

FOREST BIOMETRICS AND QUANTITATIVE ANALYSIS OF FORESTED
ECOYSTEMS IN COASTAL ALASKA

By

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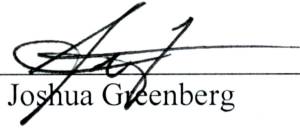
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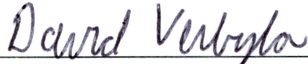
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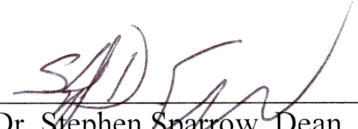


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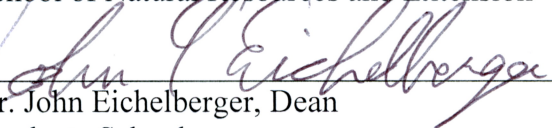


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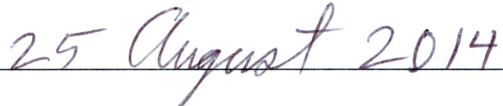
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FOREST BIOMETRICS AND QUANTITATIVE ANALYSIS OF FORESTED
ECOYSTEMS IN COASTAL ALASKA

A
THESIS

Presented to the Faculty
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By

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Abstract

Growth and yield models are a mainstay of forestry research and a necessary tool in the forest management decision process. Growth and yield models predict forest population dynamics over time and are an invaluable resource to forest managers making harvest and utilization decisions. At present, there are only a few growth models available for Alaska's coastal forests, all of which are either calibrated with even-aged data or outdated. Yield tables and growth models developed with even-aged data can be useful in even-aged management applications such as clear-cuts; however, these models are not able to predict the outcomes of uneven-aged silvicultural systems. The objective of this thesis is the development of a growth and yield model for coastal Alaska and computer applications to facilitate its use. A density-dependent, distance-independent, size- and species-specific matrix forest growth and yield model is calibrated with data collected on permanent sample plots located throughout coastal Alaska. The resulting growth and yield model enables short- and long-term predictions of stand basal area, volume, and biomass. Model assessment, with a focus on plausibility and accuracy, is evaluated on an independent dataset. Two computer programs (AlaskaPro and fgmod) are developed in conjunction with the new model. These programs can be used by forest researchers and land managers to compare the outcomes of various silvicultural prescriptions.

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Chapter 1

General Introduction

Growth and yield models are a mainstay of forestry research and a necessary tool of forest resource managers. Forest growth and yield models predict forest population dynamics and are important in making harvest and utilization decisions. At present, only a handful of models are available for coastal Alaska's forests (Ritchie 1999). Growing interest in young-growth stand management (TLMP 2008; Barbour et al. 2005), biomass utilization (Alexander et al. 2010) and recent changes to the Tongass National Forest land management plan (TLMP 2008) has reinforced the need for a forest growth and yield model that is reliable, accurate, and able to compare different management scenarios (McClellan 2005). Existing yield models focus primarily on timber volume and do not predict biomass, so a desirable feature of any new growth model would be the ability to predict yield in terms of both biomass and volume. Until recently, the development of a forest growth model in coastal Alaska had not been possible due to data constraints. The following thesis formulates a new growth and yield model for coastal Alaska as well as developing computer software to facilitate its application.

Coastal Alaska forest is composed of numerous species and forest type, but is primarily dominated by shade-tolerant conifers: *Tsuga heterophylla* (Raf.) Sarg. (western hemlock), *Tsuga mertensiana* (Bong.) Carr. (mountain hemlock), *Picea sitchensis* (Bong.) Carr. (Sitka spruce), *Chamaecyparis nootkatensis* (D. Don) Spach (Alaska cedar), *Thuja plicata* Donn ex D. Don (western red cedar), *Picea glauca* (Moench) Voss

(white spruce), and *Picea mariana* (Mill.) B.S.P. (black spruce). Deciduous hardwoods and shade-intolerant conifers comprise a much smaller percentage of Alaska coastal forests; *Betula papyrifera* Marsh. (paper birch), *Populus trichocarpa* Torr. & Gray (black cottonwood), *Populus tremuloides* Michx. (quacking aspen), *Alnus rubra* Bong. (red alder), and *Pinus contorta* Dougl. ex. Loud. (lodgepole pine). Presence-absence and abundance of tree species is highly variable and often dependent upon location and site quality, especially in the transition from coastal to boreal forest in Southcentral Alaska. The spatial extent of the region is great, so it is generally delineated into Southeast and Southcentral Alaska for descriptive purposes (Barrett and Christensen 2011; Viereck and Little 1975), although this distinction is largely vernacular.

