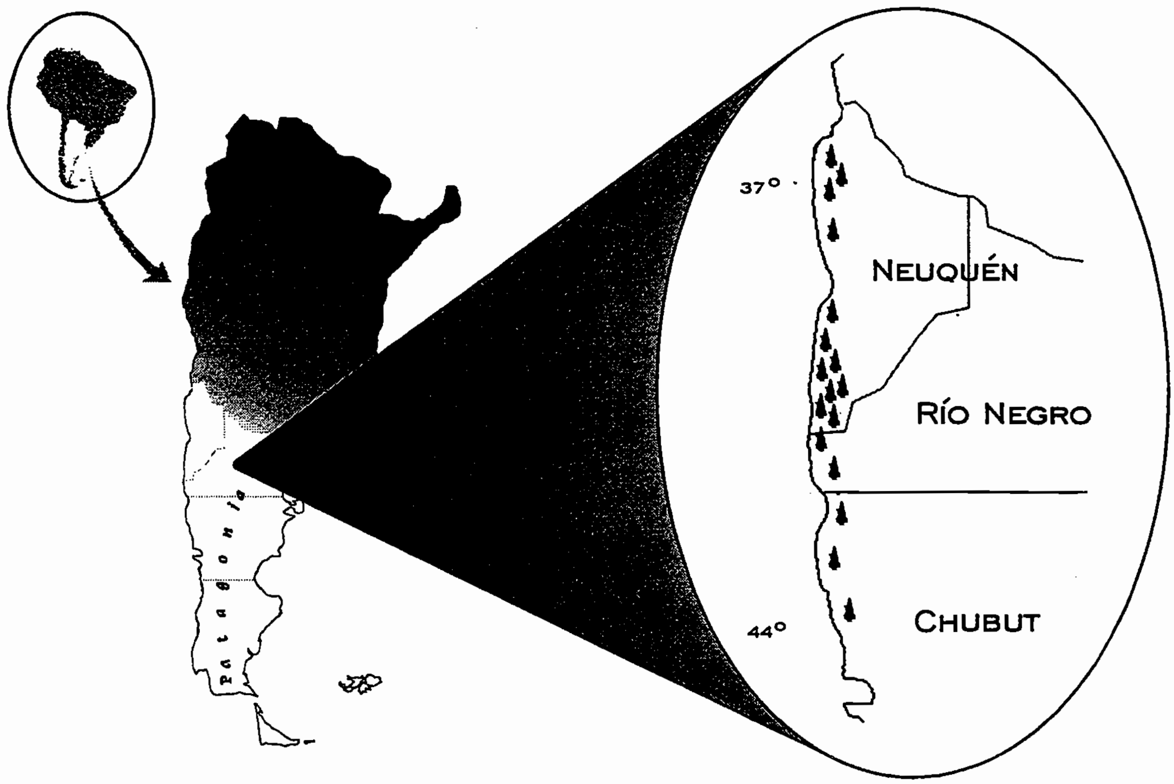

Figure V.2. From left to right: maps showing the position of Argentina in South America, Patagonia within Argentina, and the current distribution of the ponderosa pine plantations in the provinces of Neuquén, Río Negro, and Chubut. The number of pine trees is proportional to the plantation area.

are time demanding. Estimating site quality based on needle length has the potential to be applied at younger ages, and to hasten field procedures because only the length of some groups of fascicles needs to be measured. In unthinned stands that receive no other treatments, such as vegetation release, fertilization, etc., we hypothesize that, besides weather fluctuations, differences in needle length should be mainly correlated with site quality. Evaluating site quality from needle length assumes that it remains constant throughout the life of unmanaged stands, or that needle length differences between sites are much larger that those due to other causes such as yearly weather fluctuations.

Determining site quality based on needle length has the potential to be most practical in young stands, where needles can be picked by hand or with the help of a pole trimmer. In older stands with higher crowns, collecting the needles can be more cumbersome, and either the GII or the SI method might be preferable. As trees grow older, needle length may be affected by heavy cone crops. In Sierra Nevada, California, shoot and needle length in the upper crown of 30- to 50-year-old cone-bearing Douglas-fir (*Pseudotsuga menziessi* (Mirb.) Franco) trees were reduced in years of cone production, whereas on nonbearing individuals they were unchanged (Tappeiner 1969).

Several morphological parameters of conifers have the potential to be correlated with height growth, and thus with site quality. Buds and needles of some coniferous species have been shown to be sensitive to different kinds of treatments. In southwest Oregon, the number of buds on the terminal leader of Douglas-fir seedlings proved to be related directly to the amount of shrub and hardwood competition, and also a good indicator of future seedling vigor (Tappeiner et al. 1987). Competition from tanoak (*Lithocarpus densiflorus* (Hook. & Arn.)) reduced the following morphological parameters on the shoots of Douglas-fir saplings: number and size of buds; lengths of shoots, internodes, and needles; number of internodes; and biomass of foliage and wood (Harrington and Tappeiner 1991). Cattle grazing, beginning one year after planting, enhanced growth and vigor of four-year old conifer seedlings (Doescher et al. 1989). On grazed plots the terminal leader of Douglas-fir seedlings developed more lateral buds and the terminal leaders of ponderosa pine seedlings reached greater needle length than they did on ungrazed plots.

The needle dry weight produced in the first growing season after fertilization is well correlated with longer term stem growth responses for several conifers, namely Douglas-fir (Ebell 1972), jack pine (*Pinus banksiana* Lamb.) (Camire and Bernier 1981, Timmer and Morrow 1984, Sheedy and Doucet 1981, Weetman and Algar 1974), red pine (*Pinus resinosa* Ait) (Leaf et al. 1970, 1975), Japanese larch (*Larix leptolepis* (Sieb & Zucc.) Gord.) (Leyton 1957), balsam fir (Abies balsamea (L.) Mill.) (Timmer and Stone 1978), loblolly pine (Pinus taeda L.) (Wells 1968), and maritime pine (Pinus pinaster Ait) (Keay et al. 1968).

The needle length of 23-year-old dominant red pine trees growing on infertile soils with low available water capacity in Michigan was related to the number of fascicles produced per shoot and the water supply of the previous and the current year (Garret and Zahner 1973). Also in Michigan, irrigation significantly increased shoot and needle elongation of 20-year-old dominant red pine trees in comparison with individuals that were maintained under a drought treatment throughout the growing season (Lotan and Zahner 1963). Average yearly needle length of pinyon pine (*Pinus edulis* Engelm.) and Douglas-fir in Colorado were correlated with size of annual growth rings, a measure of tree vigor that was in turn correlated with precipitation and temperature (Fritts et al. 1965). These results seem to contradict our assumption that needle length remains constant throughout the life of unmanaged stands. However, the sites where these three studies were performed had a harsher environment than western Neuquén, and the authors did not report how needle length differences due to weather fluctuations compared to needle length differences due to different site conditions.

In northern California needle length of ponderosa pine seedlings significantly reflected the application of different levels of shrub and grass release operations, five years after applying the treatments (McDonald and Fiddler 1990). The more effective treatments for controlling vigorous shrub and grass, were associated with longer needles, and ineffective treatments with shorter needles. In a similar study, this correlation held for seven years, proving that 1-year-old needles could be a useful tool for indicating future seedling growth response; since they were correlated with total height and diameter (McDonald et al. 1992).

In northern Patagonia, however, competition from shrubs is of little consequence as ponderosa pine plantations are established almost exclusively on grasslands. Only the amount of bunch grasses varies among plantation sites, and so we hypothesize that needle length reflects site quality shortly after trees have reached breast height (BH).

Site quality is best estimated, applying either SI or GI methods, when volume production potential and height growth are highly correlated (Clutter et al. 1983). This is also the case for needle length, since we will examine the ability of needle length to predict site quality based on its ability to predict height. This is not a problem for the ponderosa pine plantations of Neuquén since, among the 127 plots established for the NPPSQY project, the correlation coefficient between total volume and either mean or dominant height was .93, regardless of age, spacing, or any other factors (Gonda, unpublished data).

Objectives

The first objective of this paper was to determine the location of the needles that best predicted height growth; those taken from the terminal leader or those taken from lateral branches, in unthinned ponderosa pine plantations in Neuquén. The second objective was to develop a needle length index based on the needles with the better predictive ability.

METHODS

Characteristics and Location of Plots

The 74 sample plots involved in this study were part of the 127 permanent plots established for the NPPSQY project from June to September 1995. The 74 sample plots were scattered throughout the current range of the ponderosa pine plantations in Neuquén province. However, the three southernmost plots were located in Río Negro province, only a few kilometers from the Neuquén border, because there were no ponderosa pine plantations on the Neuquén side (Figure

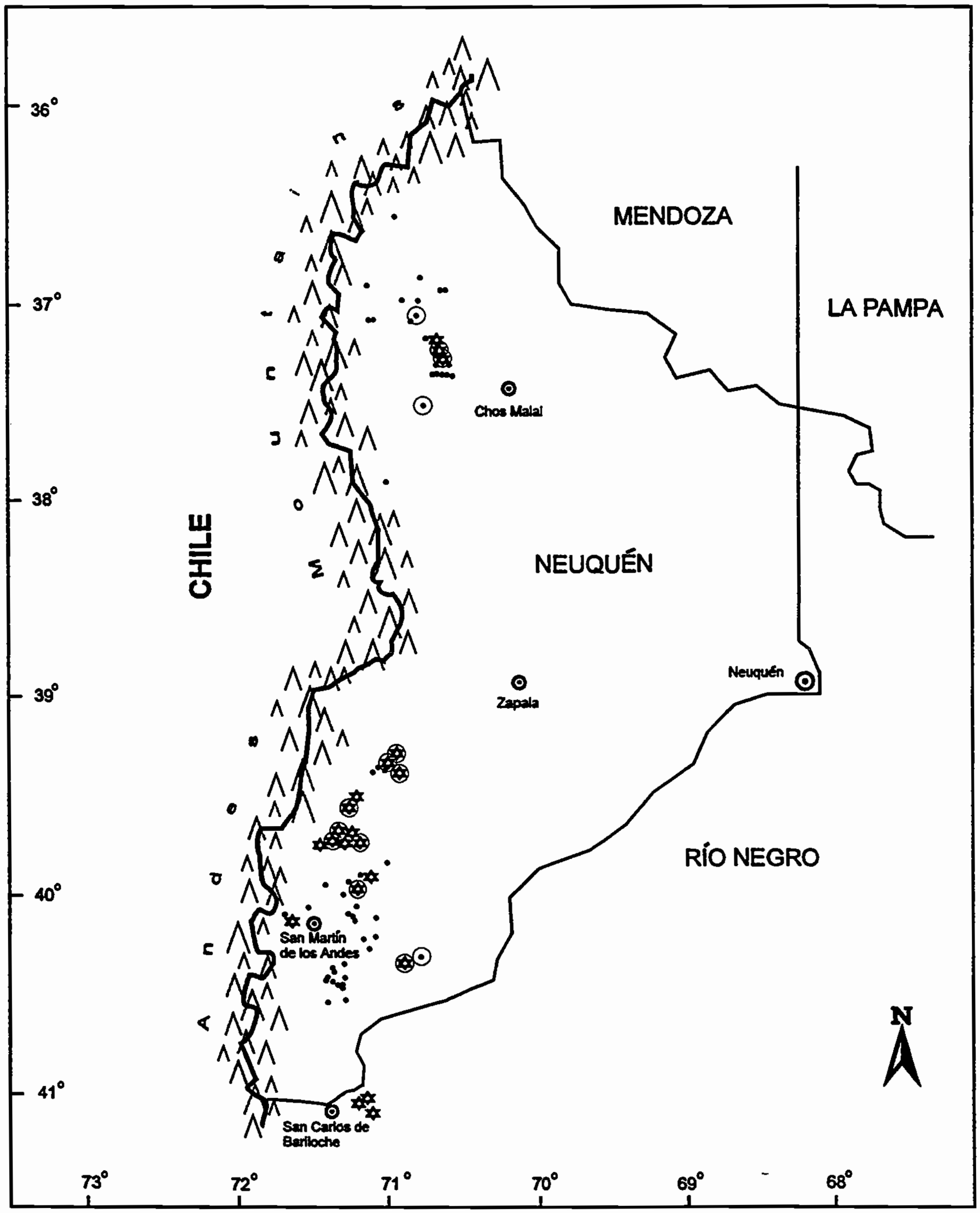

Figure V.3. Location of the 74 sample plots. The circles represent the 14 plots used to build the selected model that relates top height and needle length. The stars represent the 21 plots used to predict dominant height at age 20 based on data from a single dominant felled tree per plot.

V.3). Since in Neuquén most plantations are young, the ages of the plots varied between 11 and 38. All plots were located in a different stand, were circular in shape, and had different areas in order to include at least 40 trees.

Sample stands were established in unthinned plantations which had negligible insect, disease, or storm damage. Some of the plantations selected for the study had been pruned, and so had 36 sample plots. It was assumed that pruning did not affect significantly TH since the standard procedure consists in eliminating no more than 1/3 to 1/2 of the live crown and it had been done recently.

