

STATISTICAL AND SIMULATION MODELS FOR NATURAL MIXED FORESTS IN  
CHILE AND MEXICO

By

SEBASTIAN PALMAS PEREZ

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL  
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT  
OF THE REQUIREMENTS FOR THE DEGREE OF  
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2017

© 2017 Sebastian Palmas Perez

To Ceci, Oscar and Santiago  
To Cristina

## ACKNOWLEDGMENTS

I am deeply grateful to my advisor, Salvador Gezan for being a great mentor, colleague and for all the time he dedicated to this project. I am very thankful to Wendell Cropper, who accepted being my advisor and for all his insightful feedback. I am indebted to Karen Kainer for giving me the opportunity to come to UF and for her continuous encouragement. I also thank my committee members, Denis Valle and Jeremy Lichstein for their input, suggestions and patience.

This dissertation was made possible thanks to two incredible colleagues and friends: Antonio Sierra Huelsz and Paulo Moreno. Antonio has shared with me his extensive experience, knowledge and passion for the Mexican forests since 2011. Antonio supported me during fieldwork, courses, conferences and kayak trips. Paulo shared his brilliance and knowledge on the two *Nothofagus* chapters and, not only he opened his home to me, he supported me during difficult times in Gainesville. Their constant support and warm friendship have made this dissertation partly theirs.

Research in Quintana Roo was supported by a The Nature Conservancy grant (P116876 GLT). I am deeply grateful to Jack Putz, Bronson Griscom and Peter Ellis from TNC who have been an invaluable influence in my work in Quintana Roo.

The Tropical Conservation and Development program at the University of Florida supported travel and research funding by a Field Research Grant. The TCD program also served as a second department (and home) these six years. It was because of TCD students, faculty and staff that I made sense of graduate school, UF and Gainesville. I am also very grateful to the University of Florida and the School of Forest Resources and Conservation for the generous financial support through the Graduate School.

I am lucky to have found these research partners across the world: Francisco Escobedo at the Universidad del Rosario, Colombia. Alicia Ortega, who provided data and feedback for the project in Chile. The research was also supported by the NGOs U'yoolche and the *Organización de Ejidos Productores Forestales de la Zona Maya* in Felipe Carrillo Puerto, Quintana Roo.

This dissertation, related papers and the author's happiness, could not have happened without the friendship of many individuals in Gainesville: Sami Rifai, Todd Bertwell, Antonio Sierra, Hermes Gerardo, Natalie Cooper, Mandy Monroe, Constanza Ríos, Paulo Moreno, Milton Diaz, Claudia Navarro, Mauricio Núñez, Cristina Núñez, Michael Bauman, Farah Carrasco, Johanna Espin, et al.

I am lucky enough to have such great friends that their good vibes have been felt from 2000 km away. These are Madsa' Juárez, Guillermo Monterrubio (a.k.a. El Tío), Israel Pliego (a.k.a. El Isris), Pablo Aceves (a.k.a. El Mitades), Talib Oliver (a.k.a. El Talibi), Kaheri Illescas (a.k.a. El K), and Silvestre Zepeda (a.k.a. El Gonzo).

The love, patience and silliness from Cristina Ramos has been my main support since 2015. She makes me enjoy the present and makes me excited about the future. She pushes me to achieve my goals and makes me a better person. This is her dissertation too.

And last, but not least, I want to thank my family: Ceci, Oscar and Santiago for their always loving encouragement and support.

## TABLE OF CONTENTS

	<u>page</u>
ACKNOWLEDGMENTS.....	4
LIST OF TABLES.....	8
ABSTRACT .....	10
CHAPTER	
1 INTRODUCTION AND JUSTIFICATION .....	12
2 STAND BASAL AREA AND MORTALITY MODELS FOR MIXED NOTHOFAGUS FORESTS IN SOUTHERN CHILE.....	15
Introduction .....	15
Methods .....	18
Data Description.....	18
Model Description.....	20
Basal area.....	20
Proportion of number of Nothofagus trees .....	21
Mortality .....	21
Model Evaluation .....	22
Results.....	24
Basal Area.....	24
Proportion of Nothofagus Trees .....	26
Mortality.....	26
Discussion .....	27
Conclusion .....	30
3 VALIDATION AND COMPATIBILITY OF INDIVIDUAL- AND STAND-LEVEL GROWTH AND YIELD MODELS FOR NOTHOFAGUS FORESTS .....	38
Introduction .....	38
Methods .....	40
Available Data .....	40
Growth and Yield Models .....	41
Compatibility Methods and Evaluation .....	43
Results.....	45
Number of Trees Goodness-of-Fit Statistics.....	46
Basal Area Goodness-of-Fit .....	46
Diameter Distributions .....	47
Volume Goodness-of-Fit.....	47
Discussion .....	48
Conclusion .....	50

4	TIMBER AND CARBON SCENARIOS FOR THE MAYA FOREST OF MEXICO: AN INDIVIDUAL-BASED MODEL SIMULATION .....	56
	Introduction .....	56
	Data Sources .....	58
	Model Description .....	58
	Age Increment and Growth.....	59
	Natural and Hurricane Mortality.....	59
	Natural Recruitment .....	60
	Logging Scenarios and Minimum Cutting Diameters.....	60
	Felling Mortality and Cable Yarding.....	60
	Gap Enrichment .....	61
	Timber Volumes and Above-Ground Biomass .....	61
	Definition of Scenarios .....	62
	Results and Discussion.....	62
	Number of Extracted Trees and Volume .....	62
	Changes in Timber Basal Area and Aboveground Biomass.....	63
	Hurricane Effects.....	63
	Model Limitations .....	64
	Conclusion .....	64
5	CONCLUSIONS AND SUMMARY .....	72
	APPENDIX: ANALYSIS OF MEAN ANNUAL INCREMENTS AND RECRUITMENT DATA FOR SPECIES IN QUINTANA ROO, MEXICO .....	76
	LIST OF REFERENCES .....	79
	BIOGRAPHICAL SKETCH.....	91

## LIST OF TABLES

<u>Table</u>	<u>page</u>
2-1 Mean (standard error) and range of stand parameters between plot networks ..	31
2-2 Distribution of dominant species for the Temporal Plots 1, Temporal Plots 2 and Management Plots networks .....	32
2-3 Goodness-of-fit measures for models for basal area of <i>Nothofagus</i> , basal area of companion species, total basal area, proportion of number of <i>Nothofagus</i> trees .....	32
2-4 Parameter estimates, standard errors and Variance Inflation Factors for models of basal area of <i>Nothofagus</i> , basal area of companion species and proportion of number of <i>Nothofagus</i> trees .....	33
3-1 Mean (standard error) and range of stand parameters in the remeasured plots from the permanent network based on 33 plots .....	51
3-2 Estimated parameters for basal area of <i>Nothofagus</i> , total number of trees, AIDBH equations .....	52
3-3 Definition of scenarios considered in this study .....	53
3-4 Goodness-of-fit measures for each scenario for number of trees per hectare of <i>Nothofagus</i> , basal area of <i>Nothofagus</i> , P85/P15 and stand volume .....	53
4-1 Selected literature for the forests of Quintana Roo and the Yucatan Peninsula.....	66
4-2 Species and common names considered in the simulation .....	67
4-3 Hurricane categories annual occurrence probability and associated percentage of mortality by tree DBH.....	67
4-4 Characteristics of the scenarios simulated in this study. All scenarios ran for 40 years using a 25-year rotation cycle with directional felling and for 100 iterations .....	67
4-5 Basal area and aboveground biomass mean differences from the BAU scenario after 10, 25 and 40 years of simulation .....	68
A-1 Summary of the mean diameter growth (standard error) and range of by species from the TNC diametric bands.....	77
A-2 Average number of new recruits by hectare for species depending on percentage of stand canopy cover or timber basal area.....	78

## LIST OF FIGURES

<u>Figure</u>		<u>page</u>
2-1	Observed vs predicted values for basal area of <i>Nothofagus</i> , basal area of companion species, total basal area and number of trees per hectare estimated from the Temporal Plots networks .....	34
2-2	Observed vs predicted values for basal area of <i>Nothofagus</i> , basal area of companion species, total basal area, and number of trees per hectare estimated from the Management Plots network.....	35
2-3	Relative residuals for different simulation years in projections using the Management Plot data as validation.....	36
2-4	Quadratic diameter vs number of trees per hectare trajectories of measured stands of the Management Plot network .....	37
2-5	Model projections of 60 years.....	37
3-1	Relative residuals for predictions.....	54
3-2	Relative residuals against simulation years for predictions .....	55
4-1	Map of the south and central municipalities of Quintana Roo.....	69
4-2	Dragging mortality and cable yarding .....	70
4-3	Harvested trees, harvested volume, annual change in timber basal area, and annual change aboveground timber biomass trajectories for the five considered scenarios.....	71

Abstract of Dissertation Presented to the Graduate School  
of the University of Florida in Partial Fulfillment of the  
Requirements for the Degree of Doctor of Philosophy

STATISTICAL AND SIMULATION MODELS FOR NATURAL MIXED FORESTS IN  
CHILE AND MEXICO

By

Sebastian Palmas Perez

December 2017

Chair: Salvador A. Gezan

Major: Forest Resources and Conservation

Forest professionals need reliable information on stand dynamics to improve management decisions in their forests. One of the most important tools for this purpose are forest growth and yield models (G&Y). G&Y models have a history of over 250 years, but models for mixed forest stands were only first developed during the 20th century. This is because mixed forests have a large array of possible stand dynamics, species behaviors, interactions and productivity levels. This dissertation builds different G&Y models for two interesting mixed forests in Latin-America: the *Nothofagus* second growth forests of southern Chile and the tropical forests of Quintana Roo, Mexico. Chapter 2 fitted: a stand basal area model specified by the cohorts of *Nothofagus* and companion species, a model for changes over time in the proportion of *Nothofagus* trees in a stand, and a mortality model that considers the concept of self-thinning. To our knowledge these are the first broadly applicable models for the *Nothofagus* forest in southern Chile with dynamics of both companion species and *Nothofagus* cohorts. The models reported in this study constitute simple and valuable tools to support management decision for this resource in Chile.

Chapter 3 evaluated different compatibility methods that integrate available individual- and stand-level models. A Proportional Growth compatibilization significantly improved prediction of stand attributes without compromising predictions of individual parameters such as volume. It was also found that the length of the simulation considerably affects the fitness of the predictions

Chapter 4 provides estimates on the potential effects of silvicultural activities by simulating different scenarios within a forested area in Quintana Roo, Mexico. The simulation is an individual-level model that compiles published models on forest growth, natural and hurricane-induced mortality, recruitment and silviculture activities. The simulation shows that the recovery rates of basal area after the first 25 years are higher for those scenarios with improved management techniques such as gap enrichment and cable yarding. Simulations show that the currently applied 25-year cycle is not enough for a complete basal area recovery after two cycles.

## CHAPTER 1 INTRODUCTION AND JUSTIFICATION

Natural forests are currently being affected by pressures such as climate change, agricultural expansion, invasive species, and logging (Foley et al. 2005). In order to preserve value and promote sustainability of the natural forests, tools such as growth and yield (G&Y) models are needed to provide information on forest dynamics. A G&Y model is a representation of the natural dynamics of a forest, and includes growth, mortality, recruitment, and other changes in stand structure (Vanclay 1994). These models can be used in combination with forest inventories to determine timber productivity and examine the potential impacts of management and harvesting regimes on the commercial value and ensure sustainability of these forests. For example, a researcher can estimate an optimal age of harvest to maximize profits without risking future productivity using predictions from G&Y models (Lahvonen et al. 2010).

G&Y models have a history of over 250 years (Skovsgaard and Vanclay 2008), particularly for commercial plantations, but models for mixed stands were first developed during the 20th century (Porte and Bartelink 2002). This is because mixed forests are highly complex presenting a large array of possible stand dynamics, species behaviors, interactions and productivity levels (Filotas et al. 2014). Another reason is that plantations historically have had a greater investment in research and record of publications (Nichols et al. 2006). Furthermore, Blanco et al. (2015) reported that G&Y models for mixed forests are also limited geographically with most publications coming from North America and Europe. *Nothofagus* second growth forests of southern Chile and the tropical Maya forests of Quintana Roo in Mexico are two contrasting examples on this topic. While not as studied as pine plantations in Chile (Toro and Gessel 1999),

*Nothofagus* forests in central Chile have been monitored since 1980 with some of the first growth models published during that decade. In contrast, some of the first forest inventories and growth models published for the Maya forest just started in the 1990's.

This dissertation serves as a guidebook for researchers trying to build G&Y models for a managed mixed forest. Each chapter deals with a critical step required when building such models and are ordered considering increasing complexity. Chapter 2 deals with one of the first steps for this objective: building statistical models to describe forest dynamics. Chapter 3 validates and adjusts previously developed models to improve predictions of forest dynamics. In Chapter 4, the dissertation puts together many different models of forest dynamics to predict potential consequences of management activities.

The dissertation deals with two different mixed forest in Latin America: the *Nothofagus* forests in central Chile and the Maya forests in Quintana Roo, Mexico. This dissertation does not aim to compare the two research sites. They are not comparable because of their very different characteristics, such as different ecosystems, management strategies and sources of pressure. In addition, central Chile and the Maya forest have different trends in forest cover: Chile has now a net forest cover growth, while the Maya forest cover continues to be negative (Hansen et al. 2013; Heilmayr et al. 2016). The selection of these two sites allows this dissertation to explore different approaches on mixed forests with an array of levels of experience, data availability and history in research about G&Y models. A forest professional working in a forest without much background research can be gain more from the lessons in Chapter

2, while one in a forest with a stronger background of research can gain more from Chapters 3 and 4.

In summary, the main objective of this dissertation is to propose, fit, and validate different G&Y model approaches for *Nothofagus* forests in Chile and tropical forests of Quintana Roo in Mexico. Chapter 2 builds statistical models for: stand parameters such as stand basal area specified by the cohorts of *Nothofagus* and companion species, a model for changes over time in the proportion of *Nothofagus* trees, and a mortality model that considers the concept of self-thinning. Chapter 3 evaluates and adjusts existing models using independent data and two compatibility methods to link individual- and stand- level G&Y models. Finally, Chapter 4 constructs a complete simulation model to estimate potential effects of different management scenarios within a forested area in Quintana Roo, Mexico.

## CHAPTER 2 STAND BASAL AREA AND MORTALITY MODELS FOR MIXED *NOTHOFAGUS* FORESTS IN SOUTHERN CHILE

### **Introduction**

Forest professionals need reliable information on stand dynamics and development to improve management decisions in their forests. One of the most important tools for this purpose are forest growth and yield models (G&Y). A G&Y model is a representation of the natural dynamics of a forest, and includes growth, mortality, and other changes in stand structure (Vanclay 1994). These models can be used in combination with forest inventories to determine timber productivity and examine the potential impacts of alternative management and harvesting regimes on the value and sustainability of the forest.

One of the first steps to develop a G&Y model for mixed forests is to choose a modelling strategy (Liu and Ashton 1995; Peng 2000; Porte and Bartelink 2002; Vanclay 1994). G&Y models can be classified into: stand (whole) or individual (tree) level models. Stand-level models are those in which the modeling units are stand aggregated parameters such as, basal area, stocking, and site productivity. Individual-level models obtain aggregate stand characteristics by keeping track, and describing, each tree as a unique entity in the stand (Liu and Ashton 1995). Proposed cohort models are in-between stand- and tree-level models (Reed 1980). In cohort-level models, trees of similar species are grouped into classes of a shared attribute (e.g. diameter size, growth rates or age). Individual-level models have the disadvantage that they use data for parameterization beyond that required for stand-level models, a resource that is not always available. In contrast, stand-level models have the advantage of being more robust for long-term projections than individual models (Porte and Bartelink 2002). The

main advantage of a cohort-level model is that it gives further details than a stand-level model without the amount of data that an individual-level model requires.

South American beeches Rauli (*Nothofagus alpina* (Poepp. & Endl.) Oerst.), Roble (*N. obliqua* (Mirb.) Oerst.) and Coigüe (*N. dombeyi* (Mirb.) Oerst.) are native emergent trees present in a forest type known locally as RORACO (for the first letters of the *Nothofagus* species). This forest type occurs in the region between Concepcion and Puerto Montt cities in both the Chilean Andes and the coastal mountain range (Veblen et al. 1996) with some fragments in the Neuquen Province, Argentina (Sabatier et al. 2011). At the present, the RORACO forest type covers 1.96 million hectares, around 10% of the native forested area of Chile (CONAF 2011), and it represents a little over 45% of the sawtimber volume from native species for the country (INFOR 2016). The RORACO forest type is considered a second growth forest succession stage that colonizes areas after a disturbance such as tree-fall gaps, volcanic activities and earthquakes (Donoso et al. 1993; Echeverria and Lara 2004; Pollmann 2003; Rebertus and Veblen 1993; Veblen et al. 1980; Veblen and Ashton 1978). The relative abundance of the three *Nothofagus* species varies considerably in the RORACO forests. *Nothofagus obliqua* prefers lower elevations and drier sites, while *N. dombeyi* prefers higher elevations and wetter sites, and *N. alpina* is more prevalent on intermediate sites (Veblen et al. 1996).

The *Nothofagus* species, and primarily *N. alpina*, are extensively studied in Chile with reports available on: height and diameter growth (Salas and Garcia 2006), taper and volume equations (Gezan et al. 2009), delimitation of growth zones (Donoso et al. 1993; Gezan and Moreno 1999), silviculture (Donoso et al. 2009), site index models

(Trincado et al. 2002), and regeneration (Weinberger and Ramirez 2001), ecology (Donoso et al. 2013), among others. However, at present, there is no fully functional G&Y model system, except for some preliminary efforts reported by Ortega and Gezan (1998).

The main components of any G&Y model are tree growth, recruitment and mortality. Stand-level growth models are usually built by fitting an equation that predicts total basal area, usually depending on age, productivity and stocking. For mixed forests, this component is often separated into cohorts defined by group of species. RORACO forests can be separated into two main cohorts: the first dominated by the emergent shade-intolerant *Nothofagus* species and the second comprised by companion species, which are primarily shade tolerant. Some of the most prevalent companion species found in these forests are *Gevuina avellana* Molina, *Persea lingue* (Ruiz & Pav.) Nees, *Lomatia hirsuta* (Lam.) Diels, *Eucryphia cordifolia* Cav., *Drymis winteri* J.R. Forst. & G. Forst. and *Laurelia philippiana* (Looser) Schodde. It is considered that these two cohorts present different, and probably additive, growth dynamics; implying that stand basal area growth of *Nothofagus* is likely to be independent of the companion species (Donoso and Lusk 2007; Lusk and Ortega 2003).

Stand mortality models usually depend on productivity, competition, and differences among species for their tolerance to crowdedness. Here, knowledge of the maximum stand density for a given forest type is critical, as a stand that is close to its maximum density will experience higher levels of mortality, a process that is known as self-thinning. Reineke (1933) proposed a theoretical self-thinning rule that has been used extensively for many pure stands. In *Nothofagus*, several authors have used this

rule to define stand density diagrams (Chauchard et al. 2001; Gezan et al. 2007) for these mixed forests.

Natural forests are currently being affected by global pressures, such as climate change, agricultural expansion, invasive species, and logging (Foley et al. 2005), as is the case with the RORACO forest type (Zamorano-Elgueta et al. 2015). There has been a trend in reduction of native forests in south-central Chile in the last three decades mainly because of the its conversion to shrublands and exotic tree plantations (Heilmayr et al. 2016, Miranda et al. 2015); however, Chile is experiencing a forest transition trend towards a zero-net deforestation. In addition, insect defoliator outbreaks present a threat to *Nothofagus* forests. It is estimated that damage has increased and will intensify with a warming climate (Paritsis and Veblen 2011). Because of these and other threats, it is essential to preserve value and promote sustainability of this native ecosystem. This management goal will best be addressed with tools including G&Y models.

The main objective of this study is to build models for a stand-level G&Y model to improve predictions of stand dynamics for natural mixed secondary forests of the RORACO forest type in Chile. The specific objectives include to fit and validate stand-level models for: 1) basal area specified by the cohorts of *Nothofagus* and companion species; 2) changes over time in the proportion of *Nothofagus* trees in a stand; and 3) mortality that considers the concept of self-thinning.

## **Methods**

### **Data Description**

The data for this study originated from three independent sets: two temporal plot (TP1, TP2), and a management plot (MP) networks. All plots were established in second growth RORACO forests in Chile, and they are located between the 36° and

42°S latitude. The TP1 and TP2 data were established by the Universidad Austral de Chile between 1999 and 2000 (Ortega and Gezan 1998). The TP1 data had a total of 50 plots with an area of 250 m<sup>2</sup> formed by a conglomerate of two subplots. For the TP2 data there were a total of 120 rectangular plots with areas ranging between 250 and 500 m<sup>2</sup>. Both, the TP1 and TP2 networks, were sampled according to a stratification of this forest type based on the national forest inventory (CONAF et al. 1999). The MP network consisted in three sites and measured between 1980 and 1999. Each of these sites were remeasured up to four times. The original objective of the MP plots was to evaluate different thinning regimes on RORACO stands (Puente et al. 1980). Because the objective in this paper is to fit models for natural forests, the models are fitted with only 48 plots without treatment (i.e., controls), low thinning (less than 5% of removed basal area) and with girdling treatments. Because of the remeasurements in some of the 48 plots, the total of plot-years is 183. Summary statistics of these three datasets are presented in Table 2-1.

For all plots, trees above 5 cm of diameter at breast height (DBH, cm) were inventoried for DBH and total height (H, m). The *Nothofagus* species were identified and the rest was recorded as companion species. For all plots, the following stand-level variables were calculated: dominant age at breast height (AGE, years), dominant height (HD, m), site index (SI, m), total basal area (BA, m<sup>2</sup> ha<sup>-1</sup>), and total density of trees (NHA, trees ha<sup>-1</sup>). Quadratic diameter (DQ, cm) was measured and defined as the average tree diameter in the stand. Dominant age at breast height (AGE) is defined as the average age of 100 trees per hectare with the largest DBH. Dominant height (HD) is the average total height of the thickest 100 trees per hectare. Site index (SI) is the stand

dominant height at 20 years. Also, for each of the cohorts, basal area for *Nothofagus* and companion species (BAN and BAC, respectively,  $\text{m}^2 \text{ha}^{-1}$ ), and number of trees of *Nothofagus* and companion species (NHAN and NHAC, respectively, trees  $\text{ha}^{-1}$ ) were calculated. Finally, the proportion of basal area and number of trees of *Nothofagus* (PBAN, PNHAN) and companion species (PBAC, PNHAC) were also obtained. All plots were assigned to a growth zone (ZONE) following to Gezan and Moreno (1999). For those plots without known SI, estimates were obtained using the model reported by Gezan and Ortega (2001). In order to only use stands that were dominated by *Nothofagus*, only those plots with PBAN > 0.6 were selected for this study. Additionally, the dominant species (DOM-SP) of a given plot was defined as the *Nothofagus* species that had more than 70% of BA. The TP1 and TP2 data are primarily of *N. dombeyi* but all dominant species are present; however, the MP data contains only plots dominated by *N. alpina* (Table 2-2).

## **Model Description**

### **Basal area**

To predict basal area for the two cohorts, BAN and BAC, this study fitted two independent models. Here, the TP1 and TP2 plots were used as training data, while MP plots were used as validation data. For BAN and BAC, a linear model using a log transformation was fitted with different combinations of predictors, including AGE, HD, SI, NHA, NHAN, NHAC, PBAN, and PBAC. These predictors were considered in their original units and also transformed using the functions of natural logarithm, inverse, square of the inverse and square root of the inverse. ZONE for each stand was evaluated separately with no interactions with other predictors. To assist with model selection, a backward selection procedure was implemented based on a significance

level set to  $\alpha = 0.05$ , and models with variance inflation factors (VIF, Rawlins et al. 1998) larger than four in any of their predictors were discarded. The predictions of the final fitted models for each of these components were added to estimate total basal area; hence  $BA = BAN + BAC$ .

Later, projection equations were derived from the prediction models fitted above by differentiating with respect to age following the methodology described by Clutter (1963) and Moser and Hall (1969). These projections, allow to estimate the future values of the response over time given a starting condition. These models were evaluated using the MP permanent plot data, based on a total of 217 measurement pairs.

### **Proportion of number of *Nothofagus* trees**

To estimate the proportion of trees corresponding to *Nothofagus* (PNHAN), a linear model was fitted with the logit transformation of PNHAN using the TP1 and TP2 plots as training data (150 plots), and the MP plots as validation data (183 plots). The same predictors used in the BA model were tested and a final model was selected using a backward selection procedure as indicated above.

### **Mortality**

For this component, the self-thinning concept was used to formulate a simple mortality model that is defined by a single parameter. This study fitted a model for an annual projection of number of trees per hectare (NHA) using as training the mortality measurement pairs from the MP data. Note that TP1 and TP2 were not considered as their plots contain a single measurement. Based on the expression from Reineke (1933)

$$\ln(\text{NHA}) = \alpha + \beta DQ \quad (2-1)$$

where  $\ln$  is the natural logarithm and  $\alpha$  and  $\beta$  are the constant parameters, the proposed mortality model uses the current  $NHA_0$  value to estimate the current maximum quadratic diameter ( $DQ_{0max}$ ) with

$$DQ_{0max} = \exp\left(\frac{\ln(NHA_0) - \alpha}{\beta}\right) \quad (2-2)$$

$DQ_{0max}$  can be interpreted as the maximum DQ that is allowed at the tree density  $NHA_0$ . The parameters of above for  $\alpha$  are 11.6167, 11.3770, and 11.7639 for stands dominated by *N. alpina*, *N. obliqua* and *N. dombeyi*, respectively; and  $\beta = -1.4112$ , for all dominant species (Gezan et al. 2007). It is expected that as the current  $DQ_0$  approaches  $DQ_{0max}$  there is an increase in mortality. Hence, a model can include the ratio between  $DQ_0$  and  $DQ_{0max}$  interacting with the current number of trees ( $NHA_0$ ). Hence, the projection model suggested by this study is:

$$\ln(NHA_1) = \ln(NHA_0) \left( 1 - (\theta \Delta t) \left( \frac{DQ_0}{DQ_{0max}} \right) \right) \quad (2-3)$$

where  $\theta$  is the parameter to estimate, and can be interpreted as a maximum mortality rate when the stand is at  $DQ_{max}$  and expressing  $NHA$  on a logarithmic scale.  $\Delta t$  is the years between measurements and  $\ln$  is the natural logarithm.

### Model Evaluation

Predictions and projections for all four models described above were evaluated by calculating the following goodness-of-fit measures:  $R^2_{emp}$ , RMSE%, Bias% and Akaike Information Criteria (AIC, Akaike 1998) that are detailed below. These measures were obtained for the training and validation datasets providing two independent assessments of the models.

$$R^2_{emp} = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y}_i)^2} \quad (2-4)$$

$$\text{RMSE}\% = 100 \times \sqrt{\sum_{i=1}^n (y_i - \hat{y}_i)^2} / \bar{y} \quad (2-5)$$

$$\text{Bias}\% = 100 \times \sum_{i=1}^n (y_i - \hat{y}_i)^2 / \bar{y} \quad (2-6)$$

$$\text{AIC} = -2 \ln(L) + 2p \quad (2-7)$$

where  $y_i$  and  $\hat{y}_i$  are the  $i$ th observed and predicted (or projected) value, respectively;  $\bar{y}$  is the mean response value, and  $n$  is the number of observations.  $L$  is the likelihood of the fitted model and  $p$  is the total number of parameters in the model. All goodness-of-fit measures were evaluated using the back-transformed response variables to its original units. Because the models for BAN and BAC use the natural logarithm transformation, their back-transformed estimates were adjusted using the correction proposed by Baskerville (1972), i.e.,  $\hat{y}_i^* = \hat{y}_i \exp(\sigma^2/2)$ , where  $\sigma^2$  is the mean square error. For graphical outputs, relative residuals were used, which were defined as the difference between observed and predicted values divided by the mean observed value.

Projections models were evaluated by using all 217 possible measurement pairs within the 48 remeasured plots in the MP data (e.g. a plot with three measurements has three possible pairs for projection: measurement 1 to 2, 1 to 3, and 2 to 3). Time between measurement pairs ranged between 2 and 12 years. Normality and heterogeneity of residuals were also checked without noting important departures from these assumptions.

All generalized linear and non-linear models were done in R 3.3.2 (R Core Team 2016). Ordinary least squares procedure was used to estimate the parameters.

## Results

### Basal Area

For the plots considered in this study, the average total BA for *Nothofagus* and companion species corresponded to 38.48 and 3.41 m<sup>2</sup> ha<sup>-1</sup>, respectively. BAN ranged from 12.66 to 89.57 m<sup>2</sup> ha<sup>-1</sup>, and BAC from 0.00 to 26.40 m<sup>2</sup> ha<sup>-1</sup>.

The final selected models for BA of *Nothofagus* and companion species are

$$\ln(\text{BAN}) = \hat{\beta}_0 + \hat{\beta}_1 \ln(\text{AGE}) + \hat{\beta}_2 \ln(\text{SI}) + \hat{\beta}_3 \ln(\text{NHA}) + \hat{\beta}_4 \ln(\text{PBAN}) \quad (2-8)$$

$$\ln(\text{BAC}) = \hat{\beta}_0 + \hat{\beta}_1 \ln(\text{AGE}) + \hat{\beta}_2 \ln(\text{PNHAN}) + \hat{\beta}_3 \ln(\text{PBAN}) \quad (2-9)$$

The logarithmic transformation of the predictors returned the best results and had the additional advantage that use in the projection model is straightforward (see below). In addition, all selected predictors showed low VIF values (<2), reflecting negligible levels of multicollinearity between them. In logarithmic terms, AGE and NHA had the highest correlation with a value of 0.45, followed by AGE and SI with a value of 0.33. In addition, PBAN and NHA had a correlation of 0.32, and the other predictors had correlations below 0.15.

The resulting fitted model for BAN had  $R^2_{\text{emp}} = 0.54$ , and the fitted model for BAC had a higher  $R^2_{\text{emp}}$  with a value of 0.85 (Table 2-3). The prediction of total basal area had an  $R^2_{\text{emp}} = 0.56$ . All models presented negligible bias values (<1%). Both BAN and BAC models had good goodness-of-fit measures with the MP validation data. The goodness-of-fit measures for this validation dataset, for the BAN, BAC and BA predictions, returned slightly higher Bias% values when compared to the training data, but these were all lower than 4% (Table 2-3).

According to the estimated coefficients (Table 2-4), AGE was positively associated with both BAN and BAC (with slope coefficients of 1.23 and 0.09, respectively). Hence, as the stand gets older basal area increases, with larger effect for the *Nothofagus* cohort. For BAN, the positive coefficients for SI (0.68) and NHA (0.52) indicate that better site quality and higher levels of stocking result in higher *Nothofagus* basal area. In the BAC model, PNHAN and PBAN have negative coefficients (-0.22 and -1.87, respectively) indicating that higher proportions of *Nothofagus* abundance affect the quantity of basal area of companion species.

Predicted BAN and BAC values corresponded well with observed values in both training and validation data (Figure 2-1 and Figure 2-2). However, this correspondence decreases with larger observed BAN and BAC values, and some under prediction is found for BAN values above 75 m<sup>2</sup> ha<sup>-1</sup>. Similar results were found for BA, as this mostly corresponds to *Nothofagus* basal area (Figure 2-1-C).

Both basal area equations were used to derive their compatible projection equations. These models project future values (BAN<sub>1</sub> and BAC<sub>1</sub>) based on the current stand conditions (BAN<sub>0</sub> and BAC<sub>0</sub>, respectively). These are:

$$BAN_1 = BAN_0 \left( \frac{AGE_1}{AGE_0} \right)^{\hat{\beta}_1} \left( \frac{NHA_1}{NHA_0} \right)^{\hat{\beta}_3} \left( \frac{PBAN_1}{PBAN_0} \right)^{\hat{\beta}_4} \quad (2-10)$$

$$BAC_1 = BAC_0 \left( \frac{AGE_1}{AGE_0} \right)^{\hat{\beta}_1} \left( \frac{PNHAN_1}{PNHAN_0} \right)^{\hat{\beta}_2} \left( \frac{PBAN_1}{PBAN_0} \right)^{\hat{\beta}_3} \quad (2-11)$$

For the evaluation of the projection equations using the validation dataset, all basal area models showed excellent goodness-of-fit measures (all with R<sup>2</sup><sub>emp</sub> > 0.94). The relative residuals obtained over time for BAN, BAC and BA projections (Figure 2-3-

A, B and C) are centered around zero for shorter projections (*i.e.*, little bias) while they tend to depart for increasing projection times (*i.e.*, underestimate).

### **Proportion of *Nothofagus* Trees**

For the plots considered in this study, the average proportion of *Nothofagus* trees corresponded to 82%, where the majority of the plots presented values greater than 72%.

The final selected model for PNHAN is:

$$\text{logit(PNHAN)} = \ln\left(\frac{\text{PNHAN}}{1-\text{PNHAN}}\right) = \hat{\beta}_0 + \hat{\beta}_1\text{PBAN} + \hat{\beta}_2\text{AGE} \quad (2-12)$$

For the training data, this model had reasonable goodness-of-fit measures with  $R^2_{\text{emp}} = 0.68$  and  $\text{Bias}\% = -1.50$ . Also, predicted PNHAN values tend to correspond with observed values, but large levels of uncertainty still exist (Figure 2-1 D). Also, for MP validation data, these measures were  $R^2_{\text{emp}} = 0.56$  and  $\text{Bias}\% = 3.46$ .

The estimated parameters of this model are shown in Table 2-1. The slope coefficient for PBAN (10.29) reflects the high association between this predictor and PNHAN (these predictors present a correlation of 0.89). For AGE, its coefficient (-0.01) indicates a reduction of PNHAN with increasing stand age, reflecting the pioneer behavior of *Nothofagus* and the gradual establishment of companion species over time. These selected predictors all show low VIF values (<1.02).

### **Mortality**

Mortality rates among the remeasured plots from the MP data had an annual average of 3.0% with a maximum of 14.2%, and their patterns were consistent over time for most plots represented as parallel lines (Figure 2-4-A). This results in expected life times between 7 and 33 years.

The fitted model, using MP as training data, had a good fit with  $R^2_{\text{emp}} = 0.79$ , RMSE% = 18.46 and Bias% = -2.80. The single parameter estimate corresponded to  $\theta = 0.003595746$  (SE = 0.000213), indicating that, for future projections, the estimated number of trees always will be smaller than the current condition. For this simple model, predicted mortality values had good correspondence with observed ones over the entire range of values (Figure 2-4-B).

Because errors can accumulate over time, the projections seem to differ increasingly from the observed NHA values with longer projection times. In this case, the model showed overestimated mortality at 6 years; however, the estimations were reasonable for projection times of 12 years (Figure 2-3-D).

### **Discussion**

The fitted independent models for basal area of *Nothofagus* and companion species seem appropriate to represent the dynamics of these forests. Choosing independent models is reasonable, considering that some studies that support the hypothesis that companion species are not affected by competition with the emergent *Nothofagus* cohort (Donoso and Lusk 2007). However, future studies should consider incorporating of additive effects of the species, allowing higher production of *Nothofagus* when other species are present (Danescu et al. 2016; Donoso and Soto 2016; Vallet and Prot 2011)

The fitted model for BAN presented here is robust and realistic as it accounts for stand age, productivity and stocking (using AGE, SI and NHA, respectively). AGE and SI are common predictors used to model *Nothofagus* growth (Esse et al. 2014; Lusk and Ortega 2003; Salas and Garcia 2006). In contrast, the fitted model did not use the factor ZONE as a predictor as reported in other studies (Chauchard and Sbrancia 2003;

Echeverria and Lara 2004; Esse et al. 2013; Gezan et al. 2009; Lusk and Ortega 2003). Differences among zones are possibly associated with the effect of the SI. Without a parameter for ZONE, the suggested models in this paper are appropriate to use in the geographical range of the RORACO forest type in southern Chile.

More data should allow to explore the effects of other environmental factors that might affect *Nothofagus* growth, such as light conditions, soil compactness and nitrogen availability (Donoso et al. 2015; Soto et al. 2015, 2017; Walter et al. 2016).

Evaluations of the BAN projections presented reasonable trajectories. For example, a simulated stand with an initial BAN of  $15 \text{ m}^2 \text{ ha}^{-1}$ , initial stand age of 15 years, SI of 10 m and PBAN of 1 is shown in Figure 2-5. Here, BAN patterns, for all densities, have an asymptotic behavior, with larger BAN growth rates for stands with fewer initial trees. In addition, for NHA projections, higher initial density resulted, as expected, in higher rates of mortality, following the patterns considered in the proposed mortality model.

For projections under 6 years, the BAN model returned relative residuals lower than 10% and were centered about zero. After 6 years, the relative residuals reached higher values with a tendency to underpredict basal area. The BAC model had residuals centered around zero with no notable deviations even at 12 years of projections. However, there were some projections with residuals over 30%, which are not of relevant concern because of the low proportion of basal area from the companion cohort in the sampled plots.

For the PNHAN model a reduction of this response as the stand gets older was observed; this can be explained by the pioneer behavior of the *Nothofagus* species that

are followed by gradual establishment of shade-tolerant companion species after colonization (Veblen et al. 1996). The predictions for PNHAN tended to have less uncertainty with higher observed PNHAN as observed in Figure 1-2D.

Most inventory plots had similar mortality trajectories, seen in almost parallel lines (Figure 2-4-A). Mortality projections reached relative residuals ranging from -30% to 30% (Figure 2-3-D). While this may be considered as large model uncertainty, the fact that residuals are generally centered around zero, even after 12 years of projection, suggests a good overall accuracy of the model. While this might not be realistic, it is important to note that this model assumes that stands dominated by the same species respond to the self-thinning rule evenly.

Unfortunately, the management plot (MP) network used to fit the mortality model is the only current source of remeasured plot data. For further evaluations, there is a need for additional permanent plot data to validate and further improve these models. Currently, there is not enough information to construct a stand mortality model that considers catastrophic environmental events, such as earthquakes or volcanic activity, that are key in the forest dynamics of RORACO stands (Veblen et al. 1996).

Establishing and remeasuring inventory plots in natural forests over a wide geographical range is extremely time-consuming and costly, resulting in too few high-quality sample plots for the development and testing of forest models (Wulder et al. 2008). This problem is also exacerbated by the fact that forest inventory sampling is biased towards forests that are considered to have commercial value with little regard to natural forests (Réjou-Méchain et al. 2011) with multiple ecosystem services.

The models reported in this study adequately represent the dynamics of basal area and mortality of *Nothofagus* forests in Chile based on the available data. These, when combined with a stand volume model, provide a complete system of equations to construct a growth and yield model for this resource to support management plans and decision-making.

### **Conclusion**

In this study, several stand-level models were built to improve predictability of stand dynamics for natural mixed secondary forests of the RORACO forest type in Chile. Stand age, site index, number of trees and the proportion of basal area of *Nothofagus* were important predictors to project basal area of *Nothofagus* and companion species. Dominant age, was a significant predictor for the proportion of *Nothofagus* trees model, that indicates that as the stand ages, there is a reduction on the presence of *Nothofagus*, most likely due to the pioneer behavior of this dominant cohort. Finally, stand mortality was successfully modelled by using the concept of self-thinning with a single parameter model.

To our knowledge these are the first broadly applicable models for the RORACO forest type with dynamics of both companion species and *Nothofagus* cohorts. The models reported in this study constitute simple and valuable tools to support management decision for this resource in Chile.

Table 2-1. Mean (standard error) and range of stand parameters between plot networks

	TP1 (n = 50)		TP2 (n = 120)		MP (n = 48, m = 183)	
	Mean (SE)	Range	Mean (SE)	Range	Mean (SE)	Range
AGE	39.76 (1.89)	14.21 – 67.9	39.58 (1.54)	12.71 – 86.81	41.08 (0.60)	25 – 51
HD	21.29 (0.84)	9.99 – 34.65	21.84 (0.66)	7.83 – 42.40	23.49 (0.46)	15.25 – 37
SI	10.40 (0.42)	3.61 – 17.13	11.09 (0.39)	1.81 – 23.01	10.62 (0.32)	6.15 – 17.24
BA	47.41 (2.53)	14.48 – 98.42	41.75 (1.46)	9.54 – 86.28	40.91 (0.59)	13.35 – 69.82
NHA	2,442.11 (149.67)	880 – 5,560	2,513.83 (122.79)	200 – 5,600	1,276.58 (37.66)	340 – 3,560
DQ	16.81 (0.77)	7.74 – 30.41	16.74 (0.75)	6.78 – 70.42	22.17 (0.40)	10.38 – 40.87
BAN	42.17 (2.34)	13.9 – 89.57	36.30 (1.31)	8.76 – 85.99	38.67 (0.57)	12.66 – 63.83
BAC	5.24 (0.85)	0.00 – 23.10	5.45 (0.56)	0.00 – 26.40	2.24 (0.17)	0.00 – 15.44
NHAN	1,825.96 (135.04)	280 – 5,560	1,784.17 (105.79)	200 – 5,040	1,126.72 (32.47)	160 – 2,880
NHAC	616.14 (88.12)	0 – 3,040	729.67 (69.21)	0 – 3,480	149.86 (11.81)	0 – 1180
PNHAN	0.75 (0.03)	0.23 – 1.00	0.72 (0.02)	0.18 – 1.00	0.89 (0.01)	0.47 – 1.00
PNHAC	0.25 (0.03)	0.00 – 0.77	0.28 (0.02)	0.00–0.82	0.11 (0.01)	0.00 – 0.53
PBAN	0.89 (0.02)	0.61 – 1.00	0.88 (0.01)	0.60 – 1.00	0.95 (0.01)	0.63 – 1.00
PBAC	0.11 (0.02)	0.00 – 0.39	0.12 (0.01)	0.00 – 0.40	0.05 (0.01)	0.00 – 0.37

Note. TP1: Temporal Plots 1, TP2: Temporal Plots 2 and MP: Management Plots. n is the number of plots and m is the number of measurements. m = n in TP1 and TP2. AGE: dominant age (years), HD: dominant height (m), SI: site index (m), BA: total basal area (m<sup>2</sup> ha<sup>-1</sup>), NHA: total number of trees (trees ha<sup>-1</sup>), DQ: mean quadratic diameter (cm), BAN: basal area of *Nothofagus* (m<sup>2</sup> ha<sup>-1</sup>), BAC: basal area of companion species (m<sup>2</sup> ha<sup>-1</sup>), NHAN: number of *Nothofagus* trees (trees ha<sup>-1</sup>), NHAC: number of trees of companion species (trees ha<sup>-1</sup>), PNHAN: proportion number of trees of *Nothofagus* (0-1), PNHAC: proportion number of trees of companion species (0-1), PBAN proportion of BA of *Nothofagus* (0-1), PBAC: proportion of BA of companion species (0-1).