Tree Measurements

In all plots, the diameter at breast height (D) of every tree was measured to identify the 100 trees per ha with the largest D. Then, the total height (H) of each of these larger individuals was measured. Total height of trees less than 12 meters was measured directly with a telescopic fiberglass pole to the nearest cm. Taller trees were measured indirectly with clinometer (either *Blumme-Laiss* or *Suunto*) to the nearest 5 cm. The D was measured to the nearest 0.1 cm with diameter tape at 1.3 m from the ground.

One dominant tree was felled in the proximity of each of the 74 sample plots (Figure V.4). The H of the felled trees was equal to the mean H of the 100 to 300 trees per ha with the largest D. Felled trees did not include those open-grown, curved, forked, unhealthy, or with broken tops. Upon felling, the length of all internodes was measured with a fiber glass or metal tape. The mean length of 10 fascicles clustered around the terminal bud on the leader and the mean length of 10 fascicles located around the terminal bud of two or three first order branches located in the upper half of the crown were measured with a ruler.

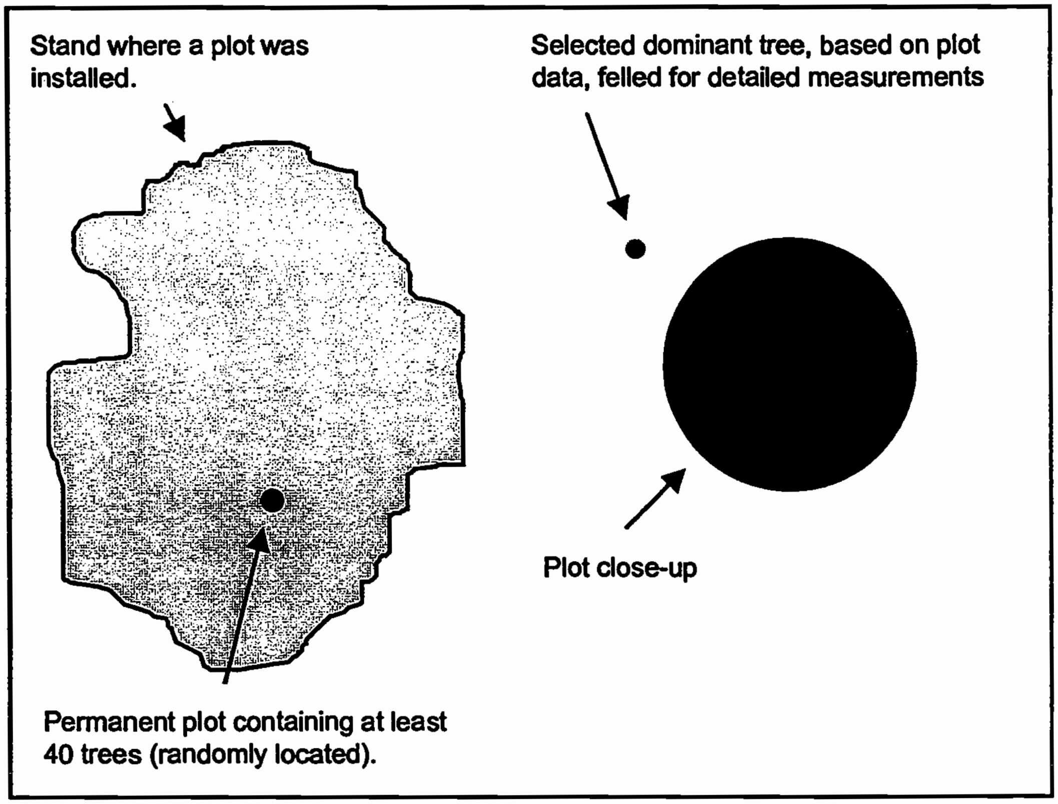

Figure V.4. Representation of how dominant trees were selected for felling, in the proximity of each of the 74 sample stands.

Top Height and Needle Length

We examined the ability of lateral branch needle length (LNL) and terminal leader needle length (TNL) to predict top height (TH) from ages 12 to 20 on 56 plots. Four to nine plots were available for each age class, except for age 17 (two plots). Top height was defined as the mean total height of the 100 trees per ha with the largest diameter at breast height. Terminal leader needle length (TNL) was defined as the mean length of 10 fascicles clustered around the terminal bud on the leader, and lateral branch needle length (LNL) as the mean length of 10 fascicles located on the tip of two or three of the first order lateral branches, located in the upper half of the crown (Figure V.5). For each plot TH was computed based on H measurements taken on standing trees within the

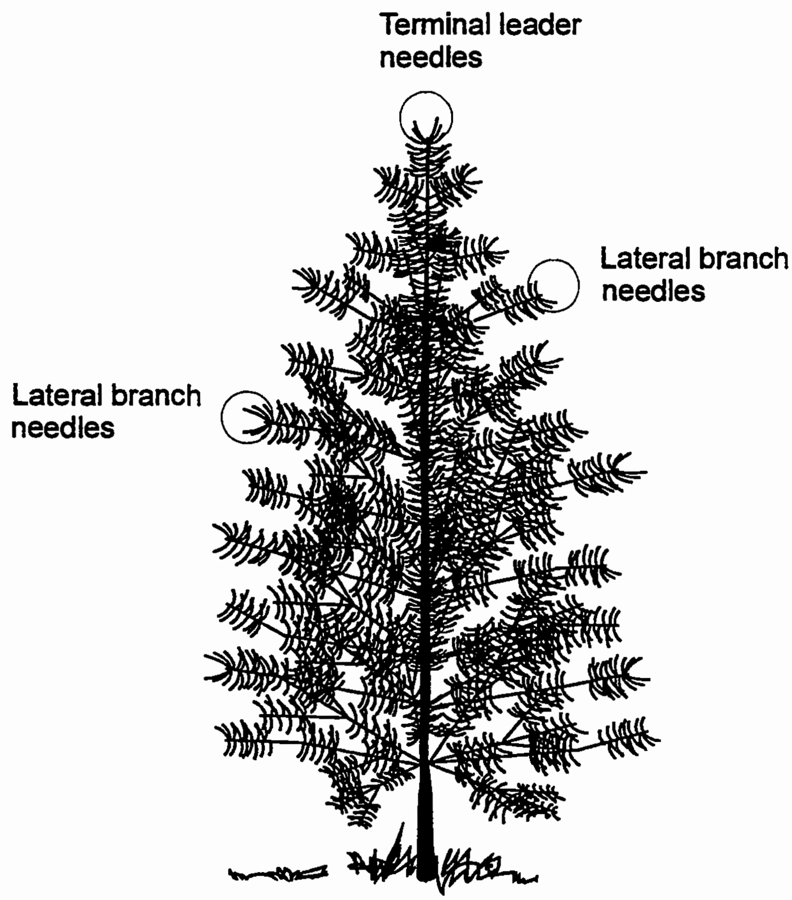

Figure V.5. Diagram of a ponderosa pine tree depicting where terminal-needle length and lateral-branch needle length where measured.

plot, and LNL and TNL were measured on a single felled tree located outside the plot.

We developed a model to predict TH at age 20 based on the needles with the better predictive ability. Since few stands older than 20 years were available for measurement, the inferential model could not be developed to predict TH at older ages. Only six sample plots were 20 years old, so TH from four 19- and four 21-year-old plots were extrapolated to age 20 in order to increase the number of observations. The length of the extrapolated internode was calculated by dividing TH and CH by the age of the respective plot minus a certain number of years. The subtraction was intended to account for the slow height growth period after outplanting. We subtracted three and four years from the 21- and 19-year-old plots respectively, based on the results of a previous study (Chapter IV). The 14 sample plots used to build the model covered most of the geographical range and environmental conditions of the ponderosa pine plantation forest in the province (Table V.1, Figure V.3). The ability of LNL and TNL to predict TH was evaluated by fitting a simple linear regression using either source of needle length as the explanatory variable and TH as the response. The significance of a square term was also examined.

Table V.1. Full range of latitude, longitude, elevation (elev), slope, aspect, annual precipitation (precip), soil depth, and density (tr/ha) for the ponderosa pine plantations in Neuquén (NPPSQY project), in comparison with the ranges covered by the 14 plots used to build the selected model (SM) and the 21 plots used to dermine the relationship between needle length and height at age 20 on individual dominant trees (DT).

Range		Latitude	Longitude	Elev (m)	Slope (degr)	Aspect (degr)	Precip (mm/yr)	Soil D (m)	Tr/ha
full	Min	36°44'19"	70°35'22"	645	0	0	400	0.4	307
	Mean	39°27'29"	70°90'75"	1059	8.6	140	929	1.0	1314
	Max	41°05'57"	71°18'24"	1715	30.0	350	2229	1.8	2500
SM	Min	36° 59'06'	70°36'47"	650	0	0	400	0.4	940
	Mean	38°80'56"	70°66'74"	1061	9.4	142	974	0.9	1583
	Max	40°17'46"	71°16'19"	1360	22.0	335	2229	1.5	2100
DT	Min	37° 07'07'	70°36'48"	650	0	0	400	0.4	889
	Mean	39°28'84"	70°85'25"	1027	10.0	145	1003	1.0	1594
	Max	41°05'19"	71°18'24"	1345	22.0	335	2229	1.4	2280

Height and Needle Length on Single Dominant Felled Trees

The ability of LNL and TNL to predict tree H between age 10 and 25 was examined on data collected from a single dominant tree, felled in the proximity of

74 permanent sample plots (Figure V.4). By measuring the length of all the internodes, each felled tree provided information that allowed reconstruction of the relationship between needle length and H in past years. The age of the felled trees varied between 11 and 38 years. This analysis was based on the assumption that needle length remains constant through time.

The main objective of this portion of the study was to examine the potential of needle length as a predictor of dominant height from ages 10-25, with all measurements made on the same felled tree. A second objective was to determine how consistent needle length tended to be at different ages. Results from this analysis were not used to develop a model because the data did not include an objective measure of dominant height such as TH.

Special attention was given to the ability of LNL and TNL in predicting tree H at age 20. The H of one of the 19-year-old plots was extrapolated to age 20, in order to expand the needle length range by 2 cm, and the H range by 80 cm. The 21 sample plots used to study the relationship between LNL, TNL and tree H of dominant trees at age 20, covered almost the entire geographical, and environmental range of the ponderosa pine plantations in Neuquén (Table V.1, Figure V.3).

The ability of LNL and TNL to predict the H of dominant felled trees was evaluated by fitting a simple linear regression using either source of needle length as the explanatory variable and the trees H as the response. The significance of a square term was also examined.

RESULTS AND DISCUSSION

Top Height and Needle Length

The relationship between LNL or TNL with TH was not consistent at different ages because of the limited number of observations available at each age class. Lateral branch needle length predicted TH more accurately than TNL for most age classes (Table V.2). There are two possible explanations for this finding. First, LNL may be a better predictor of H because it somehow accounts for the variability of needle length between different limbs, which is not the case for TNL. Second, the differences in predictive ability may be related to certain growth habits that take place in the leader (TNL) and that do not affect LNL. Data collected for this study did not provide enough information to support either theory.

Our goal was to develop a model to predict TH at the oldest possible age class. Given the available data we chose age 20, and extrapolated TH information from 19- and 21- year old plots to improve the number of observations. Lateral needle length was chosen as the explanatory variable because it provided a stronger predictive ability than TNL. The prediction intervals illustrate how well the selected model predicts TH for our data set (Figure V.6). Preferred model:

$$TH_{20} = -1.127442 + 0.653566 * LNL \qquad \text{[Selected model]}$$

Where:

MSE = 1.77769 R2 = .71
TH_{20} = top height of the stand at age 20 in meters
LNL = lateral branch needle length in centimeters

Table V.2. Coefficients of determination (R^2) for simple linear regressions fitted between LNL or TNL as explanatory variables and TH as a response variable, between ages 12 and 21. The selected model that predicts TH at age 20 contains information from 14 20-year-old plots, and extrapolated data from four 19- and four 21-year-old plots. Information is not given at age 17 because only two plots were available for measurement.

Age	Number of plots	R^2 $LNL = \beta_0 + \beta_1 TH + \varepsilon$	R^2 $TNL = \beta_0 + \beta_1 TH + \varepsilon$
Selected model (age 20)	**14**	**.71**	**.52**
21	4	.78	.42
20	6	.93	.62
19	4	.79	.79
18	7	.41	.15
17	2	-	-
16	5	.54	.73
15	7	.62	.17
14	7	.28	.02
13	9	.67	.61
12	7	.32	.26

Information from 21-year-old plots was only used for extrapolation purposes.

Height and Needle Length on Single Dominant Felled Trees

Data from the dominant felled trees confirmed that LNL had a better predictive ability than TNL, and also demonstrated that the ability of both kinds of needles to predict H increased with age (Table V.3). The fewer number of observations between age 20 and 25 made the increasing trend of the coefficients of determination less consistent, but their relatively high values (R^2>.60) indicated that the strong predictive ability of LNL would extend at least up to age 25 (Table V.3).

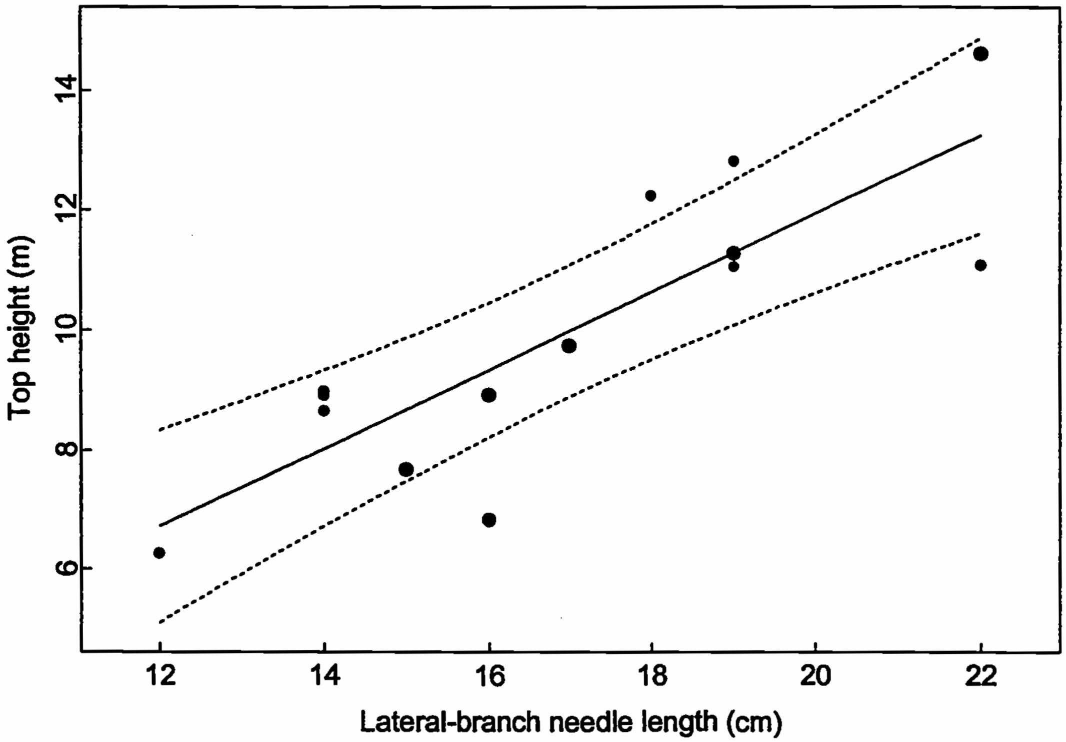

Figure V.6. Regression line (solid line) and 95% confidence level prediction bands (dashed lines) for the selected model that predicts TH at age 20 based on lateral branch needle length. Large dots correspond to 20-year old data, and small dots to data extrapolated from 19- and 21-year old plots.

The fact that the ability of needle length to predict H increased with age (Table V.3) may be due to three main reasons: a prolonged erratic early growth period, proportionally larger errors in H determination at younger ages, and inconsistent needle length throughout the life of the stand.

To test these three hypothesis we compared the H predictions of either source of needle length when the H of the felled trees was extrapolated in the past by performing stem analysis, with H predictions obtained when only the current H of the felled trees was used in the analysis (Table V.3). The H predictions based on the current H of the trees were stronger than those based on stem analysis (Table V.3). The comparison was made at only five age classes due to the

Table V.3. Coefficients of determination (R^2) of simple linear regressions fitted between lateral-branch needle length (LNL) or terminal leader needle length (TNL) as explanatory variables and height (H) as response, between ages 10 and 25. Data were collected on a single dominant tree felled in 74 stands. Results are shown for the actual age (AA) of the trees and for past years based on stem analysis (SA).

	R^2 values of regressions between LNL or TNL and H at 16 age classes															
Age	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
SA																
Plots	74	74	71	64	55	48	40	35	33	25	21	15	9	7	6	6
LNL	.14	.20	.26	.33	.33	.37	.40	.50	.59	.68	.62	.51	.55	.66	.85	.84
TNL	.08	.11	.15	.27	.33	.41	.46	.49	.53	.63	.43	.61	*NS*	*NS*	*NS*	*NS*
AA																
Plots	3	3	7	9	7	7	5	2	8	4	6	5	3	1	1	2
LNL	-	-	*NS*	.79	.83	.56	*NS*	-	*NS*	*NS*	.83	.98	-	-	-	-
TNL	-	-	*NS*	.73	*NS*	*NS*	*NS*	-	*NS*	*NS*	*NS*	.97	-	-	-	-

The R^2 values of LNL and TNL increased to .70 and .54 when the H of a 19-year-plot was extrapolated to age 20, in order to make the needle length ranges as long as they were at age 19. Underlined numbers indicate that the function includes a square term. Not significant regression equations (95% level) are shown as *NS*.

limited number of observations per age class, but the differences were consistent. This result suggested that weaker predictions at younger ages (13-15 years) would not be caused by an extended erratic early growth period. Thus, one or both of the other two possible reasons would be the cause for the increase in H predicting ability with age. Weather fluctuations could have an effect on needle length that is confounded with the effect of site quality. This problem could be ameliorated by measuring the length of 2-, 3-, or 4-year-old needles. Height predictions could be weaker at younger ages because any errors in the determination of stand age would result in larger prediction errors.

At age 20, the R^2 values for the stem analysis functions containing H and both needle lengths were lower than those at age 19 (Table V.3), not because of a poorer fit but, because of a 20% reduction in the observed range of needle length. To extend the range of the age 20 data, the H of a 19-year-old plot was extrapolated to age 20 (Figure V.7). As a result, the R^2 value for the equation involving H and LNL at age 20 increased from .62 to .70. The addition of the extrapolated observation did not change the regression line significantly, and thus it was included in the data used to build a function that shows the relationship between LNL and H at age 20 (Figure V.7).

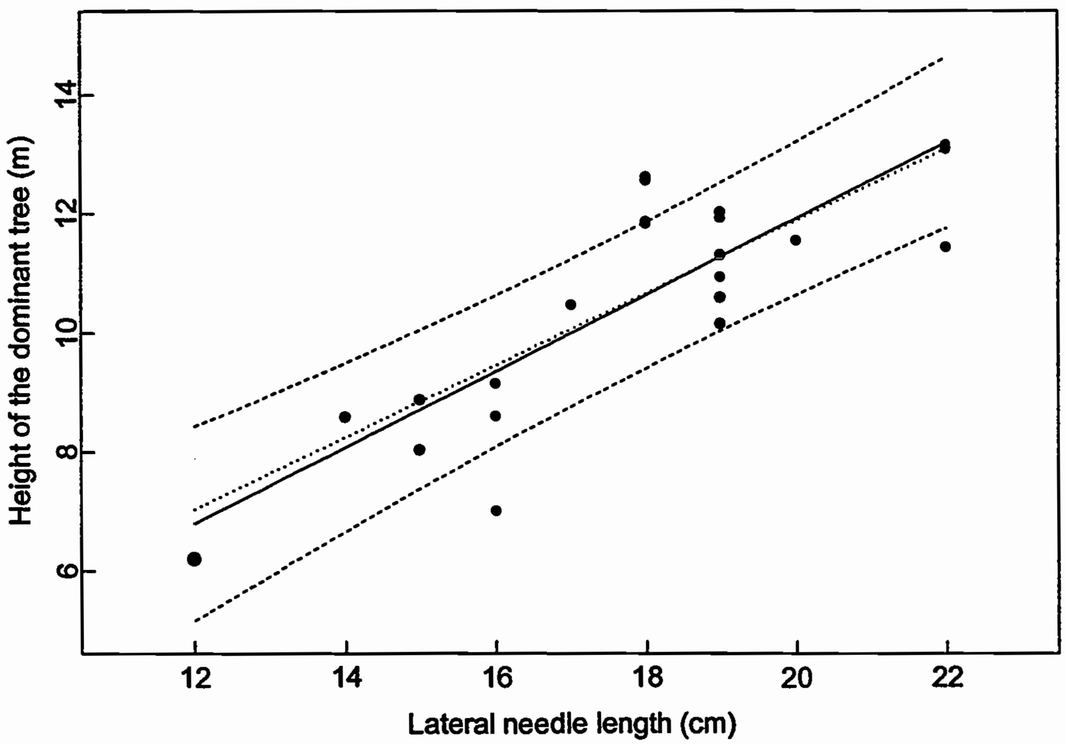

Figure V.7. Regression line (solid line) and 95% confidence level prediction bands (dashed lines) for the model that predicts H at age 20 of selected dominant felled trees based on their lateral branch needle length. The larger dot corresponds to the observation extrapolated from a 19-year-old plot. The regression line for a model that does not contain the extrapolated point is shown as a dotted line.

At age 20, the H predicted by the LNL measured on selected dominant trees (Figure V.7) was basically the same as the TH predicted by the inferential model based on H measurements taken from standing trees (Figure V.6). This suggested that at age 20, LNL would predict stand TH accurately, as long as LNL is determined on a tree with the H equal to the mean H of the 100-300 trees per ha.

A Preliminary Needle Length Index

The good fit of the selected model demonstrated that the LNL of 20-year-old dominant trees can serve as a preliminary needle length index (NLI) to determine the site quality of the ponderosa pine plantations in Neuquén. The range of LNLs in the selected model (12-22 cm) (Figure V.6) did not cover the whole range in LNLs observed among all 74 sample plots (9-27 cm). The full range of the NLI will vary between these two extreme values covering the whole spectrum of site qualities observed in the province (Table V.4).

The fact that the minimum and maximum values of LNL and growth intercept index predict almost the same THs, suggested that both methods are compatible (Table V.4).

Field Application

To determine the NLI of ponderosa pine stands in Neuquén, the following procedure is recommended. Determine the approximate shape and size of the stand and randomly locate the center of single plot. Relocate it, only if it happens to fall in an area where trees present unusual characteristics in relation to the rest of the stand in terms of density, disease, etc. Establish a circular or square plot large enough to include at least 40 trees. Select the three tallest trees within the plot, and measure the length of 10 fascicles located around the terminal bud of three first order branches, located in the upper half of the crown (Figure V.5) and calculate their average. Selecting the three tallest individuals is important, since measuring LNL on shorter trees can result in an underestimation of the site quality.

Table V.4. Top height (TH) at age 20 predicted by seven values of the preliminary needle length index (NLI) based on the mean length of 10 fascicles located on the tip of three first order lateral branches located in the upper half of the crown. The respective mean annual increment (MAI) of TH and growth intercept index (GII) values are also presented to further illustrate the growth rate associated to each NLI value.

NLI (cm)	TH at age 20 (m)	MAI of TH at age 20 (m)	GII (m)
27	16.5	.82	4.9
24	14.6	.73	4.5
21	12.6	.63	4.1
18	10.6	.53	3.6
15	8.7	.43	3.0
12	6.7	.33	2.3
9	4.7	.23	1.3

To predict the TH of the stand at age 20 using NLI, read the TH of the stand at age 20 from Table V.4, or compute TH using the selected model for a more refined estimation.

CONCLUSIONS

Site quality of unthinned ponderosa pine plantations in Neuquén can be predicted by measuring the length of needle fascicles taken from the tip of two or three primary branches on a single dominant tree. The method is based on the assumption that needle length remains constant throughout the life of the stands. Applying this procedure is most practical when determining site quality in young plantations, where sample needle fascicles can be collected without the assistance of a ladder. On taller stands, growth intercept index, may be a more sensible tool, since reaching the upper parts of the crown to obtain the sample needles can be difficult.

More thorough ways of collecting data may improve the predictive ability of needle length by accounting for some potential confounding variables. For example needle length can be measured: 1) on more than one tree per plot, 2) on more branches per tree, 2) not only on yearly needles but also on 2-, and even 3-year-old needles, 3) at a fixed tree height, i.e. upper third of the canopy, etc. Based on the fact that the selected model is represented by a straight line, new data should be collected mainly from low and high quality sites to make a more accurate estimation of the slope of the function.

The proposed model was developed with data from unthinned stands that have received no site preparation. Hence, the application of effective site preparation techniques or any other treatments that can significantly accelerate the height growth of young stands would require a revision of the function.

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VI. VARIABLE-DENSITY YIELD EQUATIONS FOR UNTHINNED YOUNG-GROWTH PONDEROSA PINE PLANTATIONS IN NEUQUÉN, PATAGONIA, ARGENTINA

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ABSTRACT

Two whole-stand yield equations were developed for unthinned young-growth ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) plantations in Neuquén, southwest Argentina. One of the equations predicts current yield based on age, growth intercept index, longitude, and basal area. The other equation predicts current yield, based on the same factors except that basal area is replaced by number of trees/ha. The data were collected from 127 plots established throughout Neuquén province. Both models provide accurate yield predictions between ages 10 and 25. A comparison with northern California ponderosa pine plantations based on Oliver and Powers' (1978b) yield models, demonstrated that Neuquén stands are more productive. Data collected from the few available sample plots between ages 26 and 41 support our hypothesis that the yield of ponderosa pine in Neuquén would remain higher up to at least age 40. Neuquén stands support very high stocking and they exhibit negligible mortality despite their very high basal areas and relative densities by North American standards.