Table 2-2. Distribution of dominant species (DOM-SP) for the Temporal Plots 1 (TP1), Temporal Plots 2 (TP2) and Management Plots (MP) networks

Network	<i>N.alpina</i>	<i>N.dombeyi</i>	<i>N.obliqua</i>	Mixed	<b>Total</b>
TP1	6	21	14	9	<b>50</b>
TP2	8	49	20	23	<b>120</b>
MP	41	0	0	7	<b>48</b>

Table 2-3. Goodness-of-fit measures for models for basal area of *Nothofagus* (BAN, Eq. 2-8 and 2-10), basal area of companion species (BAC, Eq. 2-9 and 2-11), total basal area (BA), proportion of number of *Nothofagus* trees (PNHAN, Eq. 2-12)

Model	Prediction		Projection
	Training	Validation	
<b>BAN</b>			
N	150	51	217
R <sup>2</sup> <sub>emp</sub>	0.54	0.51	0.80
RMSE%	27.31	13.63	9.04
Bias%	-0.29	2.25	-5.24
<b>BAC</b>			
n	150	183	217
R <sup>2</sup> <sub>emp</sub>	0.85	0.89	0.94
RMSE%	44.6	41.68	33.52
Bias%	0.86	-3.72	12.48
<b>BA</b>			
n	150	51	217
R <sup>2</sup> <sub>emp</sub>	0.56	0.5	0.84
RMSE%	26.29	13.36	7.83
Bias%	-0.16	1.69	-4.51
<b>PNHAN</b>			
n	150	183	-
R <sup>2</sup> <sub>emp</sub>	0.68	0.56	-
RMSE%	16.92	8.07	-
Bias%	-1.5	3.46	-

Note: The TP1 and TP2 networks were used as training data and the MP network as validation data. Validation data for the BAN and PNHAN models only includes stands with known AGE

Table 2-4. Parameter estimates, standard errors (SE) and Variance Inflation Factors (VIF) for models of basal area of *Nothofagus* (BAN, Eq. 2-8 and 2-10), basal area of companion species (BAC, Eq. 2-9 and 2-11) and proportion of number of *Nothofagus* trees (PNHAN, Eq. 2-12). All model parameters were found to be significant ( $p < 0.001$ )

<b>Model</b>	$\beta_0$	$\beta_1$	$\beta_2$	$\beta_3$	$\beta_4$
<b>BAN</b>					
Estimate	-6.16977	1.21163	0.65197	0.51841	1.24957
SE	0.71314	0.07496	0.06801	0.05290	0.17498
VIF	-	2.06	1.53	2.10	1.25
<b>BAC</b>					
Estimate	1.99503	0.09436	-0.21578	-1.87264	-
SE	0.08904	0.02513	0.04885	0.12278	-
VIF	-	1.23	3.62	3.27	-
<b>PNHAN</b>					
Estimate	-7.13684	10.29084	-0.01404	-	-
SE	0.55383	0.56703	0.00429	-	-
VIF	-	1.02	1.02	-	-

Note: The TP1 and TP2 networks were used for training

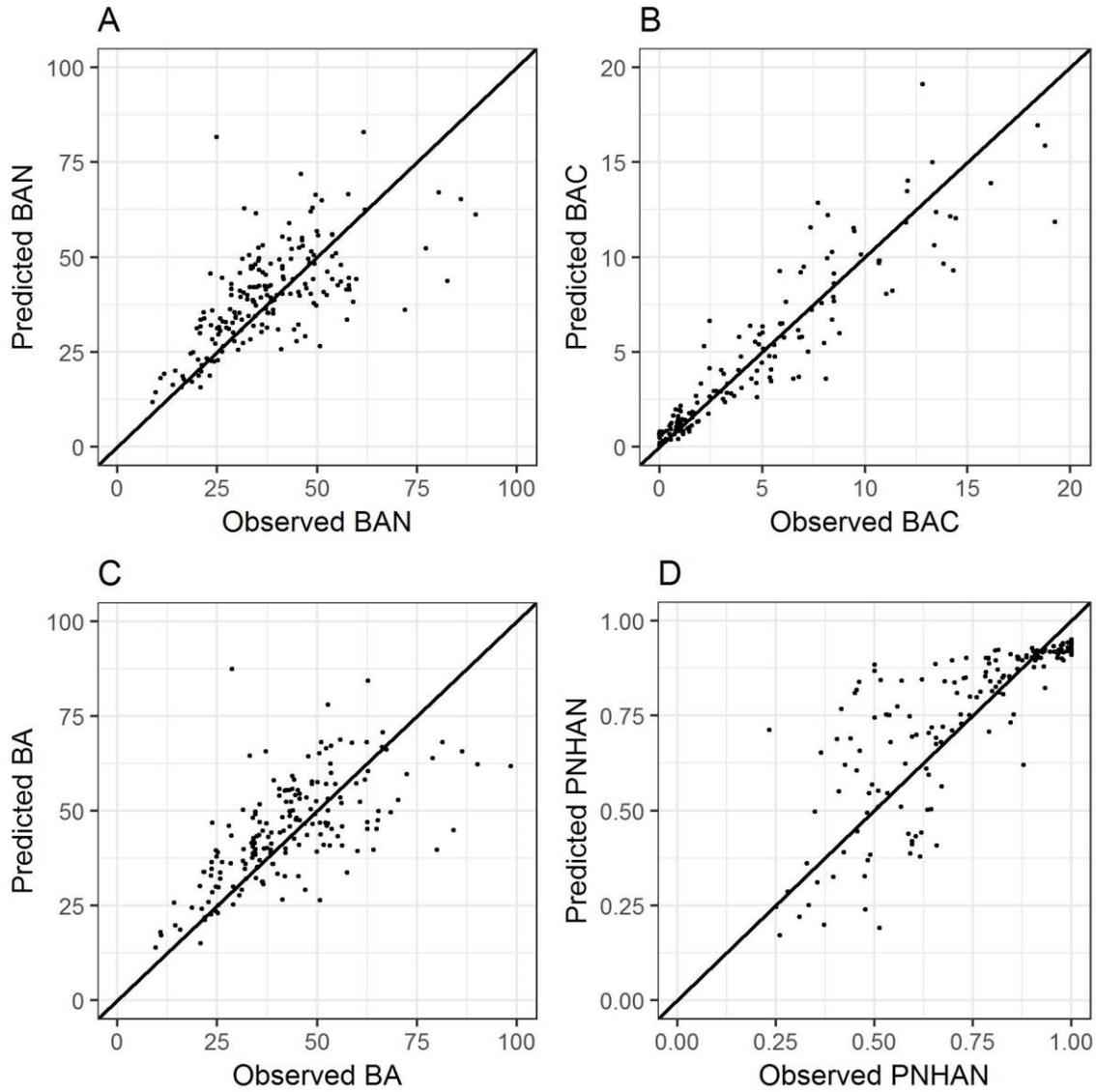


Figure 2-1. Observed vs predicted values for (A) basal area of *Nothofagus* (BAN, Eq. 2-8), (B) basal area of companion species (BAC, Eq. 2-9), (C) total basal area,  $BA = BAN + BAC$ , and (D) number of trees per hectare (NHA, Eq. 2-3). All panels are estimates from the Temporal Plots networks (TP1 and TP2)

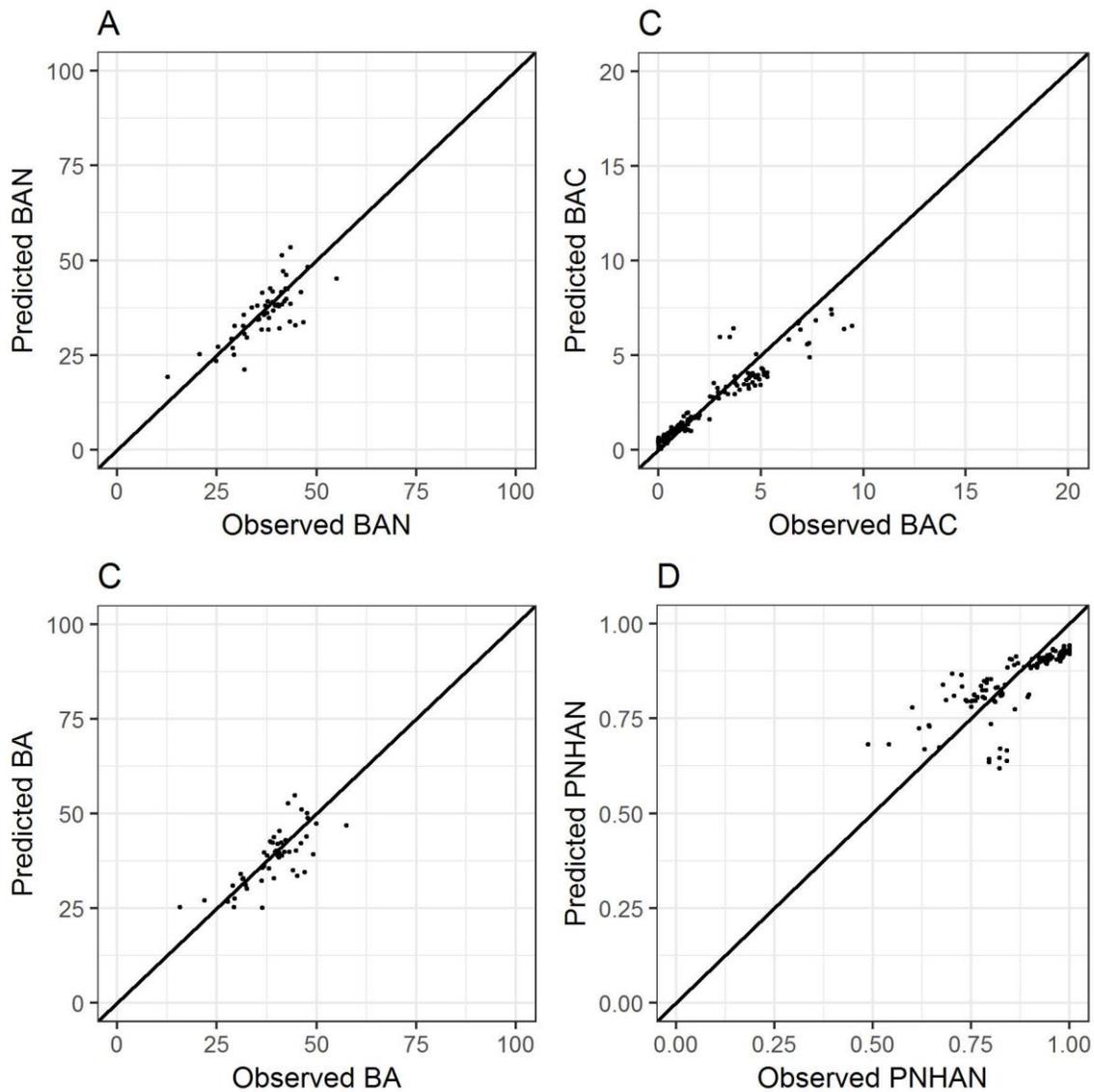


Figure 2-2. Observed vs predicted values for (A) basal area of *Nothofagus* (BAN, Eq. 2-8), (B) basal area of companion species (BAC, Eq. 9), (C) total basal area,  $BA = BAN + BAC$  and (D) number of trees per hectare (NHA, Eq. 2-3). All plots are estimates using the Management Plots (MP) network

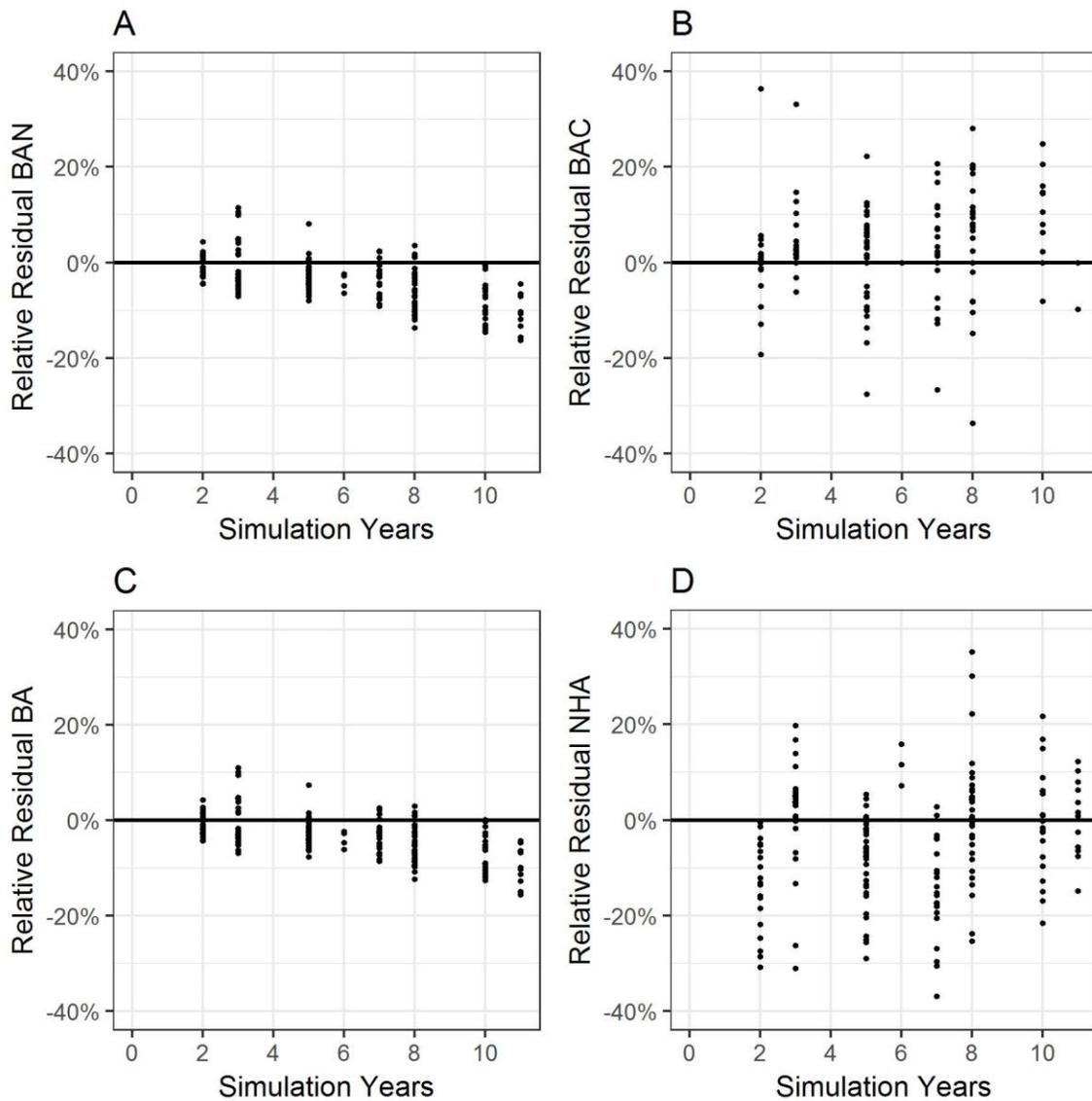


Figure 2-3. Relative residuals for different simulation years in projections of (A) basal area of *Nothofagus* (BAN, Eq. 2-10), (B) basal area of companion species (BAC, Eq. 2-11), (C) total basal area, BA = BAN + BAC, and (D) number of trees per hectare (NHA, Eq. 2-3) using the MP data as validation

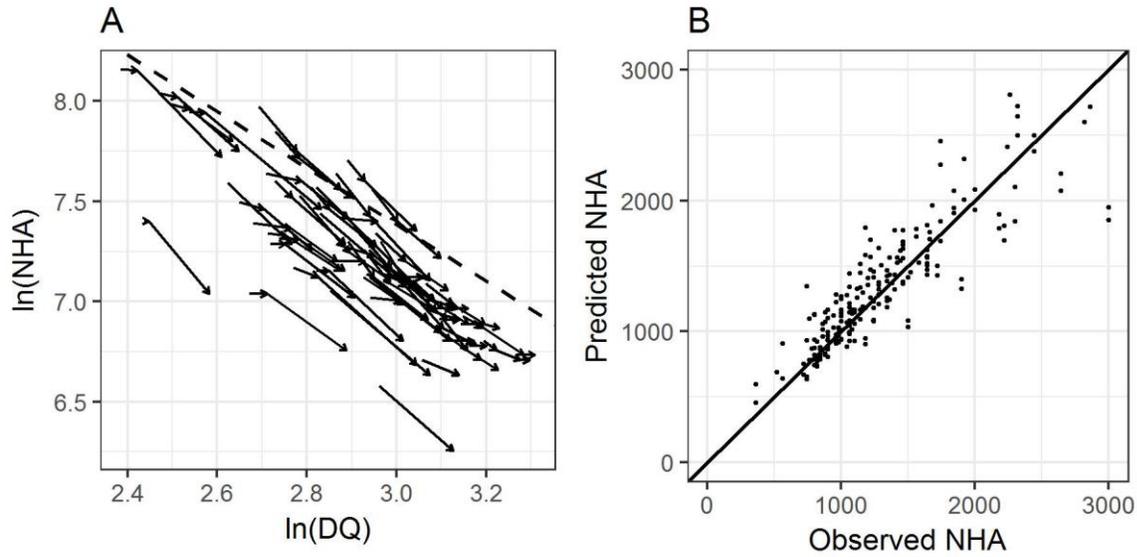


Figure 2-4. (A) Quadratic diameter (DQ) vs number of trees per hectare (NHA) trajectories of measured stands of the MP network. Dashed line is the  $DQ_{max}$  for *N. alpina*. (B) are the observed vs. projected values of number trees

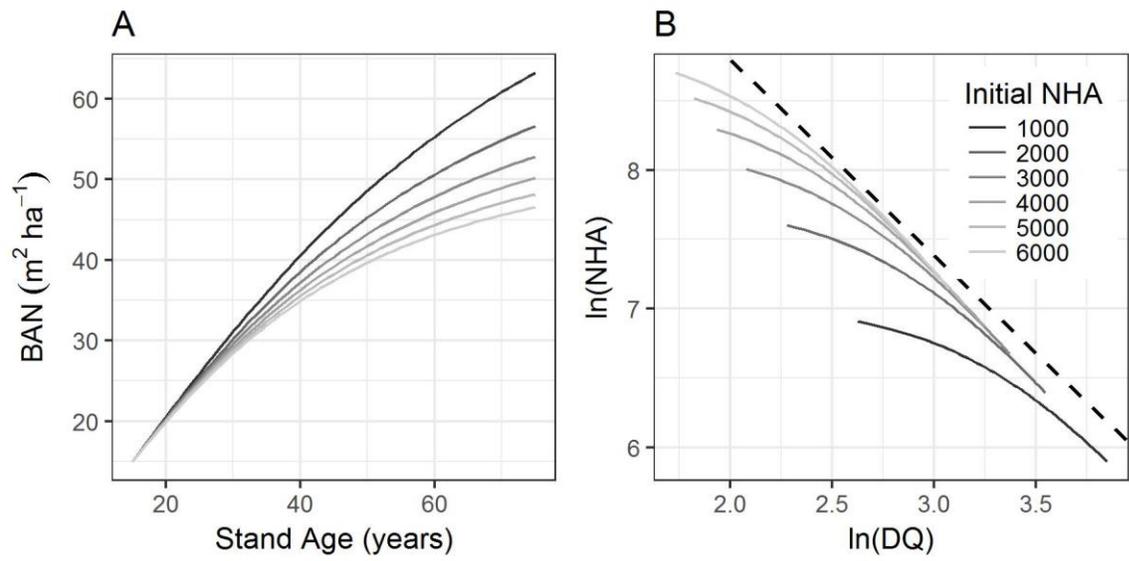


Figure 2-5. Model projections of 60 years of basal area of *Nothofagus* (BAN, Eq. 2-3 and Eq. 2-10) with different initial number of trees per hectare (NHA). Projections are based on an initial BAN of  $15 m^2 ha^{-1}$ , dominant age of 15 years, SI of 10 m and PBAN of 1. (A) Dominant age vs BAN trajectories. (B) DQ vs NHA trajectories. Dashed line is the  $DQ_{max}$  line for *N. alpina*

## CHAPTER 3 VALIDATION AND COMPATIBILITY OF INDIVIDUAL- AND STAND-LEVEL GROWTH AND YIELD MODELS FOR NOTHOFAGUS FORESTS

### **Introduction**

A growth and yield (G&Y) model is a representation of the natural dynamics of a forest and includes growth, mortality, and other changes in stand structure (Vanclay 1994). Forest G&Y models can be classified into stand-level (low resolution) or individual-level (high resolution) models (Porte and Bartelink 2002). Stand-level models are those in which the modeling units are aggregated parameters such as basal area, stocking, and site productivity (Vanclay 1995). In contrast, individual-level models can keep track and describe each tree in the stand. Both levels have advantages and disadvantages: stand-level models present well-behaved predictions on the long-term for stand parameters; however, they are inadequate to predict tree variables (such as diameter distributions or individual competition). In contrast, individual-level models are better at predicting trees' structure but lack precision when aggregating to stand-level parameters (Qin and Cao 2006).

Mathematical methods have been developed to link stand- and individual-level models into a compatible system to exploit the advantages of both and to improve predictions (Cao 2014; Hevia et al. 2015; Zhang et al. 2010). One popular method is to adjust the predicted tree yield to match the predicted stand basal area from a stand-level simulation (Qin and Cao 2006). Similarly, this method can also adjust the predicted individual mortality probabilities from an individual-level simulation to match the predicted total number of trees from a stand-level simulation (Cao 2017). A second commonly used method is the calibration of individual growth rates to match the BA growth from stand-level simulation (Cao 2006). The adjusted predictions from both

methods keep individual tree information such as diameters and mortality probabilities, therefore, they are expected to provide better individual volume and diameter distribution predictions.

The above calibration methods have been mostly applied outside natural mixed forests because, in contrast to forest plantations, establishing and remeasuring inventory plots in mixed forests over a wide geographical and temporal range is more time-consuming and costly and this causes a lack of sufficient and high-quality sample plots for the development and validation of sound forest models. Therefore, mixed forests G&Y simulations could benefit from compatibility methods to improve existing individual and stand-level models, particularly as they could calibrate each cohort individually.

A natural forest that can be benefited by model calibration is the *Nothofagus* forest type in southern Chile, known as RORACO for the dominance of the emergent trees of Rauli (*Nothofagus alpina* (Poepp. & Endl.) Oerst.), Roble (*N. obliqua* (Mirb.) Oerst.) and Coigüe (*N. dombeyi* (Mirb.) Oerst.). These *Nothofagus* species have been previously studied in Chile with several reports available, for example on basal area and diameter growth (Palmas et al. 2017; Moreno 2017); while these studies can have good accuracy, they could be improved by combining them into a calibrated G&Y system.

The main objective of this study is to evaluate different compatibility methods that integrate two available individual- and stand-level models for mixed *Nothofagus* forests in southern Chile. The specific objectives are: (1) to validate predictions of individual and stand-level models against independent data not used for model fitting; and (2) to

evaluate different methods and approaches for compatibilization that link individual- and stand-level models.

## Methods

### Available Data

The data for this study originated from a permanent plot network established in second growth RORACO forests in southern Chile, located between the 36° and 42°S latitude. The plot network was established by the Universidad Austral de Chile between 1999 and 2000 and had a total of 128 plots, each with an area of 500 m<sup>2</sup>. Only 17 of those plots were remeasured in 2006 and a subset of seven plots was remeasured a third time in 2012. These remeasured plots can be matched into 33 pairs of plot changes with 6 or 12 years between measurements.