INTRODUCTION

The Importance of Ponderosa Pine in Patagonia

Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) is the most widely planted species in the Patagonian Andes region of Argentina, where it grows vigorously and without any serious pest problems. Preliminary studies suggest that the average yield of these stands could be similar to or even higher than those growing on the more productive regions of the western United States (Gonda and Lomagno 1995, Urzúa 1991). The environmental conditions in northern Patagonia are similar to those where ponderosa pine (variety ponderosa) forests grow naturally in the western United States. The piedmont of the northern Patagonian Andes and the interior Pacific Northwest share the following main characteristics:

1. The latitudinal ranges are similar in the respective hemispheres (Figure VI.1)
2. Moisture is provided by humid winds blowing from the Pacific Ocean.
3. A rain shadow effect is produced by the Andes as well as by the Cascades and the northern Sierra Nevada ranges.
4. A Mediterranean climate prevails, imposing a well-defined dry season.
5. A high proportion of the soils are of volcanic origin.

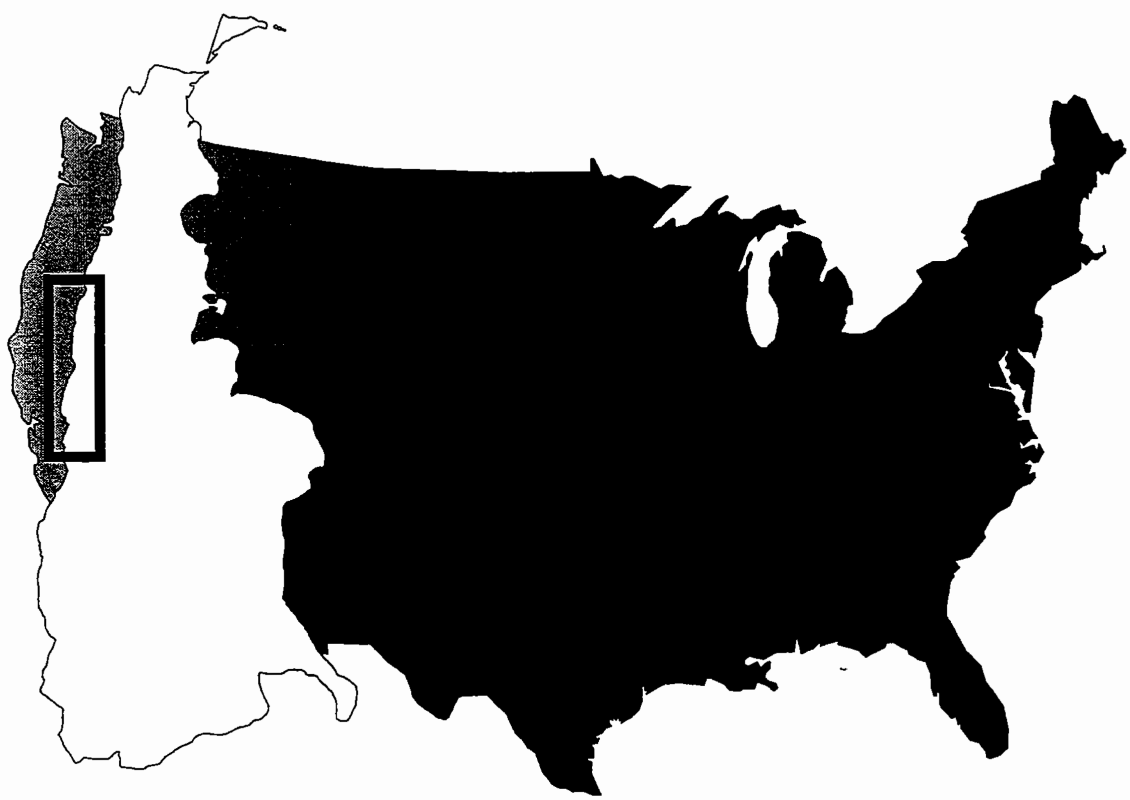

Figure VI.1. A map superimposing the Patagonian Andes (Argentina) over the Cascades and northern Sierra Nevada (United States). The rectangle includes the current distribution area of the ponderosa pine plantations in Patagonia. The latitude of both countries match, and they are drawn at the same scale.

The area planted annually with ponderosa pine in Argentina is rapidly increasing due to the subsidies and credits that the Patagonian provinces and the federal government provide for planting fast-growing species. The primary objective of this support is to promote afforestation as a means to improve the socioeconomic conditions of the region. Currently there are about 30,000 hectares of ponderosa pine forests (Urzúa 1991), with about a million hectares of grasslands suitable for commercial afforestation throughout the piedmont of the Patagonian Andes (Enricci 1993).

Information on site quality and growth of ponderosa pine in Patagonia is limited. This incomplete knowledge can dissuade potential investors from planting trees and frustrate efforts to develop sound management plans. Because species that are grown outside their native range typically exhibit growth and developmental patterns that differ significantly from those of the species within its native environment, it is also risky to extrapolate growth predictions to new geographic areas (Zobel et al. 1987).

To ameliorate these problems the Patagonian Andes Forest Research and Extension Center (CIEFAP), along with the University of Comahue Forest Technical School and the government of Neuquén, have started quantitative silvicultural studies on ponderosa pine plantations throughout Neuquén province, covering an area that includes about 80% of the present plantation forests of this species in Patagonia (Figure VI.2). These studies constitute the Neuquén Ponderosa Pine Site Quality and Yield (NPPSQY) project.

Yield Equations

Timber management decisions require accurate predictions of the productivity of the stands. The predicted volumes, and appropriate economic analysis models, make it possible to generate decisions concerning optimum rotation ages, planting density, timings of thinning, etc. The idea of yield estimation was first applied in China about 350 years ago (Vuokila 1965), but the technique to

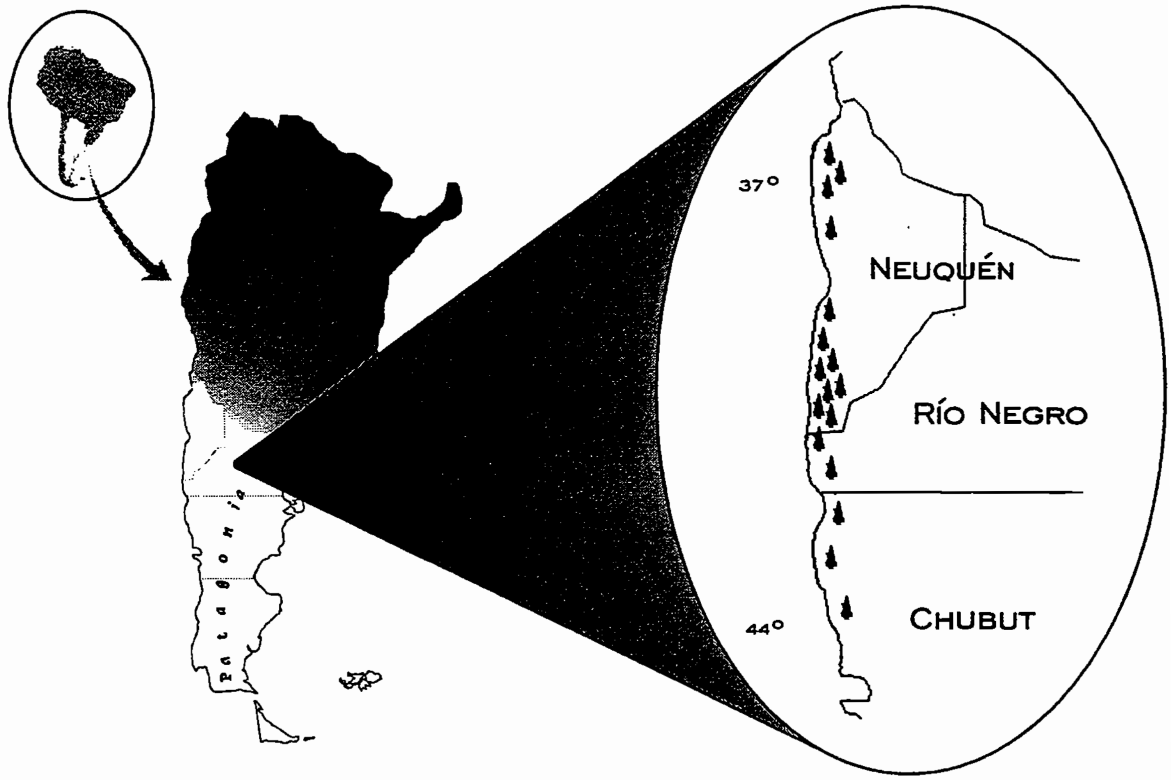

Figure VI.2. From left to right: maps showing the position of Argentina in South America, Patagonia within Argentina, and the current distribution of the ponderosa pine plantations in the provinces of Neuquén, Río Negro, and Chubut. The number of pine trees is proportional to the plantation area.

anticipate the yield of even-aged stands at various ages as it is known today was developed in Europe in the eighteenth century (Assmann 1970).

The first yield tables were devised for fully stocked or normal forest stands. The different approaches used in Europe and North America for their construction were discussed by Vuokila (1965) and Spurr (1952) respectively, and Tesch (1981) compared the evolution of yield determination in both continents over the last century. Typically, normal yield tables predict the current yield of fully stocked stands given the age, site quality, and number of trees per unit area. Preliminary normal yield tables for natural or second growth ponderosa pine stands in the western United States were first developed in the 1920s

(Behre 1928a, Behre 1928b, Show 1925), and 1930s (Dunning and Reineke 1933, Meyer 1938).

Normal yield tables, however, were not adequate for the management of plantations because they are based on the normal stocking concept. This problem was solved in the late 1930s when the first variable-density yield models were developed (MacKinney and Chaiken 1939, MacKinney et al 1937, Schumacher 1939). These models were also the first ones presented as equations rather than tables, and they provided the basis for the construction of numerous yield functions that often use slightly modified versions of the Schumacher (1939) yield equation that predicts yield based on stand age, site quality, and density (Clutter et al. 1992). Oliver and Powers (1978b) constructed these kinds of yield functions for unthinned plantations of ponderosa pine in northern California.

During the last 15 years more sophisticated models have been developed to simulate the yield and growth of ponderosa pine stands in different regions of the Western United States, such as PROGNOSIS (Wykoff 1986, Wykoff et al. 1982), CACTOS (Wensel et al. 1986), PPSIM (DeMars et al. 1987), ORGANON (Hann et al. 1993), and SYSTUM-1 (Ritchie and Powers 1993).

Depending on the complexity of the mathematical procedures involved, yield functions are usually classified as whole-stand, size-class, or individual-tree models (Clutter et al. 1992, Vanclay 1994). We decided that using whole-stand yield equations was the simplest approach and the most appropriate for the characteristics of the ponderosa pine plantations in Neuquén.

It would not be appropriate to develop more sophisticated models at this time because: 1) most stands were below 20 years of age, far below the 30- to 40-year estimated rotation age; 2) even the older and most dense sample stands had no visible dead trees, hindering the modeling of mortality; 3) the lack of stands growing at lower densities more typical of managed stands (below 600 trees per ha) did not allow us to perform meaningful studies on the effect of the number of trees per unit area on diameter growth; and 4) not enough plantations have been thinned in order to provide the information needed to develop yield equations for managed stands.

Objectives

The first objective of this study was to build whole-stand, variable-density yield equations to predict current volumes of young-growth ponderosa pine plantations in Neuquén. These models were intended to give biologically realistic predictions across the whole range of possible conditions. However, the equations were empirical because they did not have an underlying hypothesis associated with the cause of the phenomenon described by the response variables, as in the case of process or theoretical models. The second objective was to compare the productivity of ponderosa pine stands in Neuquén with the yield of ponderosa pine plantations growing on highly productive sites in northern California.

METHODS

Sample Plots

The data consisted of measurements collected from 127 permanent sample plots established in Neuquén for the NPPSQY project, from June to September 1997. The eight southernmost plots were located in Río Negro province, only a few kilometers from the Neuquén border, because no ponderosa pine plantations were located in Neuquén province at those latitudes (Figure VI.3). Each plot was located in a different stand so that we could sample most of the geographical distribution of the ponderosa pine plantations in the province, as well as the range of factors that can be associated with tree growth (Table VI.1).