For all plots, trees above 5 cm of diameter at breast height (DBH, cm) were inventoried for DBH and total height (H, m). *Nothofagus* species were identified and the rest was recorded as companion species. For all plots, the following stand-level variables were calculated: dominant age at breast height (AGE, years) as the average age of the thickest 100 trees per hectare, dominant height (HD, m) as the average total height of the thickest 100 trees per hectare, site index (SI, m), total basal area (BA, m<sup>2</sup> ha<sup>-1</sup>), total number of trees (NHA, trees ha<sup>-1</sup>), and quadratic diameter (DQ, cm). Also, for each of the cohorts, basal area for *Nothofagus* (BAN, m<sup>2</sup> ha<sup>-1</sup>) and number of trees of *Nothofagus* (NHAN, trees ha<sup>-1</sup>) were calculated. The proportion of basal area and number of trees of *Nothofagus* (PBAN, PNHAN) was also obtained. Only those plots dominated by *Nothofagus* (i.e., PBAN > 0.6) were selected for this study. For those plots without known SI, estimates were obtained using the site curve model reported by

Gezan and Ortega (2001) and Moreno (2017). All plots were assigned to a growth zone (ZONE) according to Gezan and Moreno (1999). Stand Density Index (SDI, trees ha<sup>-1</sup>) was calculated using:  $SDI = NHA \times (25.4/DQ)^\beta$  (Avery and Burkhart 2002) where  $\beta = -1.4112$ , as reported by Gezan et al. (2007). Additionally, each tree had an average annual increment in DBH (AIDBH, mm year<sup>-1</sup>), an estimated basal area of *Nothofagus* trees with larger DBH (BALn, m<sup>2</sup> ha<sup>-1</sup>) and a sociological status (SS, defined according to vertical stratification with 1: dominant; 2: codominant, 3: intermediate; or 4: suppressed). Summary statistics for the plot network are presented in Table 3-1.

### **Growth and Yield Models**

In this study, stand-level models (Palmas et al. 2017) of basal area and mortality, together with individual-level models of diameter growth (Moreno 2017) will be validated against independent data. The stand-level basal area growth model uses the predictors of AGE, SI, NHA and PBAN (Equation 3-1; Palmas et al. 2017). This model is

$$\ln(BAN) = \hat{\beta}_0 + \hat{\beta}_1 \ln(AGE) + \hat{\beta}_2 \ln(SI) + \hat{\beta}_3 \ln(NHA) + \hat{\beta}_4 \ln(PBAN) \quad (3-1)$$

where ln is the natural logarithm.

The stand mortality model is a simple annual projection of NHA defined by the single parameter  $\alpha$  and it is based on the expression from Reineke (1933). The stand mortality model uses the current NHA<sub>0</sub> to estimate the current maximum quadratic diameter (DQ<sub>0max</sub>) with

$$DQ_{0max} = \exp\left(\frac{\ln(NHA_0 - \hat{\alpha})}{\hat{\beta}}\right) \quad (3-2)$$

with different  $\hat{\alpha}$  values for stands dominated by *N. alpina*, *N. obliqua* and *N. dombeyi*, and a common  $\hat{\beta}$  for all stands (Gezan et al. 2007). The stand-level model to project future values of the number of trees of *Nothofagus* (NHA<sub>1</sub>) is

$$\ln(\text{NHA}_1) = \ln(\text{NHA}_0) \left( 1 - \alpha \Delta t \frac{DQ_0}{DQ_{0\max}} \right) \quad (3-3)$$

where  $\alpha$  is the parameter to estimate and  $\Delta t$  is the number of years between measurements. The parameters for all stand-level equations can be found in Table 3-2.

Two individual-level models for annual diameter growth (AIDBH, mm year<sup>-1</sup>) will be considered (Moreno 2017). Both models include coefficients for BAL, SDI, DBH and AGE but only the first model includes a combined factor, SpZone, of growth zone and species (Equation 3-4 and 3-5, respectively; Moreno 2017). The models are

$$\begin{aligned} \text{Model 1: } \ln(\text{AIDBH}) = & \hat{\alpha}_{11}\text{SpZone}_{11} + \hat{\alpha}_{12}\text{SpZone}_{12} + \hat{\alpha}_{14}\text{SpZone}_{14} + \\ & \hat{\alpha}_{21}\text{SpZone}_{21} + \hat{\alpha}_{22}\text{SpZone}_{22} + \hat{\alpha}_{23}\text{SpZone}_{23} + \hat{\alpha}_{24}\text{SpZone}_{24} + \hat{\alpha}_{31}\text{SpZone}_{31} + \\ & \hat{\alpha}_{32}\text{SpZone}_{32} + \hat{\alpha}_{33}\text{SpZone}_{33} + \hat{\alpha}_{34}\text{SpZone}_{34} + \hat{\beta}_1 \ln(\text{BALn} + 10) + \hat{\beta}_2 \text{SDI} + \hat{\beta}_3 \ln(\text{DBH}) + \\ & \hat{\beta}_4 \ln(\text{AGE}) + \hat{\beta}_5 \text{SS} \end{aligned} \quad (3-4)$$

$$\begin{aligned} \text{Model 2: } \ln(\text{AIDBH}) = & \hat{\beta}_0 + \hat{\beta}_1 \ln(\text{BALn} + 10) + \hat{\beta}_2 \text{SDI} + \hat{\beta}_3 \ln(\text{DBH}) + \\ & \hat{\beta}_4 \ln(\text{AGE}) + \hat{\beta}_5 \text{SS} \end{aligned} \quad (3-5)$$

where the  $\hat{\alpha}_{sz}$  represent the different coefficients for each interaction between species and ZONE.

Total stand volume (VOL, m<sup>3</sup> ha<sup>-1</sup>) from stand-level simulations can be obtained using two different equations reported by Gezan and Ortega (2001) (Equations 3-6 and 3-7). VOL models 1 and 2 require BA, HD and only the latter also requires PNHAN. The models are:

$$\text{Model 1: } \text{VOL} = \hat{\beta}_0 [\text{BA}^{\hat{\beta}_1} \text{HD}^{\hat{\beta}_2}] \quad (3-6)$$

$$\text{Model 2: } \text{VOL} = \hat{\beta}_0 [\text{BA}^{\hat{\beta}_1} \text{HD}^{\hat{\beta}_2} \text{PNHAN}^{\hat{\beta}_3}] \quad (3-7)$$

A third VOL calculation originates from a diametric distribution equation with stand parameters as predictors using a Weibull distribution and using reported DBH-

class volumes models (Gezan et al. 2001). This diametric distribution equation is based on a Weibull distribution with three parameters (Clutter et al. 1983; Gadow and Hui 1999) and provides frequencies for each DBH-class. Later, volumes for these classes were calculated using available height and taper equations by Gezan et al. (2009), which are then aggregated to the stand-level. Finally, for the simulations at the individual-tree level, their predicted tree volumes were estimated from reported taper and volume models (Gezan et al. 2009) and then aggregated to the stand-level.

### Compatibility Methods and Evaluation

Two compatibility methods were used to calibrate the projections of the individual-level models. We referred to them as the Proportional Yield (PY) and the Proportional Growth (PG; also known as disaggregation method) (Cao 2006 and Qin and Cao 2006). Both methods of calibration use two equations, one to calibrate the individual mortality probabilities based on the stand-level NHA projection (NHA<sub>1</sub>, Equation 3-3), and another to calibrate the individual diameter growth to the stand-level BA projection (Equation 3-1). The equations for the PY method are:

$$\widetilde{FT}_{1i} = \widehat{FT}_{1i} \left( \frac{N\widehat{HA}_1}{\sum_{i=1}^n \widehat{FT}_{1i}} \right) \quad (3-9)$$

$$\widetilde{DBH}_{1i}^2 = \widehat{DBH}_{1i}^2 \left( \frac{B\widehat{A}_1/K}{\sum_{i=1}^n \widehat{FT}_{1i} \widehat{DBH}_{1i}^2} \right) \quad (3-10)$$

where  $\widetilde{FT}_{1i}$  and  $\widehat{FT}_{1i}$  are the calibrated and predicted expansion factors (the number of trees that each sample tree represents) for  $i$ th tree at time 1, respectively;  $N\widehat{HA}_1$  is the trees per hectare at time 1 from Equation 3-3;  $\widetilde{DBH}_{1i}^2$  and  $\widehat{DBH}_{1i}^2$  are the calibrated and predicted squared diameters for the  $i$ th tree at time 1, respectively.  $\widehat{DBH}_{1i}$  is estimated

by adding the estimated AIDBH from Equation 3-4 or 3-5 to the to the  $DBH_{0i}$ .  $\widehat{BA}_1$  is the basal area at time 1 from Equation 3-1; and  $K = \pi/40000$ , is a constant.

The equations for the PG method are:

$$\widetilde{FT}_{1i} = \widehat{FT}_{1i}^m, \text{ subject to } \sum_{i=1}^n \widetilde{FT}_{1i} = \widehat{NHA}_1 \quad (3-11)$$

$$\widehat{DBH}_{1i}^2 = DBH_{0i}^2 + \left( \frac{\widehat{BA}_1/K - \sum_{i=1}^n \widehat{FT}_{1i} DBH_{0i}^2}{\sum_{i=1}^n \widehat{FT}_{1i} (DBH_{1i}^2 - DBH_{0i}^2)} \right) (DBH_{1i}^2 - DBH_{0i}^2) \quad (3-12)$$

Where  $DBH_{0i}^2$  is the squared diameter of the  $i$ th tree at time 0 and all other terms were previously defined. Equation 3-11 requires to find a power value  $m$  that makes the sum of the predicted expansion factors equal to  $\widehat{NHA}_1$ .

The predictions of the two compatibility methods (PY and PG) were compared with unadjusted stand-level simulations using the three VOL models and unadjusted tree-level simulations using the two AIDBH models. The total number of scenarios compared in this study is nine (Table 3-3).

Model evaluation with independent data and compatibility methods were compared using the observed and projected basal area growth and mortality based on the information from the available 17 remeasured plots, with the following goodness-of-fit measures:  $R^2_{emp}$ , RMSE% and Bias%, that are detailed below.

$$R^2_{emp} = 1 - \sum_{i=1}^n (y_i - \hat{y}_i)^2 / \sum_{i=1}^n (y_i - \bar{y})^2 \quad (3-13)$$

$$RMSE\% = 100 \times \sqrt{\sum_{i=1}^n (y_i - \hat{y}_i)^2} / \bar{y} \quad (3-14)$$

$$Bias\% = 100 \times \sum_{i=1}^n (y_i - \hat{y}_i) / \bar{y} \quad (3-15)$$

where  $y_i$  and  $\hat{y}_i$  are the  $i$ th observed and projected value, respectively;  $\bar{y}$  is the mean response of the observed value, and  $n$  is the number of observations.

In order to compare the final diameter distributions, the ratio between the 85<sup>th</sup> and 15<sup>th</sup> percentile of DBH (P85/P15) was calculated. A large P85/P15 ratio would be evidence of skewness of the stand DBH distribution to the right, towards larger trees. As stand scenarios S1 and S2 do not use diameter distribution model, they do not have a calculation of P85/P15.

For graphical outputs comparing scenarios, relative residuals were used, which were defined as the difference between observed and predicted values divided by the mean observed value and represented as a percentage. All calculations were done in R 3.3.2 (R Core Team 2016).

## Results

Scenarios had different goodness-of-fit measures for their predictions of NHAN, BAN, DQ and VOL (Table 3-4). As expected, the three previously reported stand scenarios, S1, S2 and SD, are better behaved for stand attributes as NHAN and BAN with ranges of  $R^2_{emp}$  between 0.91 and 0.94, respectively. S1 and S2 scenarios have the lowest fitness values for VOL predictions with  $R^2_{emp}$  of 0.11 and 0.10. The SD scenario demonstrates that the reported diameter distribution equation can improve the prediction of VOL from the stand-level VOL models 1 and 2. The two AIDBH models result in small or no differences in predictions as shown by the almost equal goodness-of-fit measures in T1 and T2, PY1 and PY2, and PG1 and PG2. AIDBH model 2 resulted in marginally better RMSE% and Bias% for compatibility scenarios than AIDBH model 1, PY2 better than PY1, and PG2 is better than PG1. Results below disregard the small differences between the two BAN models and the two AIDBH models.

## **Number of Trees Goodness-of-Fit Statistics**

All scenarios presented NHAN predictions with  $R^2_{emp}$  above 0.91 with compatibility scenarios PG1-PG2 and PY1-PY2 showing the highest values followed by the S1-S2-SD and T1-T2. PG1-PG2 had the lowest RMSE% and Bias% across all simulations followed by PY1-PY2 scenarios.

For NHAN, the scenarios predictions showed variable trends of underpredictions and overprediction in all scenarios (Figure 3-1 A). The length of the simulation considerably affected the fitness of the predictions. Relative residuals had larger departures from zero in 12-year than 6-year simulations. 12-year simulations had in average over 12% more of error than 6-year simulations. For NHAN, S1-S2 and T1-T2 scenarios had lower relative residuals using simulations of 6 years; while compatibility scenarios PY1-PY2 and PG1-PG2 had better residuals for simulations of 12 years (Figure 3-2 A). Mean relative residuals increased for all scenarios when the simulation years increase from 6 years to 12 simulations.

## **Basal Area Goodness-of-Fit**

In terms of BAN, the S1-S2-SD and PY1-PY2 scenarios had the highest goodness-of-fit values with average  $R^2_{emp}$  of 0.90 and 0.88, respectively. These scenarios also had the lowest RMSE% and Bias% values. The PG1-PG2 compatibility method had the poorest fit with  $R^2_{emp}$ , RMSE% and Bias% of 0.76, 12.54 and 9.57, respectively.

The S1-S2-SD and PY1-PY2 models had consistent overpredictions across all ranges of BAN (Figure 3-1 B), and they departed to a minimum of -20%. In contrast, T1-T2 and PG1-PG2 scenarios consistently underpredicted across the entire range of observed values reaching relative residuals close to 35%. At 6-year simulations, the

relative residuals for S1-S2-SD and PY1-PY2 scenarios were closer to zero than T1-T2 and PG1-PG2 scenarios (Figure 3-2 B). The relative residual trend of all scenarios was maintained in 12-year simulations, with S1-S2 and PY1-PY2 increasing overprediction and T1-T2 and PG1-PG2 increasing underprediction.

### **Diameter Distributions**

The ratio of P85/P15 using the diametric distribution was almost equal between T1-T2, PY1-PY2 and PG1-PG2 scenarios (Figure 3-1 C). These simulations had a  $R^2_{emp}$  of 0.48 and range of residual errors between -30% and 10%. Simulations tended to under and overestimate across the range of P15/P85. SD greatly differed from the other scenarios with constant underprediction that reached almost 40% for 6-year and 25% for 12-year simulations. Estimating diametric distribution from the Weibull distribution favored large trees. T1-T2, PY1-PY2 and PG1-PG2 scenarios are closer to the measured distribution.

### **Volume Goodness-of-Fit**

The S1-S2 and SD scenarios had the lowest goodness-of-fit measures for VOL with  $R^2_{emp}$  values of 0.11, 0.10 and 0.58; respectively, and the highest RMSE%. VOL from S1-S2 scenarios was highly variable in terms of relative residuals ranging from -30% to 40% (Figures 3-1 D and 3-2 D). Calculating volume using diameter distribution equations (scenario SD) performed better than the stand volume equations with relative residuals closer to zero.

T1-T2 scenarios had the highest goodness-of-fit for VOL predictions with an  $R^2_{emp}$ , RMSE% and Bias% of 0.89, 8.23 and 4.12, respectively. Relative residuals for T1-T2 scenarios were consistently closer to zero, denoting poor goodness-of-fit of the two stand-level VOL equations.

For the 6-year and 12-year simulations, the relative residuals for T1-T2 scenarios had the best performance among the systems. VOL predictions also showed the accumulation of errors trend when increasing the simulation length from 6 to 12 years; where relative residuals increased their trend between 5 to 10%.

PY1-PY2 scenarios had  $R^2_{emp}$  at 0.80, smaller than T1-T2, with values of RMSE% and Bias% of 11.06 and -8.04. Relative residuals consistently showed overpredictions with values that reached -25%. VOL predictions using PY1-PY2 scenario returned residual error means of -8% and -12% at 6 and 12 years, respectively. The compatibilization using the PG1-PG2 method returned slightly higher goodness-of-fit values than PY1-PY2 scenarios with  $R^2_{emp}$  of 0.85, and RMSE% of 9.48.

### **Discussion**

There were small differences found from the two AIDBH models, meaning that the addition of the factor SpZone, that combines growth zone and species, to the model did not markedly improved predictions. This definition of zones was reported as significant in other studies in contrast to our results (Chauchard and Sbrancia 2003; Echeverria and Lara 2004; Esse et al. 2013; Gezan et al. 2009; Lusk and Ortega 2003). This also suggests that DBH growth for RORACO stands is highly correlated with current size, competition and site factors. Similar conclusions were found in other mixed species forests (Wykoff 1990; Monsreud and Sterba 1996).

Model evaluation suggested that stand-and tree-level models presented limitations according to their resolution while compatibility methods improved predictions. Stand-level models performed better than the individual-level models to predict NHAN and BAN, but had inadequate VOL estimations as seen in the poor goodness-of-fit measures using both VOL models. On the contrary, individual-level

models do poorly when aggregating the DBH predictions to the stand parameters of NHAN and BAN. Individual-level models return the best fitness properties for VOL, agreeing with the reported advantages of both stand- and individual-level models (Qin and Cao 2006). Therefore, the performance of the previously reported stand scenarios (S1, S2 and SD) is higher when predicting BAN while the tree scenarios (T1 and T2) have higher performance when predicting VOL.

PY1-PY2 and PG1-PG2 both had higher accuracy of NHAN predictions than S1-S2-SD and T1-T1 scenarios. However, Proportional Yield and Proportional Growth methods showed different performance in predictions for BAN. Here, scenarios with PY1-PY2 improved and PG1-PG2 worsened prediction fitness compared to T1-T2 scenarios. Different results were found in birch (*Betula alba*, Hevia et al. 2015) and loblolly pine plantations (*Pinus taeda*, Cao 2006), where prediction fitness of BA was higher using the Proportional Growth than using the Proportional Yield method.

In terms of VOL, PY1-PG2 and PG1-PG2 scenarios had lower goodness-of-fit than the unadjusted T1 and T2 scenarios. This result contrast with improvements of individual volume predictions when using Proportional Growth method in Douglas-Fir stands (Zhang et al. 1993).

The compatibility adjustments, as well as the unadjusted predictions, suffer from accumulation of errors and reduction of goodness-of-fit of predictions when increasing simulation years. The compatibility methods are not only limited in their accuracy by the length of the simulation, but also by the accuracy of the stand-level of predictions.

The permanent plot network used to validate these scenarios systems is the only current resource of independent remeasured plot data for RORACO forests, which in

this case is mainly dominated by *N. dombeyi*. Thus, there is the need for additional permanent plot data to further validate and improve these models.

### **Conclusion**

This study validates previously published models, is a crucial step for effective evaluation of forest growth models. It was shown that validations with the stand-level scenarios have high goodness-of-fit when predicting stand-level parameters such as BAN and NHAN. On the other hand, tree-level scenarios had higher performance when predicting VOL.

This study evaluated two compatibility scenarios that uses published stand- and individual-level models to improve predictions for the RORACO forests in southern Chile. The compatibility scenarios evaluated resulted in better predictions for NHAN and BA than unadjusted stand- and individual-level simulations. Adjusting individual-level predictions to match stand-level predictions with a Proportional Yield method returned the best results for number of trees and basal area of *Nothofagus*. This compatibilization study provides with the first evaluation and implementation of compatibility methods to link stand- and individual-level models in mixed and uneven-aged forests.