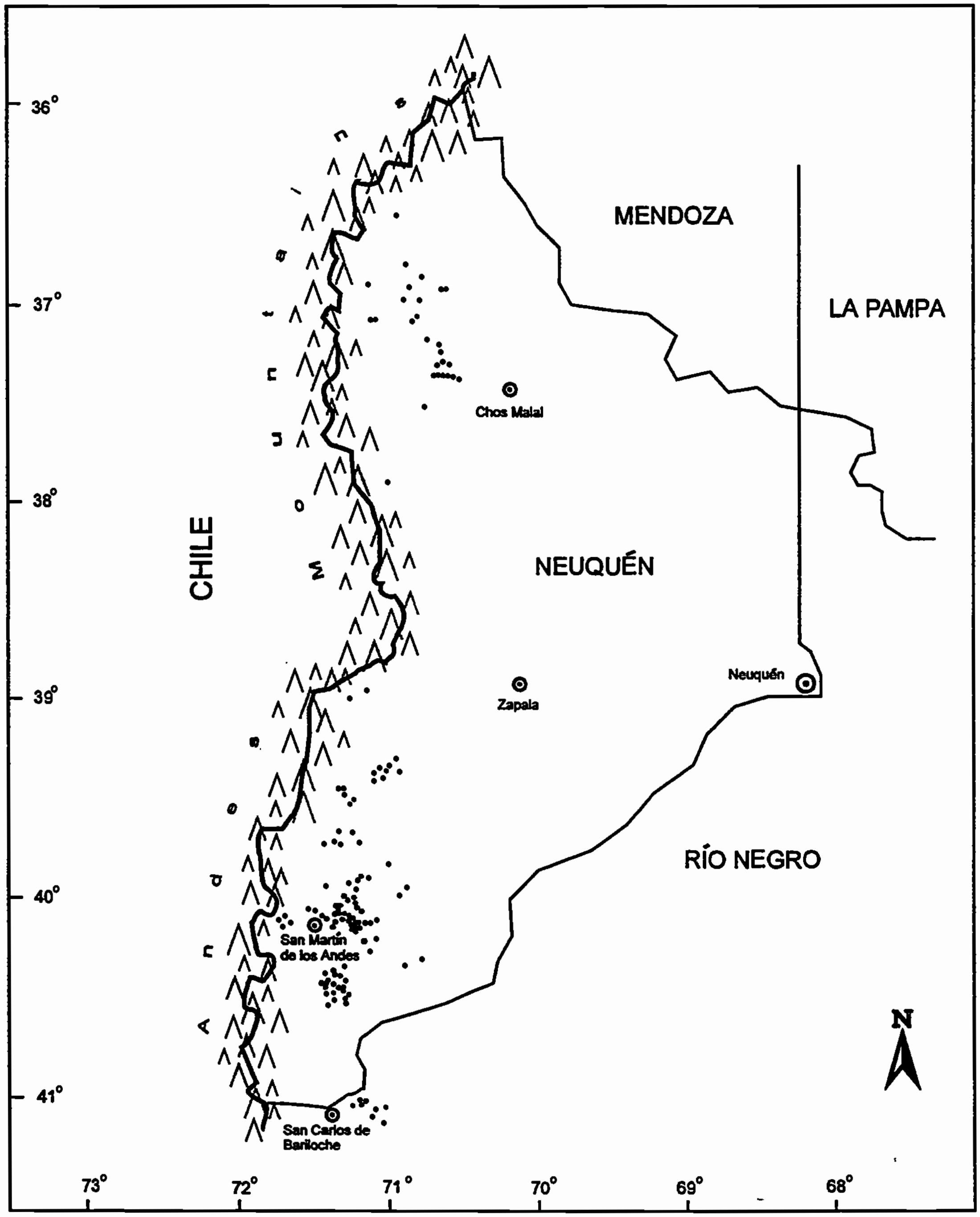

Figure VI.3. Location of the 127 sample plots in the provinces of Neuquén and Río Negro.

A few ponderosa pine stands in Neuquén were planted with the scopulorum variety (Rocky mountain ponderosa pine) of ponderosa pine, as it was defined by

Oliver and Ryker (1990). These plantations were not sampled because trees of this variety are no longer planted. Even though these individuals have a superior cold resistance, they also typically have much slower growth rates, as was demonstrated by some provenance trials in Patagonia (Enricci, unpublished data). Individuals of the ponderosa variety grow much faster, and have so far been able to withstand the low temperatures on most planting sites.

Table VI.1. Minimum, maximum, and mean values of latitude, longitude, elevation, slope, aspect, annual precipitation (precip), and soil depth (soil d) ranges of the 127 plots sampled in Neuquén province for the yield equations.

	Latitude	Longitude	Elevation (m)	Slope (degrees)	Aspect (degrees)	Precip (mm/yr)	Soil D (m)
Minimum	36°30'00"	70°35'22"	650	0	0	400	0.4
Mean	38°47'58"	71°04'18"	1059	8.6	140	929	1.0
Maximum	41°05'57"	71°33'15"	1715	30.0	350	2229	1.8

Stands Characteristics

Since ponderosa pine plantations in Neuquén are young, most sample plots were below 25 years of age (Table VI.2). We located only eight older stands between ages 26 and 41.

Trees Characteristics

Ponderosa pine plantations in Neuquén show little insect, disease, or storm damage. Thus, the vast majority of the 6188 sample trees were healthy and undamaged. Only 75 individuals, scattered among 31 plots, showed some degree of abnormality; 28 were forked, 21 bent by the snow, 16 had broken tops, and 10 shared the same stem below breast height. The height of trees bent by

Table VI.2. Minimum, maximum, and mean values of the main characteristics of the 127 plots sampled throughout Neuquén province for the yield equations. Reineke's stand density index (SDI) was computed with a slope of -1.7712 (Oliver and Powers 1978b) for a mean diameter at breast height (D) of 25 cm.

	Age	Trees/ ha	Mean D (cm)	Top height (m)	Mean height (m)	Basal area (m^2)	Volume (m^3/ha)	SDI
Minimum	10	307	7	4.0	3.1	2.6	6	66
Mean	17	1314	16	8.9	7.5	30.1	128	657
Maximum	41	2500	34	27.3	23.8	100.8	937	2012

the snow or with broken tops was computed with Wykoff's height-diameter equation (Wykoff et al. 1982). The parameters of the equation were estimated for each plot using the available height-diameter data. None of the plots contained more than five abnormal trees. One of the plots contained 43 ponderosa pine and 10 Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) trees. The Jeffrey pines were retained because these trees exhibit similar growth characteristics (Hallin 1957). Some of the sample stands had been pruned, and thus the effect of pruning on yield was examined.

Field Procedures

Plots were randomly located within each stand. All plots were circular, but had different areas in order to include at least 40 trees. The age of the plots was determined by counting the internodes on several dominant trees. In 83 of the plots, diameter at breast height (D) and total height (H) were measured on each tree. In the other 44 plots, the D of all trees was recorded; however, because of time constraints only two-thirds of the trees were measured for H. Height was always measured across the range of diameter classes, paying special attention to include the tallest and shortest individuals. Missing Hs were computed by fitting Wykoff's height-diameter equation (Wykoff et al. 1982) to each of the 37 plots: $H = 1.3 + e^{(\beta 0 + (\beta 1/(D+1)))} + \varepsilon$.

Total inside-bark stem volume (V) was computed with the two-variable equation developed for these plantations (see Chapter 3): $V = .000214 + .000030 * D^2H + .000538\ D$. The heights to the first six whorls of branches beginning at or above breast height were measured on the five tallest trees in the plot. These measurements were used to calculate the cumulative length of the five internodes starting at or above breast height. The H of trees less than 12 meters tall as well as the height to the first six whorl of branches starting at or above breast height were measured directly with a telescopic fiberglass pole to the nearest cm. Taller trees were measured indirectly with a clinometer (either *Blume-Leiss* or *Suunto*) to the nearest 5 cm. The D was measured to the nearest 0.1 cm with diameter tape at 1.3 m from the ground.

Latitude and longitude were determined with a global positioning system (GPS) receiver. Elevation, slope, and aspect were determined with an altimeter, a clinometer, and a compass respectively. Annual precipitation information was obtained from provincial or private records, when available, or from isohyet maps otherwise. A pit was dug in each plot to determine soil rooting depth and the presence of volcanic ash, clay, and silt. The presence of ash was determined by applying the test developed by Fieldes and Perrot (1966). As a measure of relative density, Reineke's stand density index (SDI) was calculated for each plot with a slope of -1.7712, the one determined by Oliver and Powers (1978b) for dense natural ponderosa pine stands in northern California, and for a mean D of 25 cm.

Yield Equations

Two yield equations were developed starting from the basic form of the Schumacher (1939) equation that predicts stand volume based on three explanatory variables: stand age, some function of site quality, and some function of stand density. Both models predict current yield and differ only by their density estimator. Basal area (BA) and number of trees per hectare (TR/HA) are the density variables in the first and second models respectively. Even though BA is a better volume predictor than TR/HA, the first model can only estimate yield at the current age of a given stand because we do not know what the BA would be at a different age. Since our study involved unthinned plantations with negligible mortality, the second equation based on TR/HA can predict the current volume of stands at different ages, based on the assumption that TR/HA remains constant. Stand age from planting (AGE) and a growth intercept index (GII) based on the length of the five internodes starting at or above breast height, were the other two explanatory variables in both basic models. The GII was developed for the ponderosa pine plantations of Neuquén (see Chapter IV).

The two basic models were fitted allowing for the inclusion of inverse and polynomial expressions of any of the three explanatory variables. Then the significance of the following environmental variables was investigated by adding them to the fitted basic equations one at a time: longitude, latitude, annual precipitation, elevation, slope, aspect, soil depth, presence of allophane (ash), and presence of clay and/or silt in the soil. Latitude and longitude were transformed into decimal units in order to treat them as continuous variables. Finally, the significance of pruning was tested by adding this term to the equations.

Because errors associated with yield prediction are heteroscedastic and the variances tend to increase with age, both equations were first fitted by logarithmic least-squares regression (Schumacher 1939). Then both selected logarithmic models were refitted in their respective nonlinear versions by applying nonlinear regression. Nonlinear models were preferred because they do not introduce a log bias correction and are more flexible. Theoretically, the log bias correction cannot be performed if the residuals are not normally distributed

(Baskerville 1972), and the choice of alternative correction factors is not always easy (Flewelling and Pienaar 1981). The flexibility of nonlinear models allows for biologically reasonable shapes (Huang et al. 1992), a feature that is highly desirable because users often perform extrapolations (Vanclay 1990).

The nonlinear models were fitted using as initial coefficients those computed for the respective logarithmic equations. Heteroscedasticity was ameliorated by transforming the equations; dividing both terms of each function by the same denominator. Age and BA to the powers 1 to 8 were tried as denominators for the TR/HA and BA equations respectively. Transformed equations were compared with Furnival's (1961) index of fit. This index has the advantage of reflecting both the size of the residuals and possible departures from linearity, normality, and homoscedasticity (Furnival 1961).

A Comparison with the Yield of Young-Growth Unthinned Ponderosa Pine Plantations in Northern California

Stand volumes predicted by the TR/HA yield equation were compared with those predicted by yield equations developed by Oliver and Powers (1978b) for ponderosa pine plantations in northern California. Comparisons with Oliver and Powers (1978b) yield models were meaningful because they worked with young plantations growing on high quality sites. The rest of the yield models developed for ponderosa pine in the western United States are typically based on natural, older stands.

Comparisons were made between stands of the same age from planting, dominant height, and number of trees per unit area. Oliver and Power's site index (SI) was converted into GII by first computing the dominant H of California stands at age 20 with their SI index equation (Oliver and Powers 1978a), and then calculating the GIIs that corresponded to those dominant Hs at age 20 with the function that relates GII with top H (see Chapter 4). We assumed that Oliver and Power's (1978a) dominant H, and the top H of Neuquén plantations, predicted the mean H of the same proportion of dominant trees.

Yield comparisons were made for SIs 60 ft (18.2 m), 90 ft (27.4 m), and 120 ft (36.6 m), defined by Oliver and Powers (1978b) as the dominant height in feet reached by the plantations at age 50. Plantations with SIs 60 ft, 90 ft, and 120 ft reach dominant heights of 6.6, 9.8 and 12.9 m respectively at age 20. These Hs corresponded to GIIs of 2.28, 3.38 and 4.15 m respectively in Neuquén plantations. Plantations with dominant Hs as low as those for California SI 40 were not found in Neuquén, and plantations growing on the best sites in Neuquén reached dominant Hs that were not found in California; if they existed they would have a hypothetical SI of 140.

Yield comparisons were made for three stand densities: 747, 1076, and 1682 trees per ha. These corresponded to spacings of 12 x 12, 10 x 10, and 8 x 8 feet, respectively. Oliver and Powers (1978b) presented function coefficients for one more spacing, 6 x 6 feet or 2990 trees per ha, but stands with this high number of trees per unit area were not found among Neuquén plantations.

We compared the maximum Reineke's SDI value observed in dense stands in northern California (Oliver and Powers 1978b) with the SDI of Neuquén plots. To make this comparison possible we computed the SDI for northern California stands in Metric units with a base diameter of 25 cm (10 in). Since in Neuquén ponderosa pine stands had not yet reached maximum relative densities, as observed by active self-thinning, the slope determined for northern California stands (-1.7712) was used for the calculations.

Oliver and Powers (1978b) computed tree volume from a 30 cm stump to tree tip; we determined it from a 5-10 cm stump to the top. We assumed that the 20-25 cm difference in stump length did not have a significant effect on tree volume.

RESULTS AND DISCUSSION

Yield Equation Based on Basal Area

The only significant environmental factors were longitude or precipitation, and either of them explained the same amount of variation in yield. Longitude was preferred because it can be readily determined from maps or with a GPS. Many areas of Neuquén province lack precipitation information, and it will take many years to collect enough data to obtain reliable records. Longitude is highly correlated to precipitation because of the strong west-east rainfall gradient resulting from the rain shadow effect produced by the Andes Mountains (Figure VI.2). Pruning did not have a significant effect on yield, probably because most stands had been pruned recently and the standard procedure consists of eliminating no more than one-third to one-half of the live crown.