Table 3-1. Mean (standard error) and range of stand parameters in the remeasured plots from the permanent network based on 33 plots

Variable	Mean (SE)	Range
AGE	45.68 (1.47)	20.73 – 63.58
HD	29.29 (0.89)	19.00 – 42.65
SI	14.71 (0.55)	8.31 – 22.61
BA	43.47 (1.49)	23.49 – 64.84
NHA	1,826.51 (163.43)	460 – 4,360
DQ	19.86 (1.03)	8.48 – 34.53
BAN	38.89 (1.50)	20.72 – 61.55
NHAN	1,283.26 (123.14)	460 – 3,440
PNHAN	0.72 (0.03)	0.44 – 1.00
PBAN	0.89 (0.01)	0.69 – 1.00
SDI	289.11 (5.95)	225.32 – 376.16
AIDBH	3.08 (2.10)	0.10 – 12.10
SS	3.24 (0.03)	2.82 – 3.68
BALn	32.44 (1.20)	16.08 – 49.68

Note. AGE: dominant age (years), HD: dominant height (m), SI: site index (m), BA: total basal area ( $\text{m}^2 \text{ha}^{-1}$ ), NHA: total number of trees ( $\text{trees ha}^{-1}$ ), DQ: mean quadratic diameter (cm), BAN: basal area of *Nothofagus* ( $\text{m}^2 \text{ha}^{-1}$ ), NHAN: number of *Nothofagus* trees ( $\text{trees ha}^{-1}$ ), PNHAN: proportion number of trees of *Nothofagus* (0-1), PBAN: proportion of BA of *Nothofagus* (0-1), SDI: stand density index, AIDBH: average annual increment in DBH ( $\text{mm year}^{-1}$ ), SS: sociological status, BALn: basal area of larger trees of *Nothofagus* ( $\text{m}^2$ )

Table 3-2. Estimated parameters for BAN, NHA, AIDBH equations

Parameter	Eq. 3-1	Eq. 3-2	Eq. 3-3	Eq. 3-4	Eq. 3-5	Eq. 3-6	Eq. 3-7
$\hat{\alpha}$	-	<sup>a</sup>	$3.596 \times 10^{-3}$	-	-	-	-
$\hat{\alpha}_{11}$	-	-	-	2.702	-	-	-
$\hat{\alpha}_{12}$	-	-	-	2.908	-	-	-
$\hat{\alpha}_{14}$	-	-	-	3.065	-	-	-
$\hat{\alpha}_{21}$	-	-	-	2.538	-	-	-
$\hat{\alpha}_{22}$	-	-	-	2.587	-	-	-
$\hat{\alpha}_{23}$	-	-	-	2.841	-	-	-
$\hat{\alpha}_{24}$	-	-	-	2.678	-	-	-
$\hat{\alpha}_{31}$	-	-	-	2.946	-	-	-
$\hat{\alpha}_{32}$	-	-	-	2.948	-	-	-
$\hat{\alpha}_{33}$	-	-	-	2.941	-	-	-
$\hat{\alpha}_{34}$	-	-	-	2.902	-	-	-
$\hat{\beta}_0$	-6.170	-	-	-	2.410	$4.332 \times 10^{-1}$	$3.469 \times 10^{-1}$
$\hat{\beta}_1$	1.212	-1.411	-	$-6.517 \times 10^{-3}$	$-7.062 \times 10^{-3}$	$9.794 \times 10^{-1}$	$9.938 \times 10^{-1}$
$\hat{\beta}_2$	0.652	-	-	$9.307 \times 10^{-1}$	$2.745 \times 10^{-4}$	$9.396 \times 10^{-1}$	$9.305 \times 10^{-1}$
$\hat{\beta}_3$	0.518	-	-	-1.175	$9.046 \times 10^{-1}$	-	$4.637 \times 10^{-2}$
$\hat{\beta}_4$	1.250	-	-	$-1.401 \times 10^{-1}$	-1.138	-	-
$\hat{\beta}_5$	-	-	-	-	$-1.336 \times 10^{-1}$	-	-

<sup>a</sup> 11.617, 11.377 and 11.764 for plots dominated by *N. alpina*, *N. dombeyi* and *N. obliqua*, respectively

Table 3-3. Definition of scenarios considered in this study

Scenario	Level	Model	Compatibility
S1	Stand	VOL Model 1	-
S2	Stand	VOL Model 2	-
SD	Stand	Diametric distribution	-
T1	Tree	AIDBH Model 1	-
T2	Tree	AIDBH Model 2	-
PY1	Tree	AIDBH Model 1	Proportional Yield
PY2	Tree	AIDBH Model 2	Proportional Yield
PG1	Tree	AIDBH Model 1	Proportional Growth
PG2	Tree	AIDBH Model 2	Proportional Growth

Table 3-4. Goodness-of-fit measures for each scenario for number of trees per hectare of *Nothofagus* (NHAN), basal area of *Nothofagus* (BAN), P85/P15 and stand volume (VOL)

Scenario	NHAN			BAN			P85/P15			VOL		
	R <sup>2</sup> <sub>emp</sub>	RMSE%	Bias%	R <sup>2</sup> <sub>emp</sub>	RMSE%	Bias%	R <sup>2</sup> <sub>emp</sub>	RMSE%	Bias%	R <sup>2</sup> <sub>emp</sub>	RMSE%	Bias%
S1	0.94	15.60	4.36	<b>0.90</b>	<b>8.15</b>	<b>-4.19</b>	-	-	-	0.11	24.14	4.57
S2	0.94	15.60	4.36	<b>0.90</b>	<b>8.15</b>	<b>-4.19</b>	-	-	-	0.10	24.29	4.92
SD	0.94	15.60	4.36	<b>0.90</b>	<b>8.15</b>	<b>-4.19</b>	0.10	28.85	14.62	0.58	14.42	7.52
T1	0.91	19.52	6.40	0.80	11.41	7.76	0.48	22.67	-0.85	<b>0.89</b>	<b>8.23</b>	4.12
T2	0.91	19.59	6.42	0.79	11.65	8.17	<b>0.50</b>	22.42	-0.34	0.88	8.48	4.50
PY1	<b>0.95</b>	15.21	2.32	0.88	8.67	-4.35	0.48	22.82	-0.85	0.80	11.06	-8.04
PY2	<b>0.95</b>	15.21	2.32	0.89	8.63	-4.32	<b>0.50</b>	<b>22.40</b>	<b>-0.17</b>	0.80	10.97	-7.97
PG1	<b>0.95</b>	14.43	1.45	0.76	12.54	9.57	0.48	22.66	-0.24	0.85	9.48	6.10
PG2	<b>0.95</b>	<b>14.40</b>	<b>1.44</b>	0.76	12.45	9.22	<b>0.50</b>	22.41	0.18	0.85	9.45	5.82

Figure 3-1. Relative residuals for predictions of (A) Number of trees per hectare of *Nothofagus* (NHAN), (B) Basal Area of *Nothofagus* (BAN), (C) P85/P15 and (D) Stand Volume (VOL) against observed values. Lines are smoothed average of the points for each scenario

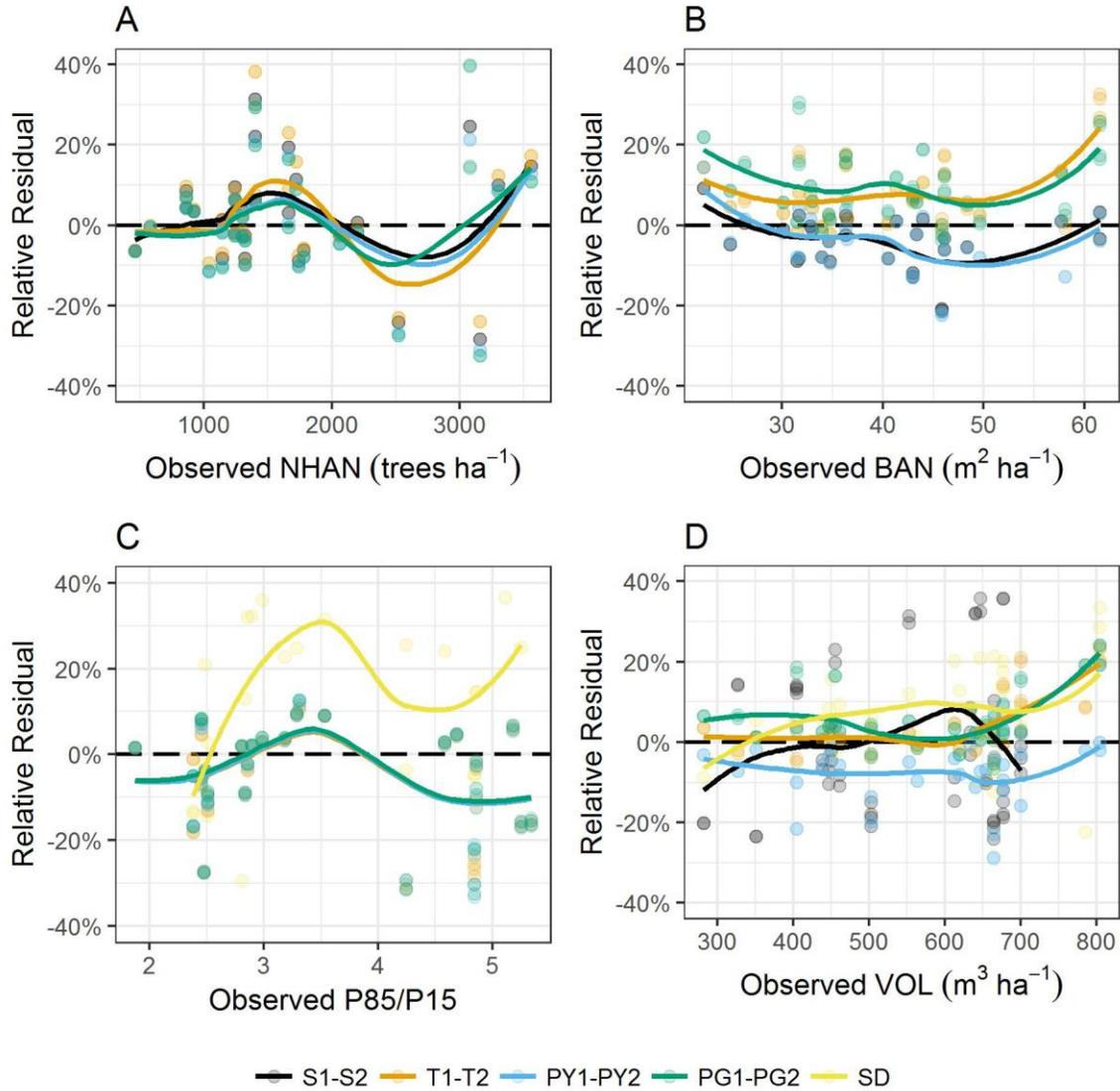
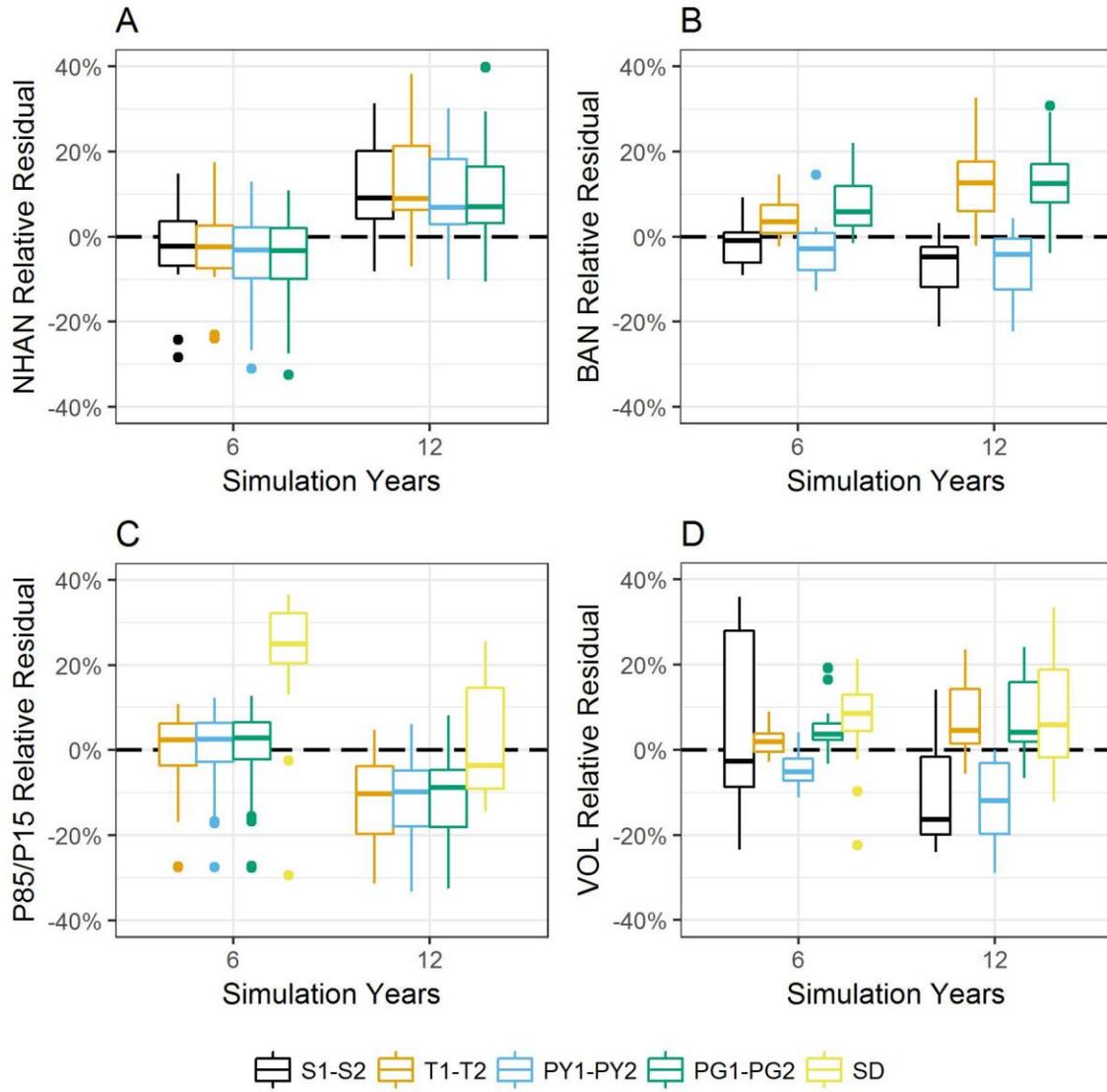


Figure 3-2. Relative residuals against simulation years for predictions of (A) Number of trees per hectare of *Nothofagus* (NHAN), (B) Basal Area of *Nothofagus* (BAN), (C) P85/P15 and (D) Volume (VOL)



## CHAPTER 4 TIMBER AND CARBON SCENARIOS FOR THE MAYA FOREST OF MEXICO: AN INDIVIDUAL-BASED MODEL SIMULATION

### **Introduction**

More than 400 million hectares of tropical forest are designated for timber production (Blaser et al. 2011) and at least 20% of their total area was logged between 2000 and 2005 (Asner et al. 2009). Even small logging operations can cause damage to the residual stand resulting in poor forest recovery, degradation, reduction of timber stocks and eventual net carbon emissions (Putz et al. 2012; Bryan et al. 2013).

A set of silvicultural techniques, that has been proposed for several years, are the called Reduced-Impact Logging (RIL) techniques aimed to reduce forest damage and carbon emissions, stabilize timber production, and increase biomass sequestration rates (Peña-Claros et al. 2008a; Putz et al. 2008; Sasaki et al. 2016; Bicknell et al. 2015; Lussetti et al. 2016; Vidal et al. 2016). These techniques vary in their effects in timber stocks sustainability, conservation effectiveness and costs of application (Medjibe and Putz 2012). Even though experimental plots have demonstrated the benefits of some RIL techniques (e.g. Peña-Claros et al. 2008b; Villegas et al. 2009; Gourlet-Fleury et al. 2013), there is not enough empirical data on all of them, requiring that researchers provide answers with the use of simulation models. Accurately accounting the carbon dynamics that arise from the use of various silvicultural techniques and harvested species, characteristic of tropical forest operations, can reduce the reported large uncertainties of the carbon balances for the tropical forests (Pan et al. 2011; Baccini et al. 2017).

A simulation model for a tropical forest can become highly complex depending on the inclusion of submodels that recreate the multiple species, ages or growth strategies

that are part of the forest (Filotas et al. 2014). Therefore, in the final predictions can be highly biased due to the accumulation of errors from each submodel. This accumulation of error occurs even if each submodel has a proven high precision. This problem can be avoided with the implicit inclusion of random effects through stochastic models.

Iterations of a stochastic model generate a range of plausible values that can be more realistic and insightful than a single and potentially biased value from a deterministic model (Vanclay 1991; Black and McKane 2012). A stochastic approach also allows accurate representation of random but nevertheless important ecosystem processes such as hurricane-caused mortality.

Quintana Roo is the Mexican state that harvests the largest volume of tropical timber in Mexico (Ellis et al. 2014). Historically, the state forest industry has focused on the extraction of timber species such as mahogany (*Swietenia macrophylla*), Spanish cedar *Cedrela odorata*, hardwoods for railroad ties (Shoch 1999) and on latex (chicle) tapping of *Manilkara zapota*. Recently, the forest industry in Quintana Roo diversified to include a cohort of polewood species and palm leaves useful for the local tourism industry (Sierra-Huelsz et al. 2017). Given that many forests in Quintana Roo are now being logged in a second rotation, and in response to the frequent calls for improved carbon retention, these forests could benefit from a simulation model to estimate the effects of silvicultural interventions on the forest basal area and biomass. As with many tropical forests of the world, currently there is no forest simulation available for the natural forests in Quintana Roo, Mexico. This study suggests that a complete simulation model for these forests can now be completed using the wide array of ecological and silvicultural studies that have taken place in the region.

This study aims to provide estimates on the potential effects of RIL techniques by simulating a forested area in Quintana Roo dedicated to the management and harvest of timber species. The specific objectives are: 1) to generate and code an individual-tree based growth model capable of simulating forest management activities; 2) to validate the simulation model with known harvesting rates and timber biomass from Quintana Roo; and, 3) to estimate and evaluate the extent to which RIL activities can reduce timber and above-ground timber biomass stocks in the region.

### **Data Sources**

Diameter growth, recruitment, mortality and harvesting rates used to build the simulation model came from multiple studies based in Quintana Roo forests, which are identified in Table 4-1. Initial forest conditions (i.e. number, species and diameter of trees present in each stand) of the were based on the permanent National Forest Inventory plots measured in the central municipalities of Quintana Roo by the National Forestry Commission (CONAFOR 2008).

### **Model Description**

The simulation coding was done in R 3.3.2 (R Core Team 2016), and the complete code can be found in [www.github.com/spalmas/RIL-Simulator](https://github.com/spalmas/RIL-Simulator) and the simulation web application in <https://spalmas.shinyapps.io/RIL-Simulator>.

The model simulates a managed forest in the south and central municipalities of Quintana Roo: Felipe Carrillo Puerto, Jose Maria Morelos, Bacalar and Othon P. Blanco (Figure 4-1). This model is based on an individual tree, distance-independent approach as it follows individual trees without consideration of spatial effects, and the simulation cycles through a sequence of submodels of diameter growth, natural mortality, hurricane mortality, natural recruitment and logging scenarios, logging mortality and gap

enrichment. To incorporate uncertainty to the simulation, several submodels are modeled in a stochastic approach following the reported distributions of the model parameters. Finally, it reports the resulting volumes of extracted timber volume and densities of above-ground biomass.

The simulation occurs on 1 ha plots of forested area. To simulate the rotation of annual cutting areas (ACA), the number of 1 ha plots is equal to the rotation cycle years. Each ACA is harvested only one year every rotation cycle. There are eleven simulated species in the model (Table 4-2) and hereafter referred to by the generic names. These species were chosen because they account for most of harvested volume for community forest enterprises in the Yucatan Peninsula (Wilshusen 2005; Racelis and Barsimantov 2008). Further details of the different submodels are presented below.

### **Age Increment and Growth**

Diameter at breast height (DBH, cm) growth is randomized annually from normal distributions with means and standard deviations for each species (Appendix A). Growth increments are limited to change by up to only 15% between years to simulate autocorrelation in growth rates over time. These diameter growth distributions were considered to not be affected by stand competition or weather patterns, this is due to lack of data and literature reported in the region.

### **Natural and Hurricane Mortality**

The simulation varies the probability of tree mortality depending on hurricane strength category and tree size (Table 4-4). The annual probability of mortality during a non-hurricane year is assumed to be 3% for trees with less than 10 cm DBH and 1% for larger individuals (Negreros-Castillo and Mize 2014). Mortality during hurricane years

vary depending on the strength category of hurricane that hits the forest (Sánchez Sánchez and Islebe 1999; Navarro-Martínez et al. 2012; McGroddy et al. 2013; Sierra-Huelsz et al. 2017). The annual probability that the forest is hit by a category 3, 4, or 5 hurricanes was set to be 30%, 20% and 10%, respectively (Bitrán Bitrán 2001).

### **Natural Recruitment**

The simulation adds each year trees of 10 cm DBH to the forest depending on the specific mean recruitment rates that vary in terms of stand basal area (Table A-2). Because the simulation does not have a model for canopy cover to assign recruitment rates based on Toledo-Aceves et al. (2009), stand basal area is used as a predictor of canopy cover using a simple linear relation. A mean recruitment rate per hectare was assigned to those species with no specific recruitment rate reported by Toledo-Aceves et al. (2009).

### **Logging Scenarios and Minimum Cutting Diameters**

The logging intensities vary the percentage of trees harvested in the ACA. Five categories are considered. A *Business as Usual* (BAU) intensity harvests 50% of the biggest eligible trees in the stand was considered (Ellis et al. 2015). *No logging*, *Low*, *High* and *All* intensities harvest 0%, 25%, 75% and 100% of eligible trees, respectively. Trees must be larger than the allowed minimum cutting diameters (MCD) for its species to be eligible to harvest. *Swietenia*, timber species and the polewood cohort have a MCD of 55 cm, 35 cm and 10 cm, respectively (Sierra-Huelsz et al. 2017).

### **Felling Mortality and Cable Yarding**

Felling mortality is caused by the downing of timber trees. The technique of directional felling can avoid all felling mortality in the nearby trees from a harvested tree (Sist et al. 2003). If directional felling is selected in the simulation, there are not killed

trees in the nearby area of the harvested tree. If directional felling is not employed, trees within a distance equivalent to the height of the felled tree have a 50% chance of mortality.

The probability of skid trail mortality is based on the locations of each tree within the 1 ha plot. A skid trail 6 m wide runs from the location of each harvested tree to the closest edge of the 1 ha plot. To simulate the avoidance of large trees (which are potentially future crops) all trees with DBH > 20 cm are spared in the skid trails (Figure 4-2). It was assumed, that no trees are killed along the skid trail in scenarios in which cable yarding is employed.

### **Gap Enrichment**

It was considered that for every three harvested trees a simulated enrichment gap area is randomized from a log normal distribution with  $\mu = 0.1$  and  $\sigma = 0.039$  (Navarro-Martinez et al. 2017). The simulator then adds seedlings of *Swietenia* to the open area at a density of 2,000 plants per hectare. To simulate the preference of *Swietenia* to sunlight, seedlings inside enrichment gaps grow at a higher rate than outside gaps with a diameter growth distribution of  $\mu = 0.039$  and  $\sigma = 0.31$ .

### **Timber Volumes and Above-Ground Biomass**

Harvested tree volumes ( $V_T$ , m<sup>3</sup>) from harvested trees are estimated using a model for *Swietenia* (Equation 4-1) and a general model for the rest of the species (Equation 4-2). The following models, first reported by Alder (1997), are used in the region for the estimates of the tree volume.

$$VT_{Sw} = 0.05055 + 0.000047705 \text{ DBH}^2H \quad (4-1)$$

$$VT_x = 0.00842 + 0.000050894 \text{ DBH}^2H \quad (4-2)$$

where H is the total height of the tree in m.

Tree above-ground biomass is estimated using Chave et al. (2014) with species' wood densities from the Global Wood Density Database (Chave et al. 2009; Zanne et al. 2009). Tree volumes and above-ground biomass are added to find the stand harvested volumes (VOL, m<sup>3</sup> ha<sup>-1</sup>) and above-ground biomass (AGB, Mg C ha<sup>-1</sup>)

### **Definition of Scenarios**

In order to evaluate the proposed model, five scenarios were simulated to represent business as usual, hurricane mortality and ideal RIL conditions. The scenarios are detailed in Table 4-4. All scenarios ran for 40 years with a 25-year rotation cycle with directional felling. The scenarios ran for 100 iterations to obtain prediction distributions given the presence of the stochastic submodels. Also, each iteration randomizes the initial trees in the forest.

## **Results and Discussion**

### **Number of Extracted Trees and Volume**

BAU scenarios can extract between 5–15 trees ha<sup>-1</sup> and 7–20 m<sup>3</sup> ha<sup>-1</sup> of VOL during the first rotation cycle. For the same period, RIL-B and RIL-WB scenarios had annual harvests of between 3–6 trees ha<sup>-1</sup> corresponding to 2–7 m<sup>3</sup> ha<sup>-1</sup> of timber volume. These extraction rates for RIL scenarios are common for RIL managed forests. For instance, harvest rates in Amazonian and Guyana studies averaged 3.6 and 2.5 trees ha<sup>-1</sup>, respectively (Miller et al. 2011; Arevalo et al. 2016). All simulations had very low or no harvested trees after the first rotation cycle, suggesting that the growth and recruitment rates assumed in this study are too low to allow for maintenance of species populations in BAU or RIL scenarios. It is important to note that the simulated growth rates for the species are in use by the forest communities in Quintana Roo.