The Furnival's index of fit for the selected nonlinear equation (i.e., 4.79) and the respective log equation (i.e., 4.72) were almost the same. The denominator selected to account for the heteroscesdasticity of the transformed final equation was $BA^{1.4}$. The residuals showed no trends when plotted against the predicted values, GII, AGE, BA, pruning, and nine environmental variables; namely, latitude, longitude, elevation, slope, aspect precipitation, and the presence of allophane, clay and silt. A plot showing the observed and fitted yields against age, illustrates the good predicting ability of the equation for our data set (Figure VI.4). The final model to predict the current yield of ponderosa pine plantations in Neuquén based on BA has the following form:

$$V = e^{5.73703}\ e^{1/GII\ (-1.93084)}\ e^{1/AGE\ (-8.4737)}\ BA^{1.00985}\ e^{BA^2\ .0000345677}\ e^{AGE^2\ .000436136}\ e^{LONGITUDE\ (-.0512352)} + \varepsilon$$

Where:

MSE: .0035259369. All terms are significant at the 95% level.
BA = basal area of the stand in square meters

GII = growth intercept index
LONGITUDE = it should be entered in decimal units with four digits after the decimal point, by adding degrees, minutes divided by 60, and seconds divided by 360; e.g. 10°15'20" = 10.3055.

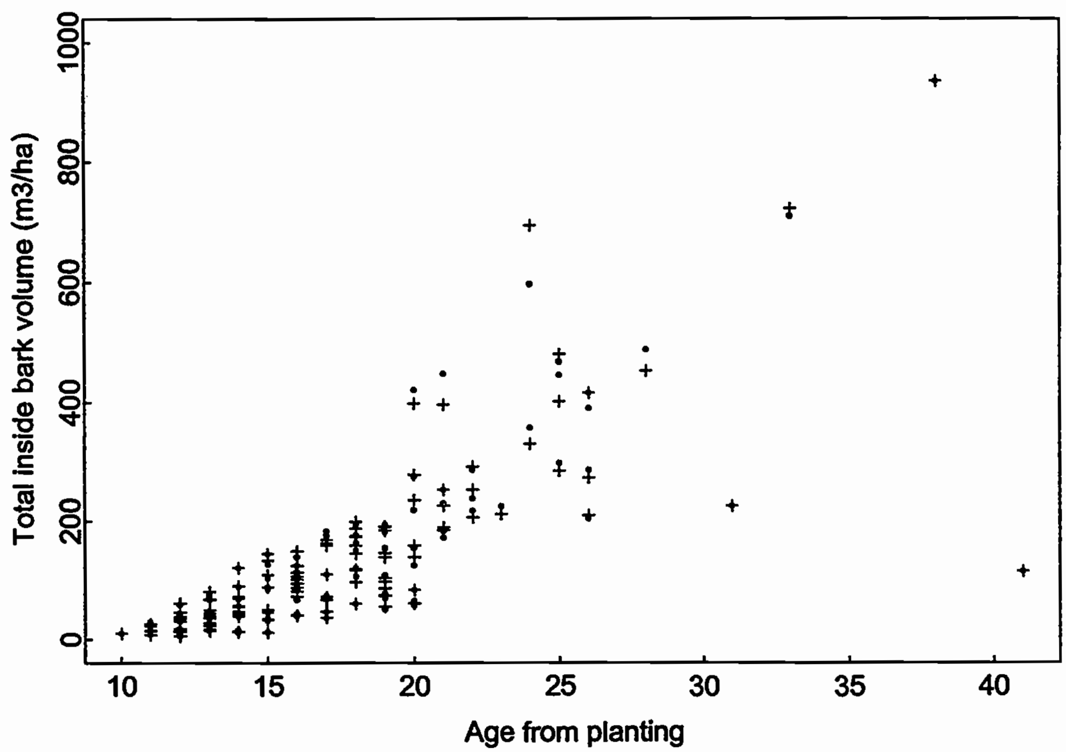

Figure VI.4. Observed (dots) and predicted (crosses) volumes based on the basal area yield equation developed for the ponderosa pine plantations in Neuquén.

This current yield model has the potential to accelerate volume estimates in the field by eliminating the need to measure total tree heights and diameters. Current volumes can be determined by measuring BA, GII, and the stand age from planting; longitude can be determined from a map or with a GPS. The model will simplify the field data collection for the inventory of the ponderosa pine plantations in Neuquén that will be carried out in the near future.

Yield Equation Based on Number of Trees per Hectare

As was the case with the BA yield equation, the only significant environmental variables were longitude or precipitation, and longitude was preferred because it can be readily determined from maps or with a GPS. Pruning did not have a significant effect on yield. Despite the fact that Furnival's index of fit for the nonlinear model was 13% larger than the one for the respective log equation, the nonlinear equation was chosen as the final model. Logarithmic models are not as flexible and they require a correction that may not necessarily eliminate all bias (Flewelling and Piennar 1981) and requires normally distributed residuals (Baskerville 1972).

The denominator selected to account for the heteroscesdasticity of the transformed final equation was $AGE^{3.2}$. The residuals showed no trends when plotted against the predicted values, GII, AGE, TR/HA, pruning, and the same nine environmental variables analyzed for the current yield model. The model selected to predict the current yield of the ponderosa pine plantations in Neuquén based on TR/HA had the following form:

$$V = e^{-21.7736} \; e^{1/GII\ (-6.69761)} \; e^{1/AGE\ (-41.5545)} \; TR/HA^{.620394} \; e^{AGE^2\ .000704828} \; e^{LONGITUDE\ .367201} + \varepsilon$$

Where:

MSE: .0000095854. All terms are significant at the 95% level.
BA = basal area of the stand in square meters
GII = growth intercept index in meters
LONGITUDE = it should be entered in decimal units in the same manner as it was explained for the basal area yield equation.

We expect the model to produce accurate predictions between ages 10 and 25 because it is based on data from 119 plots well distributed along the range of the main factors affecting yield (Tables VI.1), and on the current characteristics of the ponderosa pine plantations in Neuquén (Figure VI.2). Yield curves within this age range are presented for plantations growing at typical eastern and western longitudes within the current range of ponderosa pine stands in Neuquén. The curves are shown for stands with a commonly observed stand density of 850 trees per ha growing on six different site qualities (Figures VI.5, VI.6).

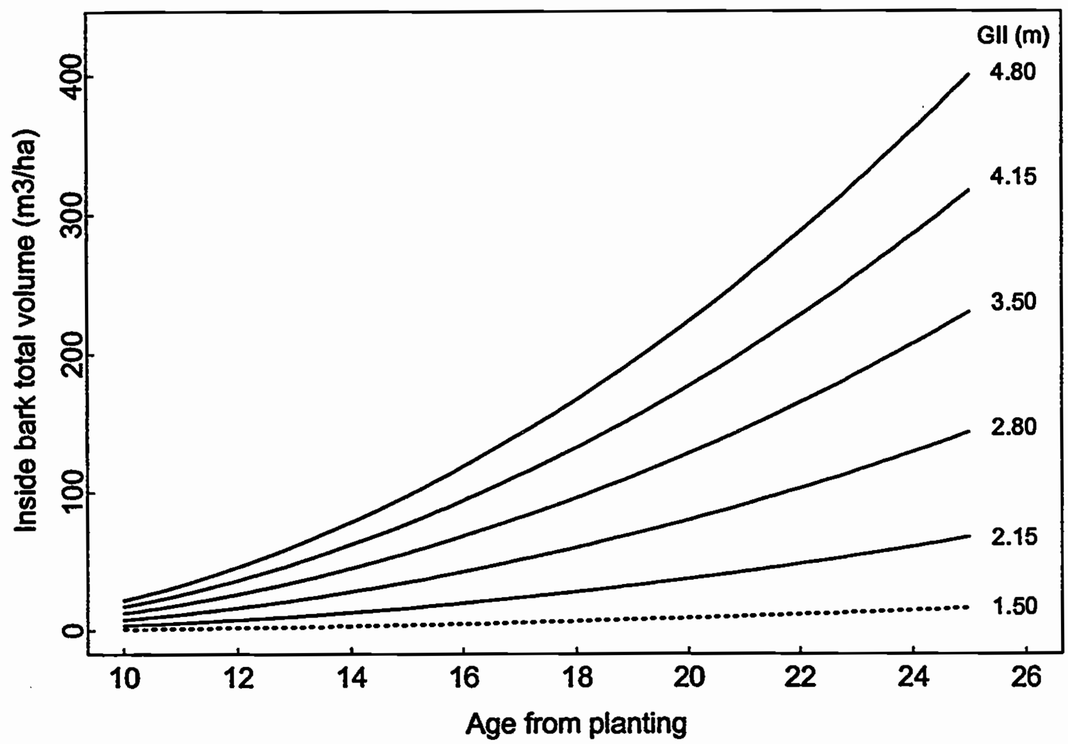

Figure VI.5. Yield curves for western (longitude: 71° 15' 00") ponderosa pine plantations in Neuquén. Curves are shown for stands with 850 trees per ha with six different growth intercept indices (GII). Yield of the lowest GII is presented as a dotted line because only one sample plot had a GII below 2.15 m.

Despite the fact that most ponderosa pine plantations in Neuquén were younger than age 20, we were able to establish plots in eight stands between ages 26 and 41. Even though they did not represent enough data to make meaningful predictions, they provided some basis to speculate about what the production of the plantations would be up to age 40. These eight plots contributed conservative yield data to the model, because they belonged to medium and low GII classes (Figure VI.4). Yield predictions between ages 26 and 40 seemed reasonable, especially when they are compared to the yield of ponderosa pine plantations in northern California, as we explain below.

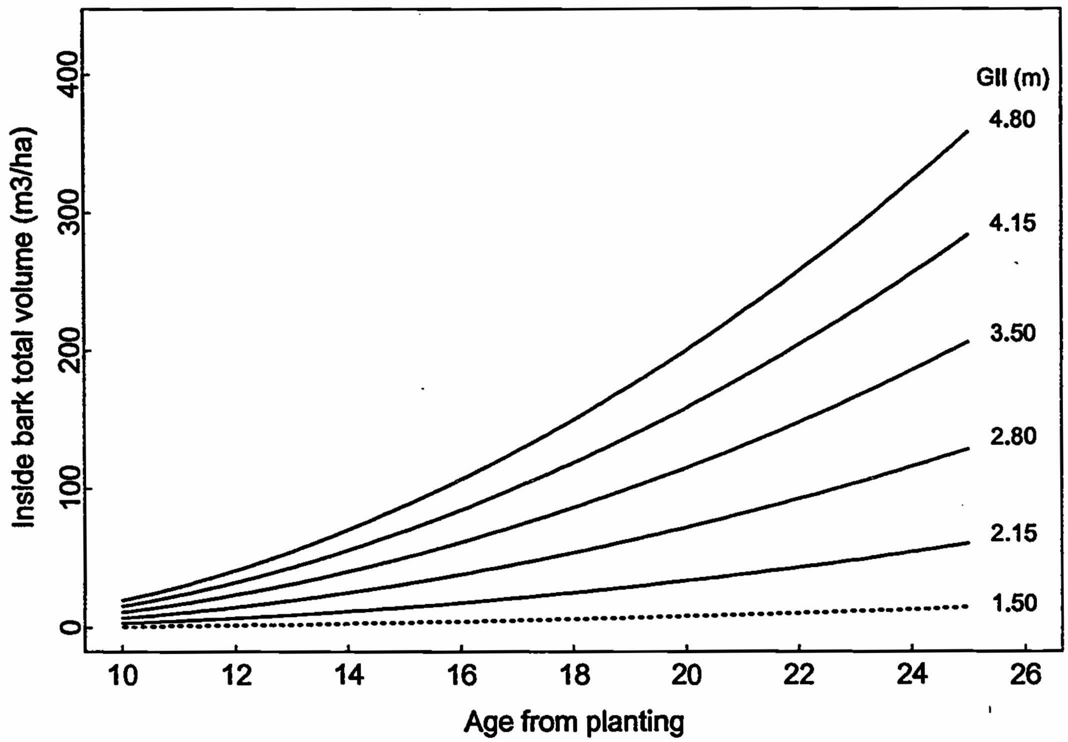

Figure VI.6. Yield curves for eastern (longitude: 70° 50' 00") ponderosa pine plantations in Neuquén. Curves are shown for stands with 850 trees per ha and six different growth intercept indices (GII). Yield of the lowest GII is presented as a dotted line because only one sample plot had a GII below 2.15 m.

A Comparison with Young-Growth Unthinned Ponderosa Pine Plantations in Northern California

Because longitude had a significant effect on the yield of the ponderosa pine plantations in Neuquén, we computed the yield of stands growing in the eastern (70°50'00") and western (71°15'00) parts of the range. We then compared the yield of Neuquén plantations from these two locations with yields of California stands of the same age and dominant height (site quality), growing at three different densities, 747, 1076, and 1682 trees per ha. The ponderosa pine plantations on better sites in Neuquén (GIIs: 4.2-4.8 m) had no match among the better sites in California stands, where the highest SI is 120 ft, equivalent to a GII of about 4.2 m.

Within the age range for which our TR/HA yield model can provide meaningful predictions (up to age 25), the volumes of Neuquén plantations growing at either eastern or western longitudes were clearly higher than the yield of California stands. We illustrate this difference in yield in a tabular (Table VI.3) as well as in a graphical form (Figure VI.7). This productivity difference increased with age. Since the comparison was made between stands of the same age, dominant height, and density, we concluded that in Neuquén ponderosa pine trees have a faster diameter growth.

The difference between the predicted volumes of Neuquén and California stands increased between ages 26 and 40 (Table VI.3, Figure VI.7). The yield of California plantations reached a plateau around age 30 for the three densities studied. This plateau occurred earlier in stands with a higher SI and density. Conversely, the yield of Neuquén plantations increased proportionally to the number of trees per unit area up to age 40, suggesting that in this province ponderosa pine can reach higher stockabilities.

The higher yield predictions for Neuquén plantations between ages 26 and 40 seemed reasonable when we compared the maximum BA and SDI values observed in both regions. California plantations growing on the best sites (SIs 100 ft and 120 ft) reached their maximum BA of approximately 64 m^2/ha by about age 30 (Oliver and Powers 1978b). In Neuquén several sampled stands had BAs near 100 m^2/ha, and we still do not know if those are the maximum possible values because the rates of increase in BA do not decrease with age.

Oliver and Powers (1978b) determined a maximum Reineke's (1933) SDI of 1235 (English SDI = 500) for the unthinned plantations of northern California,

Table VI.3. Yield of ponderosa pine plantations in northern California (Cal) (Oliver and Powers 1978) and in the eastern and western range of Neuquén stands, growing at three different densities on four sites defined in terms of site index (SI) and growth intercept index (GII), between ages 10 and 40.

		Yield (Total inside bark stem volume in m^3/ha)								
		747 trees/ha (12 x 12 feet)			1076 trees/ha (10 x 10 feet)			1682 trees/ha (8 x 8 feet)		
Site Quality	Age	Cal	Neuquén		Cal	Neuquén		Cal	Neuquén	
			East	West		East	West		East	West
	10	1	4	4	1	5	5	2	6	7
	15	7	16	19	8	21	24	9	27	32
GII: 2.29 m	20	23	37	43	25	47	54	27	62	72
(SI: 60 ft)	25	50	66	77	54	83	97	58	110	128
	30	87	106	124	92	133	155	98	175	205
	35	130	163	190	138	204	238	145	269	314
	40	178	246	287	188	308	359	195	406	474
	10	3	10	11	3	12	14	4	16	19
	15	20	42	49	22	53	62	25	70	82
GII: 3.38 m	20	66	96	112	71	120	140	76	159	185
(SI: 90 ft)	25	139	170	199	146	214	249	152	282	329
	30	231	273	318	240	342	399	242	451	526
	35	333	418	488	341	524	612	340	692	807
	40	440	632	737	445	792	924	437	1045	1219
	10	11	14	16	12	18	21	14	23	27
	15	49	61	72	54	77	90	62	102	119
GII: 4.16 m	20	132	139	162	141	174	203	151	230	268
(SI: 120 ft)	25	244	247	288	252	309	361	257	408	476
	30	369	395	461	369	495	578	360	654	763
	35	494	605	706	481	759	886	455	1002	1170
	40	613	915	1067	584	1147	1338	538	1513	1766
	10	-	16	19	-	20	24	-	27	31
	15	-	71	83	-	89	104	-	118	138
GII: 4.58 m	20	-	161	188	-	202	236	-	267	311
*(SI: 140 ft)**	25	-	286	334	-	359	419	-	474	553
	30	-	459	535	-	575	671	-	759	885
	35	-	703	820	-	882	1029	-	1163	1357
	40	-	1062	1239	-	1332	1554	-	1757	2050

* Plantations with this hypothetical SI were not observed in northern California. Yields presented in the table are within the range of Neuquén data, but only eight plots were established between ages 26 and 41.

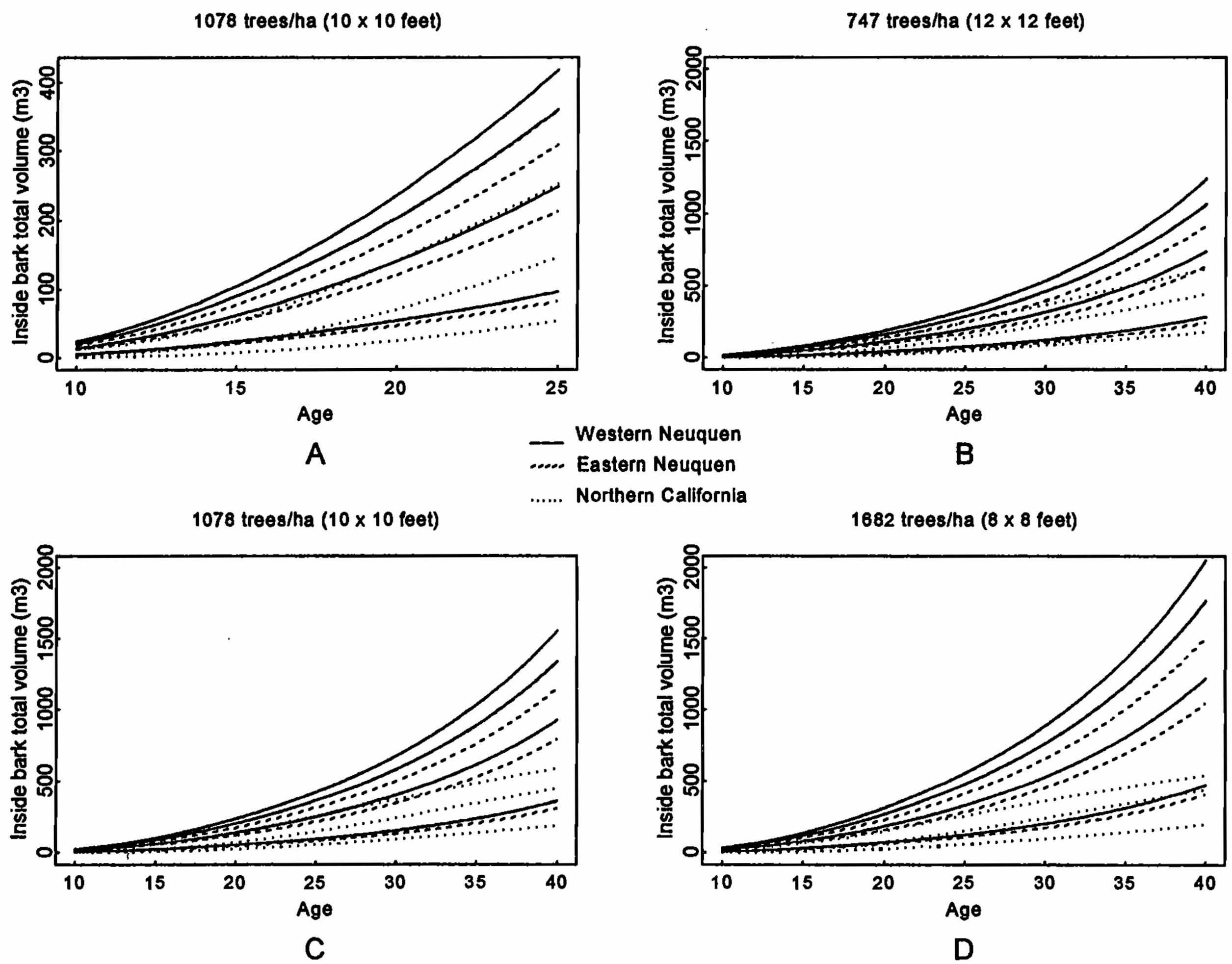

Figure VI.7. Yield curves for ponderosa pine plantations in northern California (Oliver and Powers 1978b) and in the eastern and western ranges of Neuquén stands, growing at three different densities, on four sites (site indexes 60, 90, 120, 140 ft, or GII 2.3, 3.4, 4.2, 4.6 m), between ages 20 and 41. Stands with the highest site quality were not found in California. Figure A is an enlargement of Figure C for the main inference age range of the data.

based on measurements they had taken from dense, natural, even-aged stands in the same region. The SDIs of some of the Neuquén plantations were over 1700 (English SDI=700), and the highest SDI measured was over 2012 (English SDI=814). The fact that mortality was not observed in any of the Neuquén sample plots suggests that the maximum SDI will be over 2000 (English SDI=800). This SDI will most likely be even higher than the maximum SDI Reineke (1933) determined for second growth ponderosa pine stands in California (2050, English SDI=830), which was determined by fitting the line by hand to the plots with the highest densities with a slope of -1.605 (Figure VI.8).

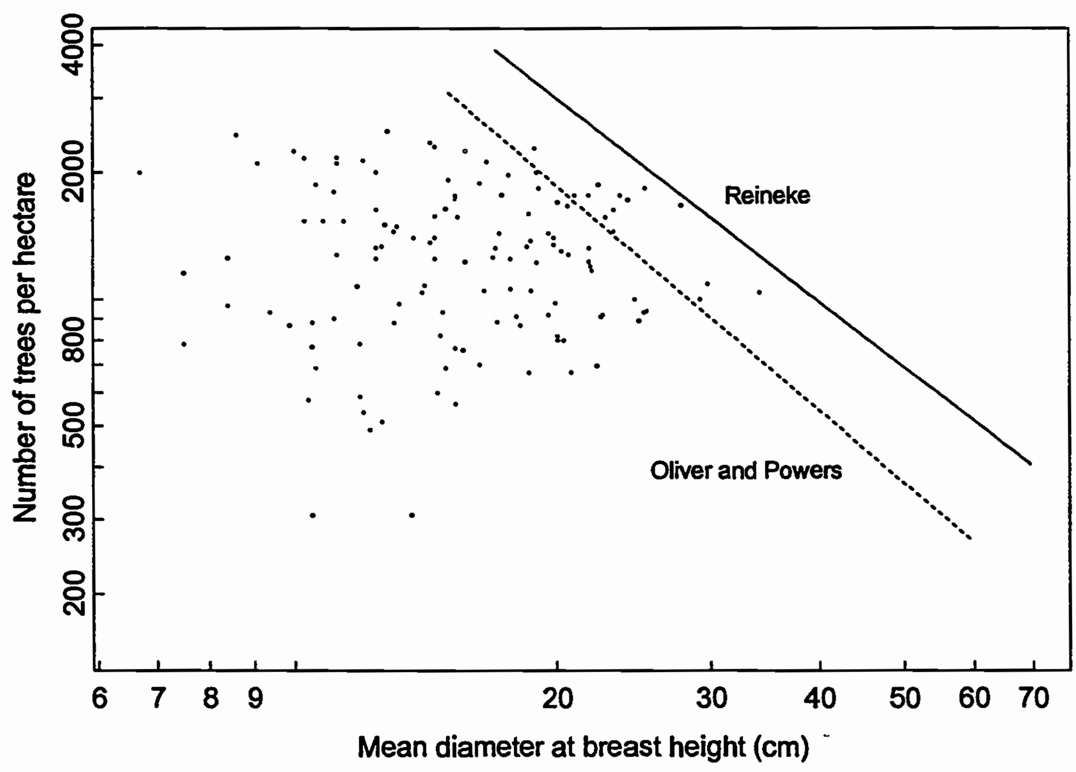

Figure VI.8. Number of trees/ha and diameter at breast height of Neuquén sample plots in a log-log scale, and maximum stand density index for northern California unthinned plantations (SDI=1235) (Oliver and Powers 1978b) and California second growth stands (SDI=2050) (Reineke 1933).

Field Application

To determine the current yield of ponderosa pine stands in Neuquén, the following procedure is recommended. Calculate the approximate shape and size of the stand and randomly locate the center of a single plot. Relocate it, only if it happens to fall in an area where trees present unusual characteristics in relation to the rest of the stand in terms of density, disease, etc. Establish a circular or square plot large enough to include at least 40 trees.

To calculate yield based on the number of trees per hectare, determine the area of your plot, count the number of trees in it, and compute how many individuals there are per hectare. To calculate yield based on basal area measure the D of all trees in the plot, compute their basal area, and calculate the basal area per hectare.

To determine GII, select the tallest five trees within the plot, and on each of them measure the cumulative length of the five internodes beginning at or above BH, and calculate the average. Selecting the five tallest individuals is important, since measuring $GI_{5\text{-}BH}$ on shorter trees can result in an underestimation of the site quality. In tall and dense stands, finding the tallest individuals may be difficult because it may not be possible to see the top of the trees from the ground. In this case we recommend that one person climb the tallest possible tree near the plot center, in order to spot the tallest individuals and point them out to other member of the crew on the ground. Be aware that in dense stands the tallest trees may not be among the ones with the largest Ds.

Determine the age of the plot from plantation records or by counting the total number of internodes on the three tallest trees and calculating the average. Determine the longitude of the plot from a map or with a GPS and covert it into decimal units with four digits after the decimal point. Finally compute current yield with either equation.

CONCLUSIONS

The yield models presented here satisfactorily predict stand volume of unthinned ponderosa pine plantations in Neuquén between ages 10 and 25. Both equations can be applied to stands with 600 - 2200 trees per ha, whose environmental and stand characteristics are within the range of those sampled for this study. The only significant environmental variable was longitude. It explained as much yield variation as did annual precipitation because of the strong rainfall gradient caused by the Andes Mountains.

A comparison demonstrated that the productivity of ponderosa pine plantations in Neuquén was greater than that of plantations growing in northern California, which is one of the most productive areas for this species in the western United States. At the same age, plantations growing on the best Neuquén sites were 25% taller than those growing on the best sites in California. Neuquén plantations contained larger volume/ha than California stands of the same age, dominant height, and trees per unit area. High basal areas and relative densities in Neuquén were observed to be at least 40% higher than the maximum basal areas and relative densities in northern California stands.