Management plans in the region for mahogany assume a mean DBH growth of MAI of

0.73 cm year<sup>-1</sup> (Negreros-Castillo and Mize 2014), which would result in a tree reaching the MCD of 55 cm in 75 years.

### **Changes in Timber Basal Area and Aboveground Biomass**

BAU scenarios showed lower values of annual changes of BA ( $\Delta$ BA) during the first rotation than RIL scenarios (Figure 4-3 C). For the first 25 years of management, BAU scenarios had a  $\Delta$ BA in the range of -0.05 to -0.15 m<sup>2</sup> ha<sup>-1</sup> year<sup>-1</sup>. Similar annual rates of  $\Delta$ BA were measured in in control and commercial cut stands (Mize and Negreros-Castillo 2007). After the first cycle, BAU-B had almost the same BA than the BAU scenario. This difference was maintained until the 40th simulation year; however, the  $\Delta$ BA seem to level after the first cycle. RIL-B and RIL-WB scenarios had  $\Delta$ BA between -0.03 to -0.1 m<sup>2</sup> ha<sup>-1</sup> year<sup>-1</sup>. RIL-B and RIL-WB scenarios ended the first cycle with 1.05 and 1.14 m<sup>2</sup> ha<sup>-1</sup> of BA more than the BAU scenario (Table 4-5).

In terms of AGB, BAU scenarios had annual changes of AGB ( $\Delta$ AGB) between -1.5 to -0.06 Mg C ha<sup>-1</sup> year<sup>-1</sup>. RIL scenarios had lower losses of AGB with  $\Delta$ AGB between -0.1–0 Mg C ha<sup>-1</sup> year<sup>-1</sup>. At the end of the first cycle, AGB for RIL-B and WIL-WB scenarios was more than 6 Mg C ha<sup>-1</sup> higher than the BAU scenario. If we consider that forests of central Quintana Roo have 110–225 Mg C ha<sup>-1</sup> (Cairns et al. 2000; 2003), going from BAU to RIL scenarios could avoid between 2–5% of emissions in 25 years

### **Hurricane Effects**

After the first cycle, the hurricane had 1.05 m<sup>2</sup> ha<sup>-1</sup> less BA than the BAU scenario. This estimate is in line with experimental plots in the region where BA measured basal area was reduced between 0.1–1.4 m<sup>2</sup> ha<sup>-1</sup> after Hurricane Dean (Navarro-Martinez et al. 2012). For the simulations, this difference between BAU and

BAU-H was reduced from  $-1.05$  to  $0.82 \text{ m}^2 \text{ ha}^{-1}$  15 years after the hurricane due to the higher number of seedlings recruited in the stands.

For AGB, BAU-H had  $6.33$  and  $5.05 \text{ Mg C ha}^{-1}$  less AGB than the BAU scenario 5 and 20 years after the hurricane. BAU-H had maximum reduction of  $2.5 \text{ Mg C ha}^{-1}$ , which could mean a reduction of 2% of the AGB for stands in Quintana Roo. These losses of AGB can increase if coarse woody debris is considered (Whigham et al. 1991).

### **Model Limitations**

An important limitation of this model is that it does not consider components such as competition, canopy openness or climatic conditions for many processes. For instance, sun-tolerant large tree species such as *Manilkara*, can have higher growth rates related to canopy openness in open stands and result in higher  $\Delta\text{BA}$ . The simulation is also limited since only considers eleven species of the more 50 commercially species used in Quintana Roo (Sierra-Huelsz et al. 2017). Future improvements of the model should attempt to solve some of these limitations.

The correlation that the simulation uses between canopy cover and basal area is not validated and should be studied further, perhaps with a model for canopy openness. The use of this method is defended because the study by Toledo-Aceves et al. (2009) considers more species than any other study in Quintana Roo. Further advancement of simulations depends on updated studies on recruitment rates.

### **Conclusion**

The publicly available simulator together with its computer code gives the opportunity to further explore more scenarios than those considered in this study. In this study, the evaluated simulations showed that the current 25-year cycle is not enough for

a complete basal area recovery even after 40 years after tree harvest even when RIL parameters are considered. The simulation results suggest there is a need to change the management from business as usual if there is the objective to have constant harvesting of trees.

The scenarios simulated for this study are just a few of the many possible scenarios that can be projected with this system. The simulator can be used to further evaluate the effects of extending cutting cycles, enhancement of tree growth or enrichment with multiple species.

Table 4-1. Selected literature for the forests of Quintana Roo and the Yucatan Peninsula

Study	Description
<b>Growth</b>	
Alder (1997, 1998)	Growth rates and volume equations and for several timber species.
Negreros-Castillo and Martínez-Salazar (2011)	Annual increment rates from <i>Lysiloma latisiquum</i> trees.
<b>Recruitment</b>	
Alder (1997)	Number of seedlings per hectare recruited every 4 years.
Toledo-Aceves et al. (2009)	Regeneration rates for 22 commercial tree species in plots with different canopy openings, disturbances conditions such as log landings, skid trails and roads.
<b>Mortality</b>	
Mize and Negreros-Castillo (2007)	Species presented annual mortality probabilities from 0.2–3.7%.
Negreros-Castillo and Mize (2014)	1% annual mortality probability using seven years of measurements.
<b>Hurricane mortality</b>	
Bitrán Bitrán (2001)	Official figures of damaged forest hectares from Hurricanes Gilbert, Roxanne and Opal.
Navarro-Martinez et al. (2012)	Estimates of types of hurricane stand and tree damage. Hurricane Dean reduced stand BA from 0.1 to 1.4 m <sup>2</sup> ha <sup>-1</sup> . Smaller DBH trees have a greater probability of mortality.
McGroddy et al. (2013)	After Hurricane Dean, an average of 49% of the trees had no or little damage. 57% of the trees had damages.
Whigman et al. (1991)	Estimates of mortality after Hurricane Gilbert. Measured that larger trees had lower mortality probabilities
<b>Silviculture and RIL</b>	
Cairns et al. (2003)	Estimates of AGB in permanent forest areas.
Mize and Negreros-Castillo (2007)	Experimented with basal area reduction plots and measured growth for 25 canopy and subcanopy species in X-Hazil.
Navarro-Martinez et al. (2017)	Areas of enrichment gaps and survival progrowth rates of <i>Swietenia macrophylla</i> inside these.
Sierra-Huelsz et al. (2017)	Evolution of management and use of polewood, thatching materials and chicozapote tree ( <i>Manilkara zapota</i> ) posts
Snook and Negreros-Castillo (2004)	Analysis of diameter and height growth has also been analyzed for seedling inside felling gaps.

Table 4-2. Species and common names considered in the simulation

Species	Common local name
<i>Brosimum alicastrum</i> Sw.	Ramon
<i>Bursera simaruba</i> (L.) Sarg.	Chaka rojo
<i>Dendropanax arboreus</i> (L.) Decne. & Planch.	Chaka blanco
<i>Lysiloma latisiliquum</i> (L.) Benth.	Tzalam
<i>Manilkara zapota</i> (L.) P. Royen	Chicozapote
<i>Metopium brownei</i> (Jacq.) Urb.	Chechem
<i>Piscidia piscipula</i> (L.) Sarg.	Jabin
<i>Pouteria unilocularis</i> (Donn. Sm.) Baehni	Zapotillo
<i>Simarouba glauca</i> DC.	Paasak
<i>Swartzia cubensis</i> (Britton & P. Wilson) Standl.	Katalox
<i>Swietenia macrophylla</i> King	Caoba

Table 4-3. Hurricane categories annual occurrence probability and associated percentage of mortality by tree DBH

Hurricane category	Annual occurrence probability	Mortality	
		DBH < 20 cm	DBH > 20 cm
3	30%	10%	20%
4	20%	20%	30%
5	10%	30%	40%

Table 4-4. Characteristics of the scenarios simulated in this study. All scenarios ran for 40 years using a 25-year rotation cycle with directional felling and for 100 iterations

Scenario	Harvesting intensity	Gap enrichment	Cable yarding	Hurricane
BAU	50%	No	No	-
BAU-B	50%	Yes	No	-
BAU-H	50%	No	No	Cat. 5, at year 20
RIL-B	25%	Yes	No	-
RIL-WB	25%	Yes	Yes	-

Note. BAU: business as usual, RIL: reduced-impact-logging, B: gap enrichment (*bosquetes*), H: hurricanes and W: cable yarding (winching)

Table 4-5. Basal area (BA) and aboveground biomass (AGB) mean differences from the BAU scenario after 10, 25 and 40 years of simulation

Scenario	Years	BA (m <sup>2</sup> ha <sup>-1</sup> )			AGB (Mg C ha <sup>-1</sup> )		
		10	25	40	10	25	40
BAU-B		0.02	0.03	0.03	0.06	-0.05	-0.05
BAU-H		0.01	-1.05	-0.82	0.04	-6.33	-5.05
RIL-B		0.45	1.05	1.07	2.64	6.17	6.37
RIL-WB		0.51	1.14	1.15	2.92	6.51	6.67

Note. BAU: business as usual, RIL: reduced-impact-logging, B: gap enrichment (*bosquetes*), H: hurricanes and W: cable yarding (winching)

Figure 4-1. Map of the south and central municipalities of Quintana Roo

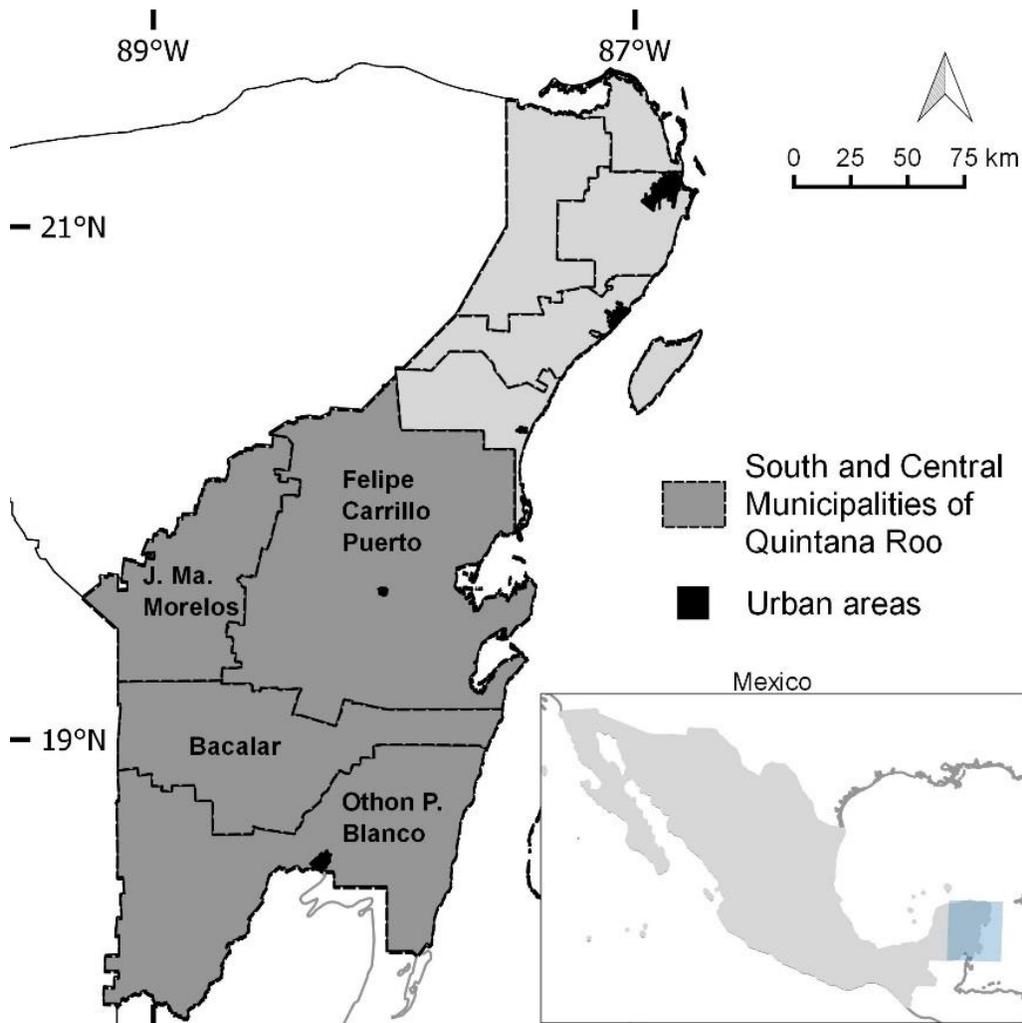


Figure 4-2. Dragging mortality and cable yarding. Small trees (DBH < 20 cm) between the harvested tree and the road are killed due to dragging. If a yarding cable is used, there is avoided mortality

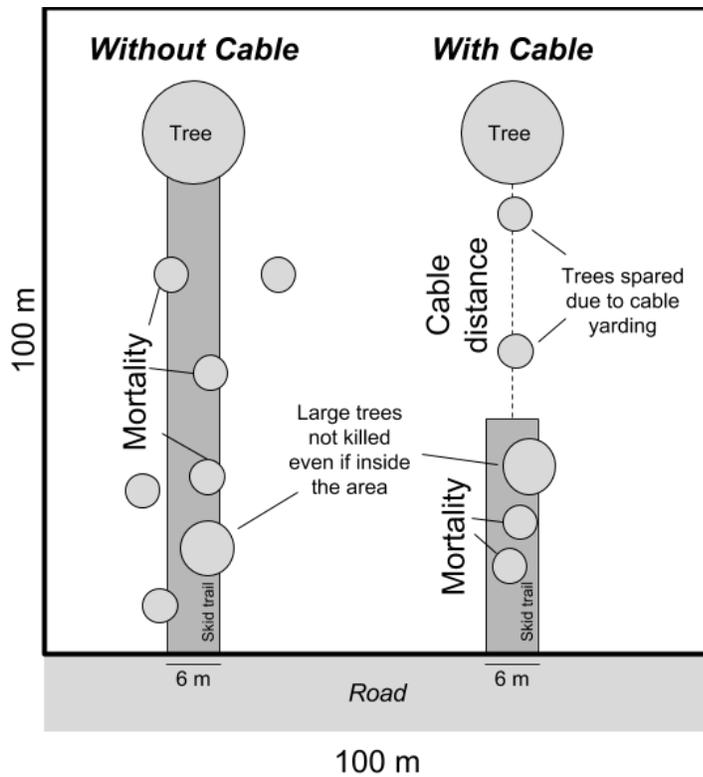
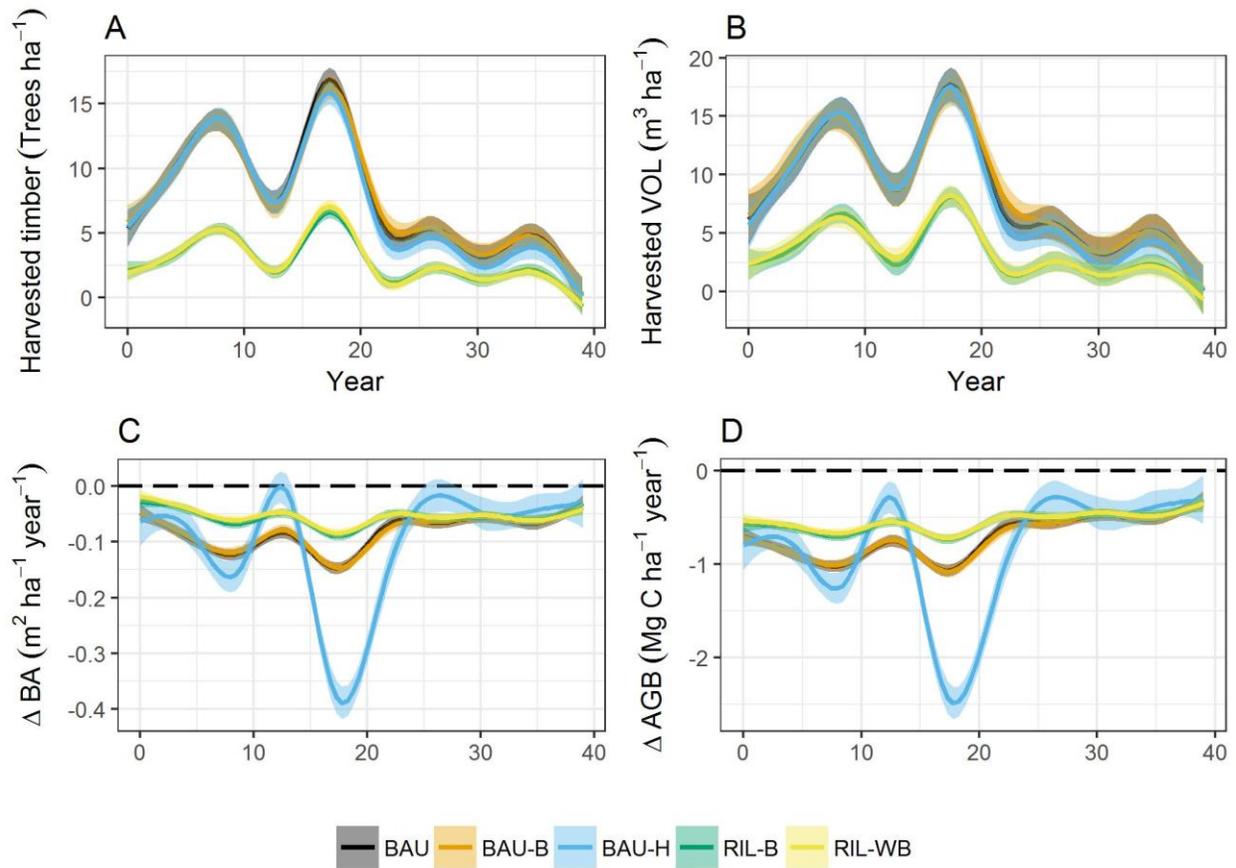


Figure 4-3. (A) harvested trees, (B) harvested volume (VOL, m<sup>3</sup>), (C) annual change in timber basal area ( $\Delta$ BA, m<sup>2</sup>), and (D) annual change aboveground timber biomass ( $\Delta$ AGB, Mg C ha<sup>-1</sup>) trajectories for the five considered scenarios



## CHAPTER 5 CONCLUSIONS AND SUMMARY

The models reported in this study constitute simple and valuable tools to support management decision for forest resources in southern Chile and Quintana Roo, Mexico. In both sites, the models can be used as part of cost-benefit analyses to promote sustainable yields and decrease deforestation and degradation pressures.

Models in Chapter 2 can predict when the basal area has such a reduced growth that the cost of maintaining the forest is higher than the incomes from a timber sale. The mortality model can be used to project how a thinning or selective harvest can reduce the tree mortality and promote basal area growth. Thinning is a silvicultural strategy that, if accurately planned, can significantly increase the value of these forests. The model for the proportion of number of *Nothofagus* trees is important to predict the cohort dominance, an important characteristic in any mixed forests.

The models presented in Chapter 3 answer frequently asked questions in forest management, such as: how accurate are the existing G&Y models? And, how can we improve future predictions? The validation of the models presented in Chapter 3 is certainly not exhaustive because the validation dataset does not represent the entire range of the RORACO forest type and does not include a long span of measurements and all species. However, it does show that the models accurately predict future stand basal area conditions within the range of parameters of the fitting dataset and, crucially, that the models are sound and appropriate to use in *Nothofagus* forests. Answering the second question, the Proportional Yield and Proportional Growth methods resulted in better predictions for basal area than unadjusted stand- and individual-level models. This encourages forest professionals to make use of these compatibility methods to

improve the predictions of existing models for *Nothofagus* forest or any other G&Y with mixed forest.

Since, validation is a crucial step for effective evaluation of forest growth models (Vanclay and Skovsgaard 1997), the models in Chapter 2 and 3 are validated against independent data resulting in high goodness-of-fit (higher than with the training data). This high goodness-of-fit does not imply that the final statistical models are “correct” or, in other words, completely valid; however, they are reasonable and are a faithful representation of the dynamics of the systems they model.

Developers of forest management plans may have the problem of selecting and implement silvicultural practices depending on its cost and potential analysis of benefits. Chapter 4 deals with the problem of estimating carbon emissions as a consequence of the implementation of different silvicultural practices in the context of mixed forests. This estimate is necessary when to calculate payments from the reduction in carbon emissions (e.g. REDD+ programs). The simulations presented in Chapter 4 also give the opportunity to include models that require information on each tree. For instance, a module can be added that predicts the response of a tree to plot conditions such soil nutrients. Because the model records the position each tree in the plot; a module can be added that estimates tree responses to a local condition such as canopy openness.

It is important to note the models reported in this study require stand or individual parameters that come directly (or easily estimated) from forest inventories. Therefore, their use is not restricted to forests with a high investment in research and are not highly complex in their mathematical methods. The online interactive simulations available

from this study for the *Nothofagus* and Maya forests also represent an effort to broaden the access to the final research products.

Many improvements can be made to these models reported in this study. Further model validations can be done because of the advances in technology that are now increasing the amount of forest data available (e.g. remote sensing products). Validating and fitting models with the inclusion of information with higher spatial and temporally significance can increase the accuracy of the models. Also, Bayesian statistics is a technique that is appropriate for this improvement.

The construction of the simulation models using submodels gives the possibility of adding more submodules to increase the realism of the system. For instance, realism can be improved with submodels of competition models that take into account species' light preferences or one for the response to climate change scenarios.

Sensitivity analysis is another important improvement that can be done with the simulation systems presented in this study. Sensitivity analyses estimates how the variation in the output of a numerical model can be attributed to variations of its input factors (Pianosi et al. 2016). For instance, an analysis could be done to estimate how much the site index affects the final basal area projections This sensitivity analysis can provide information on model uncertainty and validity of the evaluated models.

One of the characteristics that makes the models reported in this study easy to improve is the availability of the code and interactive simulations. Open source code can make science reproducible, facilitate and accelerate research and improvements by other scientists (Hampton et al. 2015; Mislán et al. 2016). The code in this study is written in R, a language that has had increased its importance in research on

agricultural and biological sciences (Tippmann 2015). The author of this study encourages other scientists to use and improve the published code and simulators in their own research.

APPENDIX  
ANALYSIS OF MEAN ANNUAL INCREMENTS AND RECRUITMENT DATA FOR  
SPECIES IN QUINTANA ROO, MEXICO

The Nature Conservancy (TNC) installed dendrometer bands in several ejidos in the Yucatan Peninsula. This appendix uses the data collected by these permanent dendrometer bands to estimate mean annual increments of important and lesser known species in the Yucatan Peninsula. The growth rates estimated in this study will then be used to calibrate an individual-tree model for forest management in the Yucatan Peninsula.

A total of 5,073 diameter were installed in 2007 and 2014 in 7 ejidos of the Yucatan Peninsula. Two bands projects were established: Purata and Snook. The Purata project installed bands on *Bursera simarouba*, *Dendropanax arboreous*, *Lonchocarpus castilloi*, *Lysiloma latisiliquum*, *Manilkara zapota*, *Metopium brownei*, *Piscidia piscipula*, *Platymiscium yucatanum* and *Swietenia macrophylla*. The Snook project installed bands on 84 lesser studied species. For this short study, only those species with more than 30 individuals measured were analyzed for mean annual increment. The Snook project included measurements of trees in areas with several treatments: partial clearing such as mechanic, and slash and burn. Table A-1 summarizes the means, standard error of the mean and ranges of diameter growth using the bands.

The growth rates reported in this Appendix are simple mean annual increments found from different bands installed in the region. It is evident that these growth rates cannot be generalized to the whole region. Further analysis with more sophisticated statistical methods will need more diameter measurements and environmental data from the study sites.

Table A-1. Summary of the mean diameter growth (standard error) and range of by species from the TNC diametric bands

Species	n	Mean (SE)	Range
<i>Bursera simarouba</i>	374	0.17 (-0.01)	-0.19 – 1.30
<i>Croton reflexifolius</i>	119	0.16 (-0.01)	-0.1 – 0.58
<i>Dendropanax arboreus</i>	109	0.34 (-0.03)	0.00 – 1.46
<i>Guettarda combsii</i>	208	0.11 (-0.01)	-0.13 – 0.73
<i>Gymnantes lucida</i>	105	0.09 (-0.01)	-0.19 – 0.43
<i>Lonchocarpus castilloi</i>	119	0.37 (-0.03)	0.00 – 1.11
<i>Lysiloma latisiliquum</i>	588	0.32 (-0.01)	-0.44 – 1.49
<i>Manilkara zapota</i>	221	0.12 (-0.01)	-0.03 – 0.76
<i>Metopium brownei</i>	107	0.35 (-0.02)	0.00 – 0.93
<i>Nectandra coriacea</i>	287	0.16 (-0.01)	-0.19 – 0.91
<i>Piscidia piscipula</i>	297	0.13 (-0.01)	-0.12 – 0.81
<i>Pouteria unilocularis</i>	71	0.17 (-0.02)	-0.07 – 0.59
<i>Sebastiania adenophora</i>	115	0.20 (-0.02)	-0.29 – 1.11
<i>Swietenia macrophylla</i>	68	0.39 (-0.04)	0.00 – 1.27
<i>Vitex gaumerii</i>	159	0.19 (-0.02)	-0.26 – 1.36
All	4,497	0.18 (0.00)	-0.49 – 1.49

Table A-2. Average number of new recruits by hectare for species depending on percentage of stand canopy cover or timber basal area (BA). Data from Toledo-Aceves et al. (2009)

Species	Canopy cover (%)	50	60	65	70	75	80	85	Mean
	BA ( $m^2 ha^{-1}$ )	1	2	3	4	5	6	7	
<i>Brosimum alicastrum</i>		0.0	0.0	12.3	10.8	14.1	19.9	14.5	9.0
<i>Bursera simarouba</i>		25.0	0.0	84.3	218.6	13.8	10.8	2.8	44.4
<i>Dendropanax arboreus</i>		0.0	66.7	82.1	31.5	59.6	30.5	23.5	36.7
<i>Manilkara zapota</i>		0.0	13.8	81.1	165.8	200.9	212.2	219.9	111.7
<i>Metopium brownei</i>		0.0	242.9	53.4	37.9	12.6	3.8	6.4	44.6
<i>Simarouba glauca</i>		0.0	49.0	44.0	9.3	10.4	13.1	5.7	16.5
<i>Swartzia cubensis</i>		8.3	0.0	0.0	3.2	9.4	8.5	21.3	6.3
<i>Swietenia macrophylla</i>		0.0	19.8	2.6	10.3	5.7	1.4	0.0	5.0
Mean from all species		-	-	-	-	-	-	-	49.0

## LIST OF REFERENCES

- Akaike, H. 1998. Information theory and an extension of the maximum likelihood principle. In Selected papers of Hirotugu Akaike. Edited by Parzen, E., Tanabe, K., Kitagawa, G. Springer, New York, NY. pp. 199–213. doi:[10.1007/978-1-4612-1694-0\\_15](https://doi.org/10.1007/978-1-4612-1694-0_15).
- Alder, D. 1997. Report on a consultancy to the Quintana Roo forest management project. Tech. rep., Denis Alder (Consulting) Ltd.
- Asner, G.P., Rudel, T.K., T, Mitchell A, DeFries R, Emerson RTH. 2009. A contemporary assessment of change in humid tropical forests. *Conserv. Biol.* **23**(6):1386–1395. doi:[10.1111/j.1523-1739.2009.01333.x](https://doi.org/10.1111/j.1523-1739.2009.01333.x).
- Avery, T.E., Burkhart, H.E. 2002. *Forest measurements*. 5th ed. McGraw-Hill, New York, USA.
- Baccini, A., Walker, W., Carvalho, L., Sulla-Menashe, D., Houghton, R.A. 2017. Tropical forests are a net carbon source based on aboveground measurements of gain and loss. *Science*:10.1126/science.aam5962. doi:[10.1126/science.aam5962](https://doi.org/10.1126/science.aam5962).
- Baskerville, G.L. 1972. Use of logarithmic regression in the estimation of plant biomass. *Can. J. For. Res.* **2**(1):49–53. doi:[10.1139/x72-009](https://doi.org/10.1139/x72-009).
- Bicknell, J.E., Struebig, M.J., Davies, Z.G. 2015. Reconciling timber extraction with biodiversity conservation in tropical forests using reduced-impact logging. *J. Appl. Ecol.* **52**(2):379–388. doi:[10.1111/1365-2664.12391](https://doi.org/10.1111/1365-2664.12391).
- Bitrán Bitrán, D. 2001. Características del impacto socioeconómico de los principales desastres ocurridos en México en el periodo 1980–99. Sistema Nacional de Protección Civil, CENAPRED, Mexico City, Mexico.
- Black, A.J., McKane, A.J. 2012. Stochastic formulation of ecological models and their applications. *Trends Ecol. Evol.* **27**(6):337–345. doi:[10.1016/j.tree.2012.01.014](https://doi.org/10.1016/j.tree.2012.01.014).
- Blaser, J., Sarre, A., Poore, D., Johnson, S. 2011. *Status of Tropical Forest Management 2011*. International Tropical Timber Organization, Yokohama, Japan.
- Bryan, J.E., Shearman, P.L., Asner, G.P., Knapp, D.E., Aoro, G., Lokes, B. 2013. Extreme differences in forest degradation in Borneo: Comparing practices in Sarawak, Sabah, and Brunei. *PLoS ONE* **8**(7):e69679. doi:[10.1371/journal.pone.0069679](https://doi.org/10.1371/journal.pone.0069679).
- Cairns, M.A., Haggerty, P.K., Alvarez R., de Jong, B.H.J., Olmsted, I. 2000. Tropical Mexico's recent land-use change: a region's contribution to the global carbon cycle. *Ecol. Appl.* **10**(5):1426–1441. doi:[10.1890/1051-0761\(2000\)010\[1426:TMSRLU\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2000)010[1426:TMSRLU]2.0.CO;2).

- Cairns, M.A., Olmsted, I., Granados, J., Argaez, J. 2003. Composition and aboveground tree biomass of a dry semi-evergreen forest on Mexico's Yucatan Peninsula. *For. Ecol. Manage.* **186**(1–3): 125–132. doi:[10.1016/S0378-1127\(03\)00229-9](https://doi.org/10.1016/S0378-1127(03)00229-9).
- Cao, Q.V. 2006. Predictions of individual-tree and whole-stand attributes for loblolly pine plantations. *For. Ecol. Manage.* **236**(2):342–347. doi:[10.1016/j.foreco.2006.09.019](https://doi.org/10.1016/j.foreco.2006.09.019).
- Cao, Q.V. 2014. Linking individual-tree and whole-stand models for forest growth and yield prediction. *For. Ecosyst.* **1**(1):18. doi:[10.1186/s40663-014-0018-z](https://doi.org/10.1186/s40663-014-0018-z).
- Cao, Q.V. 2017. An integrated system for modeling tree and stand survival. *Can. J. For. Res.* **47**(10):1405–1409. doi:[10.1139/cjfr-2017-0229](https://doi.org/10.1139/cjfr-2017-0229).
- Cao, Q.V., Baldwin, V.C. 1999. A new algorithm for stand table projection models. *For. Sci.* **45**(4):506–511.
- Chauchard, L., Sbrancia, R. 2003. Modelos de crecimiento diamétrico para *Nothofagus obliqua*. *Bosque* **24**(3):3–16. doi:[10.4067/S0717-92002003000300001](https://doi.org/10.4067/S0717-92002003000300001).
- Chauchard, L., Sbrancia R., Gonzalez M., Maresca. L, Rabino. A, Mazzuchelli. M. 2001. Aplicación de leyes fundamentales de la densidad a bosques de *Nothofagus*: Línea de inicio de competencia y diagramas de manejo de la densidad. *Bosque* **22**(1):3–10.
- Chave, J., Coomes, D.A., Jansen, S., Lewis, S.L., Swenson, N.G., Zanne, A.E. 2009 Towards a worldwide wood economics spectrum. *Ecology Letters* **12**(4):351–366. doi:[10.1111/j.1461-0248.2009.01285.x](https://doi.org/10.1111/j.1461-0248.2009.01285.x).
- Chave, J., Rejou-Mechain, M., Burquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B., Duque, A., Eid, T., Fearnside, P.M., Goodman, R.C., Henry, M., Martínez-Yrizar, A., Mugasha, W.A., Muller-Landau, H.C., Mencuccini, M., Nelson, B.W., Ngomanda, A., Nogueira, E.M., Ortiz-Malavassi, E., Pélissier, R., Ploton, P., Ryan, C.M., Saldarriaga, J.G., Vieilledent, G. 2014 Improved allometric models to estimate the aboveground biomass of tropical trees. *Glob. Chang. Biol.* **20**(10):3177–3190. doi:[10.1111/gcb.12629](https://doi.org/10.1111/gcb.12629).
- Clutter, J.L. 1963. Compatible growth and yield models for loblolly pine. *For. Sci.* **9**(3):354–371.
- Clutter, J.L., Forstson, J.C., Pienaar, L.V., Brister, G.H., Bailey, R.L. 1983. Timber management: a quantitative approach. John Wiley & Sons, New York, USA.
- CONAF. 2011. Catastro de los Recursos Vegetacionales Nativos de Chile: Monitoreo de Cambios y Actualizaciones, Periodo 1997 – 2011. CONAF, Ministerio de Agricultura, Chile.

- CONAF, CONAMA, BIRF. 1999. Catastro y evaluación de los recursos vegetacionales nativos de Chile. Corporación Nacional Forestal, Chile (CONAF), Comisión Nacional del Medio Ambiente, Chile (CONAMA), Banco Internacional de Reconstrucción y Fomento, USA (BIRF), Universidad Austral de Chile, Pontificia Universidad Católica de Chile, Universidad Católica de Temuco, Ministerio de Agricultura, Chile.
- CONAFOR. 2008. Inventario Nacional Forestal y de Suelos, Informe Preliminar 2007. Comisión Nacional Forestal, Mexico (CONAFOR), Zapopan, Mexico.
- Cusack, D.F., Karpman, J., Ashdown, D., Cao, Q., Ciochina, M., Halterman, S., Lydon, S., Neupane, A. 2016. Global change effects on humid tropical forests: Evidence for biogeochemical and biodiversity shifts at an ecosystem scale. *Rev. Geophys.* **54**(3):523–610. doi:[10.1002/2015RG000510](https://doi.org/10.1002/2015RG000510).
- Danescu, A., Albrecht, A.T., Bauhus, J. 2016. Structural diversity promotes productivity of mixed, uneven-aged forests in southwestern Germany. *Oecologia* **182**(2):319–333. doi:[10.1007/s00442-016-3623-4](https://doi.org/10.1007/s00442-016-3623-4).
- Donoso, P.J., Lusk, C.H. 2007. Differential effects of emergent *Nothofagus dombeyi* on growth and basal area of canopy species in an old-growth temperate rainforest. *J. Veg. Sci.* **18**(5):675–684. doi:[10.1111/j.1654-1103.2007.tb02581.x](https://doi.org/10.1111/j.1654-1103.2007.tb02581.x).
- Donoso, P.J., Donoso, C., Sandoval, V. 1993. Proposición de zonas de crecimiento de renovales de roble (*Nothofagus obliqua*) y raulí (*Nothofagus alpina*) en su rango de distribución natural. *Bosque* **14**(2):37–55.
- Donoso, P.J., Soto, D.P. 2016. Does site quality affect the additive basal area phenomenon? Results from Chilean old-growth temperate rainforests. *Can. J. For. Res.* **46**(11):1330–1336. doi:[10.1139/cjfr-2016-0167](https://doi.org/10.1139/cjfr-2016-0167).
- Donoso, P.J., Soto, D.P., Gerding, V. 2009. Efectos de la poda de tallo y fertilización de liberación controlada en vivero sobre el comportamiento de plántulas de *Nothofagus nervosa* en terreno. *Bosque* **30**(1):48–53. doi:[10.4067/S0717-92002009000100007](https://doi.org/10.4067/S0717-92002009000100007).
- Donoso, P.J., Soto, D.P., Coopman, R.E., Rodriguez-Bertos, S. 2013. Early performance of planted *Nothofagus dombeyi* and *Nothofagus alpina* in response to light availability and gap size in a high-graded forest in the south-central Andes of Chile. *Bosque* **34**(1):23–32. doi:[10.4067/S0717-92002013000100004](https://doi.org/10.4067/S0717-92002013000100004).
- Donoso, P.J., Soto, D.P., Fuentes, C. 2015. Differential growth rates through the seedling and sapling stages of two *Nothofagus* species underplanted at low-light environments in an Andean high-graded forest. *New For.* **46**(5):885–895. doi:[10.1007/s11056-015-9480-x](https://doi.org/10.1007/s11056-015-9480-x).

- Echeverria, C., Lara, A. 2004. Growth patterns of secondary *Nothofagus obliqua*-*N. alpina* forests in southern Chile. For. Ecol. Manage. **195**(12):29–43. doi:[10.1016/j.foreco.2004.02.034](https://doi.org/10.1016/j.foreco.2004.02.034).
- Ellis, E.A., Kainer, K.A., Sierra-Huelsz, J.A., Negreros-Castillo, P., Rodríguez-Ward, D., DiGiano, M. 2015. Endurance and adaptation of community forest management in Quintana Roo, Mexico. Forests **6**(11):4295–4327. doi:[10.3390/f6114295](https://doi.org/10.3390/f6114295).
- Ellis, E.A., Kainer, K.A., Sierra-Huelsz J.A., Negreros-Castillo, P. 2014. Community-based forest management in Quintana Roo. In: Katila, P., WD J, Pacheco, P., Mery, G. (eds) Forests Under Pressure: Local Responses to Global Issues, International Union of Forest Research Organizations, pp 131–151.
- Esse, C., Donoso, P.J., Gerding, V., Encina-Montoya, F. 2013. Determination of homogeneous edaphoclimatic zones for the secondary forests of *Nothofagus dombeyi* in central-southern Chile. Ciencia e Investigación Agraria **40**(2):351–360. doi:[10.4067/S0718-16202013000200010](https://doi.org/10.4067/S0718-16202013000200010).
- Esse, C., Donoso, P.J., Gerding, V., Navarro, C., Encina-Montoya, F. 2014. Modelling dominant height and site index in different edaphoclimatic zones of *Nothofagus dombeyi* secondary forest in the Andes of south-central Chile. Southern For. **76**(4):221–228. doi:[10.2989/20702620.2014.956026](https://doi.org/10.2989/20702620.2014.956026).
- Filotas, E., Parrott, L., Burton, P.J., Chazdon, R.L., Coates, K.D., Coll, L., Haeussler, S., Martin, K., Nocentini, S., Puettmann, K.J., Putz, F.E., Simard, S.W., Messier, C. 2014. Viewing forests through the lens of complex systems science. Ecosphere **5**(1):1–23. doi:[10.1890/ES13-00182.1](https://doi.org/10.1890/ES13-00182.1).
- Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K. 2005. Global consequences of land use. Science **309**(5734):570. doi:[10.1126/science.1111772](https://doi.org/10.1126/science.1111772).
- Gadow, K., Hui, G. 1999. Modelling Forest Development. Springer, Dordrecht, Netherlands.
- Gezan, S.A., Moreno, P. 1999. Establecimiento y medición de una red de parcelas permanentes para renovales de roble (*Nothofagus obliqua*), raulí (*Nothofagus alpina*) y coigüe (*Nothofagus dombeyi*). Bosque Nativo **22**:9–11.
- Gezan, S.A., Ortega, A. 2001. Desarrollo de un simulador de rendimiento para renovales de roble, raulí y coigüe. FONDEF D97I1065. Universidad Austral de Chile, Chile.
- Gezan, S.A., Ortega, A., Andenmatten, E. 2007. Diagramas de manejo de densidad para renovales de roble, raulí y coigüe en Chile. Bosque **28**(2):97–105. doi:[10.4067/S0717-92002007000200002](https://doi.org/10.4067/S0717-92002007000200002).

- Gezan, S.A., Moreno, P., Ortega, A. 2009. Modelos fustales para renovales de roble, raulí y coigue en Chile. *Bosque* **30**(2):61–69. doi:[10.4067/S0717-92002009000200001](https://doi.org/10.4067/S0717-92002009000200001).
- Gourlet-Fleury, S., Mortier, F., Fayolle, A., Baya, F., Ouédraogo, D., Bénédet, F., Picard, N. 2013. Tropical forest recovery from logging: a 24 year silvicultural experiment from Central Africa. *Philos. Trans. R. Soc. B* **368**:20120302. doi:[10.1098/rstb.2012.0302](https://doi.org/10.1098/rstb.2012.0302).
- Grosse, H., Cubillos, V. 1991. Antecedentes generales para el manejo de renovales de rauli, roble, coigüe y tepa. 127, Instituto Forestal.
- Haefner, J. 1996. *Modeling Biological Systems: Principles and Applications*. Chapman & Hall, New York, USA.
- Hampton, S.E., Anderson, S.S., Bagby, S.C., Gries, C., Han, X., Hart, E.M., Jones, M.B., Lenhardt, W.C., MacDonald, A., Michener, W.K. 2015. The Tao of open science for ecology. *Ecosphere* **6**(7):1–13. doi:[10.1890/ES14-00402.1](https://doi.org/10.1890/ES14-00402.1).
- Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., Townshend, J.R.G. 2013. High-resolution global maps of the 21st-century forest cover change. *Science* **342**(6160):850–853. doi:[10.1126/science.1244693](https://doi.org/10.1126/science.1244693).
- Heilmayr, R., Echeverría, C., Fuentes, R., Lambin, E.F. 2016. A plantation-dominated forest transition in Chile. *Appl. Geogr.* **75**:71–82. doi:[10.1016/j.apgeog.2016.07.014](https://doi.org/10.1016/j.apgeog.2016.07.014).
- Hevia, A., Cao, Q.V., Ivarez Gonzalez, J.G., Ruiz-González, A.D., Gadow, K. 2015. Compatibility of whole-stand and individual-tree models using composite estimators and disaggregation. *For. Ecol. Manage.* **348**:46–56. doi:[10.1016/j.foreco.2015.03.035](https://doi.org/10.1016/j.foreco.2015.03.035).
- INFOR. 2016. *Bosque Nativo, Boletín 12. Área de Información y Economía Forestal*, INFOR, Ministerio de Agricultura, Chile.
- Kleinschroth, F., Healey, J.R. 2017. Impacts of logging roads on tropical forests. *Biotropica* **49**(5):620-635. doi:[10.1111/btp.12462](https://doi.org/10.1111/btp.12462).
- Liu, J., Ashton, P.S. 1995. Individual-based simulation models for forest succession and management. *For. Ecol. Manage.* **73**(1):157–175. doi:[10.1016/0378-1127\(94\)03490-N](https://doi.org/10.1016/0378-1127(94)03490-N).
- Lusk, C.H., Ortega, A. 2003. Vertical structure and basal area development in second-growth *Nothofagus* stands in Chile. *J. Appl. Ecol.* **40**(4):639–645. doi:[10.1046/j.1365-2664.2003.00827.x](https://doi.org/10.1046/j.1365-2664.2003.00827.x).