The eight sample plots established in plantations between ages 26 and 41 provided conservative yield information because they belonged to medium and low site classes. Thus, we speculated that the real yields for that age range are most likely higher than those predicted by the models. This hypothesis was supported by the fact that Neuquén plantations can achieve much higher densities than those in California. As plantations grow older, more data should be collected to build a model that can accurately predict yields over age 25.

These yield models should be revised if new technology, such as the use of site preparation techniques, significantly alters the growth rates of the ponderosa pine plantations in Neuquén.

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VII. SUMMARY AND SYNTHESIS

INTRODUCTION

In the general introduction I discussed the importance of the ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) plantations in Patagonia, and how the limited knowledge available about growth and yield was one of the main factors preventing potential investors from planting, and managers from making sound decisions. The main objective of this research was to ameliorate these problems by performing yield studies for the variable-density unthinned plantations in Neuquén. The first goal of this chapter is to summarize the main findings to illustrate how the research goals were accomplished.

The second objective of the chapter is to describe the immediate application of the different models, as well as their scope of inference and potential applications to other areas in Patagonia. The third objective is to state the main subjects I believe further research efforts should be devoted to, based on the objective of the plantations and these preliminary findings. Finally the general conclusions for the whole thesis are presented.

DATA

The data consisted of measurements collected from standing trees in 127 permanent sample plots established in Neuquén for the NPPSQY project, from June to September 1997. Each plot was located in a different stand to sample most of the geographical distribution of the ponderosa pine plantations in the province, as well as the range of factors that can be associated with tree growth. In addition stem analysis was performed on 156 sample trees. Two trees were felled adjacent to 78 of the plots, one with the diameter at breast height (D) of the tree of mean basal area and mean plot height (H), and the other one with the mean D and H of the 300 largest trees per hectare in the plot. The different chapters relied on subsets of these basic data.

MAIN FINDINGS

Height-Diameter Equations

Two linear and two nonlinear H-D equations commonly used in the western United States were examined. The four functions were fitted to each of the 127 sample plots. A nonlinear H-D function previously applied by Wykoff et al. (1982) was selected as the final model as it converged more efficiently than other nonlinear functions, and was more flexible than the linear equations: $H = 1.3 + e^{(\beta 0 + (\beta 1 / (D + 1)))} + \varepsilon$.

The results demonstrated that the selected H-D equation should be applied at the stand level to obtain correct predictions. Applying this function with the same coefficients to different stands can result in strong biases, suggesting than regional curves do not produce correct results when applied to estimate missing Hs on individual stands.

Neither nonlinear function produced satisfactory H predictions when fitted to the whole Neuquén data set with coefficients developed for ponderosa pine plantations in different areas of the western United States (Dolph et al. 1995, Larsen and Hann 1987, Moore et al. 1996, and Wang and Hann 1988). This suggested that regional H-D models for ponderosa pine forests should be refitted before being extrapolated to different regions.

The selected H-D equation will accurately predict tree H when fitted to stands with Ds between 2 and 35 cm. In stands where tree Ds are between 35 and 50 cm, H predictions should be still satisfactory as was observed for the sample plots with the largest Ds. Extrapolations of the function for individuals with Ds beyond 50 cm is not advisable.

Volume Equations

Two 3-variable equations (H, D, and crown ratio (CR)), twelve 2-variable equations (H and D), and seven 1-variable equations (D) were fitted in order to identify models capable of accurately predicting total inside bark volume (V). The data consisted of stem analysis measurements from the 156 felled trees.

On the basis of Furnival's index of fit (1961) and model behavior, a linear function containing D^2H and D as explanatory variables was selected as the final two-variable model. A one-variable linear model of the form $V = \beta_0 D + \beta_1 D^2 + \varepsilon$, was selected to predict stand volume when H data is not available. Crown ratio was not a significant variable when added to D and H. Both final models are most appropriate for trees with Ds between 10 and 30 cm, which is the D range of 96% of the sample trees used for the study. Volume predictions for trees with diameters between 30 and 40 cm may not be as accurate, and extrapolations beyond 40 cm are not recommended.

Several one- and two-variable volume functions developed for ponderosa pine in different areas of the western United States (Chapman et al. 1982, Cochran 1985, Oliver and Powers 1978, Wensel 1977) underestimated the volume of the trees in our data set. All functions developed in the western United States predicted similar volumes even though, they had been fitted by different authors, for different regions, and for different tree sizes. This reinforced the idea that tree shape differences between the two countries were not due to chance.

It was concluded that those shape differences illustrated that ponderosa pine trees of the same D and H would be more conical in California than in Neuquén. I speculated that these volume differences can be mainly attributed to: a) the detrimental effect of abundant competing vegetation on the growth of ponderosa pine trees in the western United States, b) the more rapid crown recession observed in California trees, and c) the faster D growth of Neuquén trees. In Neuquén, ponderosa pine trees typically compete exclusively with bunch grasses that have often been overgrazed. The faster D growth of Neuquén trees was confirmed in Chapter VI, when the yield of these stands was compared with the yield of plantations of the same species in northern California (Oliver and Powers 1978).

Growth Intercept Index

Developing a model to determine the site quality of the ponderosa pine plantations of Neuquén was probably the most challenging part of the thesis because I could not apply conventional techniques. Site index (SI), the most widely used indicator of site potential (Clutter et al. 1983, Smith et al. 1997), is usually not suitable for young plantations because small miscalculations of stand age can result in large site index errors, and total H can be highly influenced by the erratic early growth period. Thus, a growth intercept index (GII) was developed, because growth intercept (GI) tends to be a more accurate indicator of site quality than SI in young plantations (e.g. Alban 1979, Beck 1971, Ferre et al. 1958, Oliver 1972, Wakeley and Marrero 1958) such as the ponderosa pine stands in Neuquén.

The ability of the cumulative length of different numbers of internodes, starting at different points on the stem or growth intercepts, to predict stand crop height (CH) and top height (TH) from ages 12 to 20 was examined. Top height and CH were defined as the mean total height of the 100 and 300 trees per hectare with the largest D at breast height, respectively. Data were used from 104 of the sample plots, and eight to 14 plots were available for each age class.

A growth intercept index (GII) based on the length of five internodes beginning at or above breast height was chosen as the site quality indicator for the ponderosa pine plantations in Neuquén. The length of these five internodes was not only highly correlated to TH, but is also practical to measure in the field. An equation to predict TH at age 20 based on the GII was also developed.

It was estimated that the minimum age at which the GII can be determined on most commercial sites would vary between nine and 11. The selected GII was developed with data from unthinned stands that have not received any site preparation. Hence, the application of effective site preparation techniques or any other treatments that can significantly accelerate the height growth of young stands would require a revision of the index.

Needle Length as Site Quality Indicator

The ability of lateral branch needle length (LNL) and terminal leader needle length (TNL) to predict TH from ages 14 to 20 was evaluated. Terminal leader needle length was defined as the mean length of 10 fascicles clustered around the terminal bud on the leader, and LNL as the mean length of 10 fascicles located on the tip of two or three first order branches, located in the upper half of the crown. The data were collected from 56 of the plots, and four to nine plots were available for each age class.

Evaluating site quality from needle length assumes that needle length remains constant throughout the life of unmanaged stands, or that needle length differences among sites are much larger that those due to other causes such as yearly weather fluctuations.

Since LNL proved to be an accurate predictor of TH at age 20, it was concluded that LNL has the potential to be a reliable site quality indicator for the unthinned ponderosa pine stands in Neuquén. This was the most original finding of my research because I do not know of previous studies on the potential of needle length as site quality estimator. A LNL index to be used as a preliminary site quality indicator, as well as an equation to predict TH at 20 from LNL were developed.

Determining site quality by measuring needle length will be most practical for young plantations, where needle fascicles can be reached without the assistance of a ladder. Because the LNL index was based on data from 14 plots, and the location of the needles on the tree was roughly defined, this LNL index was considered preliminary. More thorough ways of collecting data have the potential to dramatically improve the prediction ability of needle length by accounting for some of the potential confounding variables, such as yearly weather fluctuations, needle length differences among trees and branches within the same stand, etc.

Variable-Density Yield Equations

Two nonlinear whole-stand yield equations based on data collected from the 127 sample plots were developed. The first equation predicts current yield based on age, growth intercept index, longitude, and basal area. The second equation predicts current yield based on the same factors except that basal area is replaced by number of trees per hectare. Both models provide accurate predictions of yield between ages 10 and 25.

A comparison demonstrated that the yield of ponderosa pine plantations in Neuquén was greater than for those growing in northern California, one of the most productive areas for this species in the United States. The dominant heights of 20-year-old stands growing on the best sites in both regions were 25% taller in Neuquén. Neuquén plantations attained larger volumes than California plantations of the same age, dominant height and trees per unit area. Neuquén stands were also observed to reach higher stockabilities. The highest basal areas and relative densities observed in Neuquén stands were at least 40% higher than the maximum values that have been observed in California plantations. Yet, mortality was not observed in any of the Neuquén sample plots.

The eight sample plots established in older plantations (26-41 years old) provided conservative yield information because they belonged to medium and low site classes. Thus, it was speculated that the real yields for that age range should be higher than those predicted by the models. This hypothesis was supported by the fact that Neuquén plantations can achieve much higher densities than those in California. As plantations grow older, more data should be collected to build a model that can accurately predict yields over age 25.

USEFULNESS AND SCOPE OF THE RESULTS

The H-D equation and the two volume functions will be useful tools for research and management, since they will allow for an accurate and more practical prediction of the H and volume of individual trees in the ponderosa pine stands of Neuquén.

The GII index and the yield equations will make it possible to estimate site quality and the current yield of the plantations. The application of these models does not require the measurement of Ds and Hs, which are typically the most time demanding tasks. These equations will be particularly useful if the province of Neuquén undertakes an inventory of all ponderosa pine plantations in the province, as is likely to happen in the near future. The preliminary NLI will be most practical to determine the site quality of young plantations because only the length of some groups of fascicles needs to be measured.

The yield equation based on basal area will predict the current volume of unthinned plantations very accurately. The yield equation based on the number of trees per hectare will predict the volume of unthinned plantations at any age within the inference range of the study (10-25 years). This is possible because mortality does not occur within the sampled range of relative densities. Knowing the potential productivity of the stands will enable foresters to take more meaningful management decisions.

All the models developed are applicable to any of the ponderosa pine stands in Neuquén, since the data used to build them were collected from plantations that covered most of the geographical distribution of the species. All models also included the whole range of most of the environmental factors that can affect tree growth. Since functions should be applied to plantations within the same age and number of trees per hectare ranges for which they were developed, these models should be revised as plantations grow older and lower densities become more common.

Most of the planted area with ponderosa pine in Patagonia is located in Neuquén province, mainly because its government started an aggressive afforestation program about 20 years ago. However, the provinces of Río Negro and Chubut together have about the same area of land suitable for commercial afforestation with this species, and they are committed to promote afforestation with fast-growing exotic species as well. The yield equations developed for the ponderosa pine stands in Neuquén can provide a preliminary basis to estimate the productivity of the plantations established in Río Negro and Chubut, but models should be adjusted for this more southern range.

FURTHER RESEARCH

The yield equations will be a useful tool for managers and investors. However, stand averages are insufficient for making certain decisions, such as time of earliest thinning. This would require information on the diameter distribution of the stands, which would also allow estimation of the timber value of the plantations. Revisions of the yield tables should include this kind of information.

Since the main objective of the ponderosa pine plantations in Neuquén is to produce high quality timber, yield equations for thinned stands should be developed as soon as this kind of information is available. In the meantime, it is advisable to establish thinning trials along the whole geographical and environmental range of the planted area.

Since ponderosa pine is exotic to Patagonia, plantations are established on lands were trees of this species are not present. Thus a site quality classification system based on environmental factors would be most useful. A site classification system based on the environmental data collected from the 127 permanent plots established for this thesis will be soon attempted.

The potential shown by needle length as a site quality indicator should be further tested. This method could not only make it possible to determine site quality at very early ages, but also dramatically expedite site quality determination in the field.

The reason that Neuquén ponderosa pine trees seem to be able to carry more foliage and reach higher stockabilities than those growing in the western United States is not clear yet. The lack of natural enemies such as insects and diseases, the presence of deep soils with volcanic ash, and the limited amount of competing vegetation are some of the factors that may be speed up the growth of Neuquén trees. Determining the importance of these factors and others will require future research.

CONCLUSION

The overall conclusion of this thesis is that the volume yield of ponderosa pine plantations in Neuquén is relatively high. The productivity of these stands is noticeably greater than that of ponderosa pine plantations growing on highly productive areas in the western United States. This suggests that ponderosa pine could be to the Patagonian Andes region what Monterey pine (*pinus radiata* D. Don) is to some other countries located in the southern hemisphere, such as New Zealand and Chile.

Several challenges need to be faced before the highly productive plantations can be expected to improve the socioeconomic development of Neuquén province. Defining optimum rotations and management procedures through financial analyses, defining wood products and their marketing, and establishing efficient fire prevention and control systems are just some of the tasks that should be undertaken.

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