- Lussetti, D., Axelsson, E.P., Ilstedt, U., Falck, J., Karlsson, A. 2016. Supervised logging and climber cutting improves stand development: 18 years of post-logging data in a tropical rain forest in Borneo. *For. Ecol. Manage.* **381**:335–346. doi:[10.1016/j.foreco.2016.09.025](https://doi.org/10.1016/j.foreco.2016.09.025).
- McGroddy, M., Lawrence, D., Schneider, L., Rogan, J., Zager, I., Schmook, B. 2013. Damage patterns after Hurricane Dean in the southern Yucatan: Has human activity resulted in more resilient forests? *For. Ecol. Manage.* **310**:812–820. doi:[10.1016/j.foreco.2013.09.027](https://doi.org/10.1016/j.foreco.2013.09.027).
- Medjibe, V.P., Putz, F.E. 2012. Cost comparisons of reduced-impact and conventional logging in the tropics. *J. For. Econ.* **18**(3):242–256. doi:[10.1016/j.jfe.2012.05.001](https://doi.org/10.1016/j.jfe.2012.05.001).
- Miller, S.D., Goulden, M.L., Hutrya, L.R., Keller, M., Saleska, S.R., Wofsy, S.C., Silva Figueira, A.M., da Rocha, H.R., de Camargo, P.B. 2011. Reduced impact logging minimally alters tropical rainforest carbon and energy exchange. *Proc. Natl. Acad. Sci.* **108**(48):19431–19435. doi:[10.1073/pnas.1105068108](https://doi.org/10.1073/pnas.1105068108).
- Mislan, K.A.S., Heer, J.M., White, E.P. 2016. Elevating the status of code in ecology. *Trends Ecol. Evol.* **31**(1):4–7. doi:[10.1016/j.tree.2015.11.006](https://doi.org/10.1016/j.tree.2015.11.006).
- Miranda, A., Altamirano, A., Cayuela, A., Pincheira, F., Lara, A. 2015. Different times, same story: Native forest loss and landscape homogenization in three physiological areas of south-central of Chile. *Appl. Geogr.* **60**:20–28. doi:[10.1016/j.apgeog.2015.02.016](https://doi.org/10.1016/j.apgeog.2015.02.016).
- Mize, C., Negreros-Castillo, P. 2007. Stand and species growth of a tropical forest in Quintana Roo, Mexico. *J. Sustainable For.* **23**(3):83–95. doi:[10.1300/J091v23n03\\_04](https://doi.org/10.1300/J091v23n03_04).
- Monsreud, R.A., Sterba, H. 1996. A basal area increment model for individual trees growing in even- and uneven forest stands in Austria. *For. Ecol. Manage.* **80**(1–3):109–123. doi:[10.1016/0378-1127\(95\)03638-5](https://doi.org/10.1016/0378-1127(95)03638-5).
- Moreno, P. 2017. Individual-tree diameter growth models and variability of mixed *Nothofagus* second growth forests in southern Chile. M.Sc. thesis, School of Forest Resources and Conservation, University of Florida, Gainesville, FL.
- Moser, J.W., Hall, O.F. 1969. Deriving growth and yield functions for uneven-aged forest stands. *For. Sci.* **15**(2):183–188.
- Navarro-Martínez, A., Durán-García, R., Méndez-González, M. 2012. El impacto del Huracán Dean sobre la estructura y composición arbórea de un bosque manejado en Quintana Roo, México. *Madera y Bosques* **18**(1):57–76.
- Navarro-Martínez, A., Palmas, S., Ellis, A.E., Blanco-Reyes, P., Vargas-Godínez, C., Iuit-Jímenez, C.A., Hernández-Gómez, U.I., Ellis, P., Álvarez-Ugalde, A., Carrera-Quirino, G.Y., Armenta-Montero, S., Putz, E.F. 2017. Remnant trees in

- enrichment planted gaps in Quintana Roo, Mexico: Reasons for retention and effects on seedlings. *Forests* **8**(8). doi:[10.3390/f8080272](https://doi.org/10.3390/f8080272).
- Negreros-Castillo, P., Mize, C.W. 1993. Effects of partial overstory removal on the natural regeneration of a tropical forest in Quintana Roo, Mexico. *For. Ecol. Manage.* **58**(3–4):259–272. doi:[10.1016/0378-1127\(93\)90149-H](https://doi.org/10.1016/0378-1127(93)90149-H).
- Negreros-Castillo, P., Mize, C.W. 2014. Mahogany growth and mortality and the relation of growth to site characteristics in a natural forest in Quintana Roo, Mexico. *For. Sci.* **60**(5):907–913. doi:[10.5849/forsci.14-031](https://doi.org/10.5849/forsci.14-031).
- Nichols, J.D., Bristow, M., Vanclay, J.K. 2006. Mixed-species plantations: Prospects and challenges. *For. Ecol. Manage.* **233**(2–3):383–390. doi:[10.1016/j.foreco.2006.07.018](https://doi.org/10.1016/j.foreco.2006.07.018).
- Ortega, A., Gezan, S.A. 1998. Cuantificación de crecimiento y proyección de calidad en *Nothofagus*. *Bosque* **19**(1):123–126.
- Palmas, S., Moreno, P., Cropper, W.P., Gezan, S.A. 2017. Stand basal area and mortality models for mixed *Nothofagus* forests in southern Chile. Manuscript submitted to publication.
- Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D. 2011. A large and persistent carbon sink in the world's forests. *Science* **333**(6045):988–993. doi:[10.1126/science.1201609](https://doi.org/10.1126/science.1201609).
- Paritsis, J., Veblen, T. 2011. Dendroecological analysis of defoliator outbreaks on *Nothofagus pumilio* and their relation to climate variability in the patagonian Andes. *Global Change Biol.* **17**(1):239–253. doi:[10.1111/j.1365-2486.2010.02255.x](https://doi.org/10.1111/j.1365-2486.2010.02255.x).
- Peña-Claros, M., Fredericksen, T.S., Alarcon, A., Blate, G.M., Choque, U., Leano, C., Licona, J.C., Mostacedo, B., Pariona, W., Villegas, Z., Putz, F.E. 2008a. Beyond reduced-impact logging: Silvicultural treatments to increase growth rates of tropical trees. *For. Ecol. Manage.* **256**(7):1458–1467. doi:[10.1016/j.foreco.2007.11.013](https://doi.org/10.1016/j.foreco.2007.11.013).
- Peña-Claros, M., Peters, E.M., Justiniano, M.J., Bongers, F., Blate, G.M., Fredericksen, T.S., Putz, F.E. 2008b. Regeneration of commercial tree species following silvicultural treatments in a moist tropical forest. *For. Ecol. Manage.* **255**(3–4):1283–1293. doi:[10.1016/j.foreco.2007.10.033](https://doi.org/10.1016/j.foreco.2007.10.033).
- Peng, C. 2000a. Growth and yield models for uneven-aged stands: past, present and future. *For. Ecol. Manage.* **132**(2–3):259–279. doi:[10.1016/S0378-1127\(99\)00229-7](https://doi.org/10.1016/S0378-1127(99)00229-7).

- Peng, C. 2000. Understanding the role of forest simulation models in sustainable forest management. *Environ. Impact Assess. Rev.* **20**(4):481–501. doi:[10.1016/S0195-9255\(99\)00044-X](https://doi.org/10.1016/S0195-9255(99)00044-X).
- Pianosi, F., Beven, K., Freer, J., Hall, J.W., Rougier, J., Stephenson, D.B., Wagener, T. 2016. Sensitivity analysis of environmental models: A systematic review with practical workflow. *Environ. Modell. Softw.* **79**:214–232. doi:[10.1016/j.envsoft.2016.02.008](https://doi.org/10.1016/j.envsoft.2016.02.008).
- Pollmann, W. 2003. Stand structure and dendroecology of an old-growth *Nothofagus* forest in Conguillio National Park, south Chile. *For. Ecol. Manage.* **176**(1–3):87–103. doi:[10.1016/s0378-1127\(02\)00279-7](https://doi.org/10.1016/s0378-1127(02)00279-7).
- Porte, A., Bartelink, H.H. 2002. Modelling mixed forest growth: a review of models for forest management. *Ecol. Model.* **150**(1–2):141–188. doi:[10.1016/s0304-3800\(01\)00476-8](https://doi.org/10.1016/s0304-3800(01)00476-8).
- Puente, M., Penaloza, R., Donoso, C., Paredes, R., Núñez, P., Morales, R., Engdahl, O. 1980. Estudio de raleo y otras técnicas para el manejo de renovales de raulí y roble. segunda fase: Informe de avance de instalación de ensayos de raleo en renovales de raulí. informe de convenio 30. proyecto conaf/pnud/fao-chi/76/003. Tech. rep., Facultad de Ciencias Forestales, Universidad Austral de Chile, Chile.
- Putz, F.E., Romero, C. 2015. Futures of tropical production forests. Occasional Paper 143, Center for International Forestry Research. Bogor, Indonesia.
- Putz, F.E., Sist, P., Fredericksen, T., Dykstra, D. 2008. Reduced-impact logging: Challenges and opportunities. *For. Ecol. Manage.* **256**(7):1427–1433. doi:[10.1016/j.foreco.2008.03.036](https://doi.org/10.1016/j.foreco.2008.03.036).
- Putz, F.E., Zuidema, P.A., Synnott, T., Peña-Claros, M., Pinard, M.A., Sheil, D., Vanclay, J.K., Sist, P., Gourlet-Fleury, S., Griscom, B., Palmer, J., Zagt, R. 2012. Sustaining conservation values in selectively logged tropical forests: the attained and the attainable. *Conserv. Lett.* **5**(4):296–303. doi:[10.1111/j.1755-263X.2012.00242.x](https://doi.org/10.1111/j.1755-263X.2012.00242.x).
- Qin, J., Cao, Q.V. 2006. Using disaggregation to link individual-tree and whole-stand growth models. *Can. J. For. Res.* **36**(4):953–960. doi:[10.1139/x05-284](https://doi.org/10.1139/x05-284).
- R Core Team. 2016. R: A Language and Environment for Statistical Computing. Vienna, Austria.
- Racelis A.E., Barsimantov, J.A. 2008. The management of small diameter, lesser-known hardwood species as polewood in forest communities of central Quintana Roo, Mexico. *J. Sustainable F.* **27**(1–2):122–144.
- Rawlins, J.P., Pantula, S.G., Dickey D.A. 1998. Applied Regression Analysis: A Research Tool, 2nd ed. Springer, New York, NY.

- Rebertus, A.J., Veblen, T.T. 1993. Structure and tree-fall gap dynamics of old-growth *Nothofagus* forests in Tierra del Fuego, Argentina. *J. Veg. Sci.* **4**(5):641–654. doi:[10.2307/3236129](https://doi.org/10.2307/3236129).
- Reed, K.L. 1980. An ecological approach to modelling the growth of forest trees. *For. Sci.* **26**(1):33–50.
- Reineke, L. 1933. Perfecting a stand-density index for even-aged forests. *Agric. Res.* **46**:627–638.
- Réjou-Méchain M., Fayolle, A., Nasi, R., Gourlet-Fleury, S., Doucet, J.L., Gally, M., Hubert, D., Pasquier, A., Billand, A. 2011. Detecting large-scale diversity patterns in tropical trees: Can we trust commercial forests inventories? *For. Ecol. Manage.* **261**(2):187–194. doi:[10.1016/j.foreco.2010.10.003](https://doi.org/10.1016/j.foreco.2010.10.003).
- Sabatier, Y., Azpilicueta, M., Marchelli, P., Gonzalez-Penalba, M., Lozano, L., Garcia, L., Martinez, A., Gallo, L., Umana, F., Bran, D., Pastorino, M. 2011. Distribución natural de *Nothofagus alpina* y *Nothofagus obliqua* (Nothofagaceae) en Argentina, dos especies de primera importancia forestal de los bosques templados norpatagónicos. *Boletín de la Sociedad Argentina de Botánica* **46**(1):131–138.
- Salas, C., Garcia, O. 2006. Modelling height development of mature *Nothofagus obliqua*. *For. Ecol. Manage.* **229**(13):1–6. doi:[10.1016/j.foreco.2006.04.015](https://doi.org/10.1016/j.foreco.2006.04.015).
- Salas, C., LeMay, V., Núñez, P., Pacheco, P., Espinosa, A. 2006. Spatial patterns in an old-growth *Nothofagus obliqua* forest in south-central Chile. *For. Ecol. Manage.* **231**(13):38–46. doi:[10.1016/j.foreco.2006.04.037](https://doi.org/10.1016/j.foreco.2006.04.037).
- Sánchez Sánchez, O., Islebe, G.A. 1999. Hurricane Gilbert and structural changes in a tropical forest in south-eastern Mexico. *Global Ecol. Biogeogr.* **8**(1):29–38. doi:[10.1046/j.1365-2699.1999.00317.x](https://doi.org/10.1046/j.1365-2699.1999.00317.x).
- Sasaki, N., Asner, G.P., Pan, Y., Knorr, W., Durst, P.B., Ma, H.O., Abe, I., Lowe, A.J., Koh, L.P., Putz, F.E. 2016. Sustainable management of tropical forests can reduce carbon emissions and stabilize timber production. *Front. Environ. Sci.* **4**(50):1–13. doi:[10.3389/fenvs.2016.00050](https://doi.org/10.3389/fenvs.2016.00050).
- Shoch, D. 1999. An ecological and economic evaluation of railroad tie harvest in the Ejido Xpichil, Quintana Roo, Mexico. PhD thesis, Duke University, 68p.
- Sierra-Huelsz, J.A., Kainer, K.A., Keys, E., Colli-Balam, S.S. 2017. Three stories under the same hut: Market preferences and forest governance drive the evolution of tourism construction materials. *For. Pol. Econ.* **78**:151–161. doi:[10.1016/j.forpol.2017.01.022](https://doi.org/10.1016/j.forpol.2017.01.022).
- Sist, P., Sheil, D., Kartawinata, K., Priyadi, H. 2003. Reduced-impact logging in Indonesian Borneo: some results confirming the need for new silvicultural

- prescriptions. *For. Ecol. Manage.* 179(1–3):415–427. doi:[10.1016/S0378-1127\(02\)00533-9](https://doi.org/10.1016/S0378-1127(02)00533-9).
- Skovsgaard, J., Vanclay, J. 2008. Forest site productivity: a review of the evolution of dendrometric concepts for even-aged stands. *Forestry* **81**(1):13–31. doi:[10.1093/forestry/cpm041](https://doi.org/10.1093/forestry/cpm041).
- Snook, L.K., Negreros-Castillo, P. 2004. Regenerating mahogany (*Swietenia macrophylla* King) on clearings in Mexico's Maya forest: the effects of clearing method and cleaning on seedling survival and growth. *For. Ecol. Manage.* **189**(1–3):143–160. doi:[10.1016/j.foreco.2003.07.038](https://doi.org/10.1016/j.foreco.2003.07.038).
- Soto, D.P., Donoso, P.J., Salas, C., Puettmann, K.J. 2015. Light availability and soil compaction influence the growth of underplanted *Nothofagus* following partial shelterwood harvest and soil scarification. *Can. J. For. Res.* **45**(8):998–1005. doi:[10.1139/cjfr-2014-0353](https://doi.org/10.1139/cjfr-2014-0353).
- Soto, D.P., Jacobs, D.F., Salas, C., Donoso, P.J., Fuentes, C., Puettmann, K.J. 2017. Light and nitrogen interact to influence regeneration in old-growth *Nothofagus*-dominated forests in south-central Chile. *For. Ecol. Manage.* **384**:303–313. doi:[10.1016/j.foreco.2016.11.016](https://doi.org/10.1016/j.foreco.2016.11.016).
- Tahvonen, O., Pukkala, T., Laiho, O., Lahde, E., Niinimäki, S. 2010. Optimal management of uneven-aged Norway spruce stands. *For. Ecol. Manage.* **260**(1):106–115. doi:[10.1016/j.foreco.2010.04.006](https://doi.org/10.1016/j.foreco.2010.04.006).
- Tippmann, S. 2015. Programming tools: Adventures with R. *Nature* **517**(7532):109–110. doi:[10.1038/517109a](https://doi.org/10.1038/517109a).
- Toledo-Aceves, T., Purata-Velarde, S., Peters, C.M. 2009. Regeneration of commercial tree species in a logged forest in the Selva Maya, Mexico. *For. Ecol. Manage.* **258**(11):2481–2489. doi:[10.1016/j.foreco.2009.08.033](https://doi.org/10.1016/j.foreco.2009.08.033).
- Toro, J., Gessel, S. 1999. Radiata pine plantations in Chile. *New For.* **18**(1):33–44. doi:[10.1023/A:1006597823190](https://doi.org/10.1023/A:1006597823190).
- Trincado, G., Kiviste, A., Von Gadow, K. 2002. Preliminary site index models for native roble (*Nothofagus obliqua*) and raulí (*N. alpina*) in Chile. *N. Z. J. For. Sci.* **32**(2):322–333.
- Vallet, P., Pérot, T. 2011. Silver fir stand productivity is enhanced when mixed with Norway spruce: evidence based on large-scale inventory data and a generic modelling approach. *J. Veg. Sci.* **22**(5):932–942. doi:[10.1111/j.1654-1103.2011.01288.x](https://doi.org/10.1111/j.1654-1103.2011.01288.x).
- Vanclay, J.K. 1991. Notes: Compatible deterministic and stochastic predictions by probabilistic modeling of individual trees. *For. Sci.* **37**(6):1656–1663.

- Vanclay, J.K. 1994. Modelling Forest Growth and Yield: Applications to Mixed Tropical Forests. CAB International, Wallingford, UK.
- Vanclay, J.K. 1995. Synthesis: Growth models for tropical forests: A synthesis of models and methods. *For. Sci.* **41**(1):7–42.
- Vanclay, J.K., Skovsgaard, J.P. 1997. Evaluating forest growth models. *Ecol. Modell.* **98**(1):1–12. doi:[10.1016/S0304-3800\(96\)01932-1](https://doi.org/10.1016/S0304-3800(96)01932-1).
- Veblen, T., Schlegel, F.M., Escobar B. 1980. Structure and dynamics of old-growth *Nothofagus* forests in the Valdivian Andes, Chile. *J. Ecol.* **68**(1):1–31. doi:[10.2307/2259240](https://doi.org/10.2307/2259240).
- Veblen, T., Donoso, C., Kitzberger, T., Rebertus, A. 1996. Ecology of southern Chilean and Argentinean *Nothofagus* forests. In *The Ecology and Biogeography of Nothofagus Forests* Edited by Veblen, T., Hill, R., Read, J. Yale University Press, New Haven, CT. pp 293–353.
- Veblen, T.T., Ashton, D.H. 1978. Catastrophic influences on the vegetation of the Valdivian Andes, Chile. *Vegetatio* **36**(3):149–167. doi:[10.1007/BF02342598](https://doi.org/10.1007/BF02342598).
- Vidal, E., West, T.A.P., Putz, F.E. 2016. Recovery of biomass and merchantable timber volumes twenty years after conventional and reduced-impact logging in Amazonian Brazil. *For. Ecol. Manage.* **376**:1–8. doi:[10.1016/j.foreco.2016.06.003](https://doi.org/10.1016/j.foreco.2016.06.003).
- Villegas, Z., Peña-Claros, M., Mostacedo, B., Alarcón, A., Licona, J.C., Leaño, C., Pariona, W., Choque, U. 2009. Silvicultural treatments enhance growth rates of future crop trees in a tropical dry forest. *For. Ecol. Manage.* **258**(6):971–977. doi:[10.1016/j.foreco.2008.10.031](https://doi.org/10.1016/j.foreco.2008.10.031).
- Walter, C., Prez, C.A., Thomas, F.M. 2016. Weather or weathering? growth of *Nothofagus dombeyi* on volcanic soils differing in nitrogen and phosphorus concentrations. *J. Plant Ecol.* **9**(5):596–607. doi:[10.1093/jpe/rtv079](https://doi.org/10.1093/jpe/rtv079).
- Weinberger, P., Ramirez, C. 2001. Microclima y regeneración natural de raulí, roble y coigüe (*Nothofagus alpina*, *N. obliqua* y *N. dombeyi*). *Bosque* **22**(1):11–26.
- Whigham, D.F., Olmsted, I., Cano, E.C., Harmon, M.E. 1991. The Impact of Hurricane Gilbert on trees, litterfall, and woody debris in a dry tropical forest in the northeastern Yucatan Peninsula. *Biotropica* **23**(4):434–441. doi:[10.2307/2388263](https://doi.org/10.2307/2388263).
- Wilshusen, P.R. 2005. ITTO Country Case Study: Petcacab, Sociedad de Productores Forestales Ejidales de Quintana Roo (SPFEQR), Quintana Roo, Mexico. The Rights and Resources Initiative, Washington, DC.

- Wulder, M.A., White, J.C., Fournier, R.A., Luther, J.E., Magnussen, S. 2008. Spatially Explicit Large Area Biomass Estimation: Three Approaches Using Forest Inventory and Remotely Sensed Imagery in a GIS. *Sensors* **8**(1):529–560. doi:[10.3390/s8010529](https://doi.org/10.3390/s8010529).
- Wykoff, W.R. A basal area increment model for individual conifers in the northern Rocky Mountains. *For. Sci.* **36**(4):1077–1104.
- Yue, C., Kohnle, U., Hein, S. 2008 Combining tree- and stand-level models: a new approach to growth prediction. *For. Sci.* **54**(5):553–566.
- Zamorano-Elgueta, C., Rey Benayas, J.M., Cayuela, L., Hantson, S., Armenteras, D. 2015. Native forest replacement by exotic plantations in southern Chile (1985-2011) and partial compensation by natural regeneration. *For. Ecol. Manage.* **345**:10–20. doi:[10.1016/j.foreco.2015.02.025](https://doi.org/10.1016/j.foreco.2015.02.025).
- Zanne, A.E., Lopez-Gonzalez, G., Coomes, D.A., Ilic, J., Jansen, S., Lewis, S.L., Miller, R.B., Swenson, N.G., Wiemann, M.C., Chave, J. 2009. Data from: Towards a worldwide wood economics spectrum. Dryad Digital Repository. doi:[10.5061/dryad.234](https://doi.org/10.5061/dryad.234).
- Zhang, L., Moore, J.A., Newberry, J.D. 1993. Disaggregating stand volume growth to individual trees. *For. Sci.* **39**(2):295–308.
- Zhang, X., Lei, Y., Cao, Q.V. 2010. Compatibility of stand basal area predictions based on forecast combination. *For. Sci.* **56**(6):552–557.
- Zhang, X., Lei, Y., Cao, Q.V., Chen, X., Liu, X. 2011. Improving tree survival prediction with forecast combination and disaggregation. *Can. J. For. Res.* **41**(10):1928–1935. doi:[10.1139/x11-109](https://doi.org/10.1139/x11-109).

## BIOGRAPHICAL SKETCH

Born in Mexico City, Sebastian has been a Chilango most of his life. He developed an interest in numbers, formulas and science from his parents and brother, all mathematicians. He always intended in pursuing a degree in mathematics or engineering, however that changed after only one semester at the School of Engineering at UNAM, when he left to pursue a BSc in biology at UAM-Xochimilco.

Studying biology, Sebastian greatly enjoyed field trips to many ecosystems of Mexico, with particular interest in tropical regions. In 2011, while he was working with researchers at the Center for Tropical Research of the University of Veracruz, Mexico he met Dr. Karen Kainer, who was a visiting scholar from UF. She offered him a graduate assistantship to study a MS at the UF School of Forest Resources and Conservation, where he got his degree with a concentration in Tropical Conservation and Development in 2013. During the master's program, he worked along Dr. Salvador Gezan and Sebastian kept going into his PhD under his guidance.

This dissertation is the end of 6 ½ years in Gainesville for Sebastian. He does not know where he is going next.