Coastal Alaska forest spans roughly 25 degrees longitude, 8 degrees latitude, envelops a number of ecoregions, and is comprised of numerous species and forest types (Figure 2.1; Ruefenacht et al. 2008; Nowacki et al. 2002). Species such as western red cedar and Alaska cedar reach the western- and northern-most portions of their range. Western hemlock is more abundant at lower elevations than mountain hemlock, but this relationship changes as elevation increases. Western hemlock-Sitka spruce forests, which are both commercially and ecologically important, tend to prefer mesic sites at lower elevations. Xeric sites in Southeast, although few in number, are often occupied by lodgepole pine.

Steep slopes, heavy precipitation, and temperate weather characterize maritime Southeast Alaska, all of which affect forest dynamics and species. Southcentral Alaska is a mixture of transitional and coastal ecoregions. Coastal forests extend to the eastern

portion of the Kenai Peninsula where the climate is maritime, but do not extend far into the western portion of the peninsula, where the climate is continental. Mountain hemlock is found throughout the Kenai Peninsula, but this is the northernmost portion of its range. Sitka spruce is found in great abundance on Kodiak and Afognak Islands and hybridizes with white spruce in the transition zones (*Picea X lutzii* Little).

A comprehensive forest inventory was not completed until recently due to coastal Alaska's large geographic extent and difficulty of access. Beginning in 1995, permanent sample plots were established throughout coastal Alaska by the United States Forest Service (USFS) Pacific Northwest Research Station (PNW) Forest Inventory and Analysis (FIA) Program (O'Connell et al. 2013). Plots are established every three miles (4.8 km) on a systematic and orthogonal grid and consist of four circular 0.017-ha (0.042-acre) subplots. FIA personnel first stratify plots as forested or non-forested in the office before visiting plots (Bechtold and Patterson 2005). Plots identified as potentially forested land are then visited by FIA field crews. One outcome of this fieldwork is a comprehensive forest inventory database that provides information able to represent forest dynamics (O'Connell et al. 2013). FIA plots are further selected to meet the following criteria: 1) measured twice, 2) fully forested and 3) no signs of disturbance (Figure 1.2). The previous criteria are necessary to meet model assumptions. Additional data collected by the Cooperative Alaska Forest Inventory (CAFI) is also leveraged to insure model accuracy (Malone et al. 2009).

Chapter 2 constructs a growth and yield model for all major species in the coastal Alaska. The proposed matrix growth model separates forest dynamics into three

components (growth, mortality, and recruitment) and is an extension of earlier models (e.g. Liang 2010; Liang et al. 2005; Buongiorno and Michie 1980). The model is density-dependent, distance-independent, species- and size-specific. Variables of statistical significance are identified for each component of growth. Physiographic and stand diversity metrics (Liang et al. 2007) are among some of the variables tested. The new model is validated with data not used in model development. Short- and long-term predictions of forest dynamics in coastal Alaska are made using the new model. Predictions are compared to the results of the Forest Vegetation Simulator Southeast Alaska and Coastal British Columbia (FVS-SEAPROG) in terms of model accuracy, scientific plausibility and utility to forest researchers and managers. Due to the region's large extent, the prediction errors of both models are investigated for spatial autocorrelation, which can be indicative of problems within a model.

Chapter 3 details the development and purpose of two computer programs that were developed in conjunction with the new model: AlaskaPro and the forest growth modeler (fgmod). AlaskaPro and fgmod are both cross-platform software and developed to be easy to use. Both programs enable the prediction of forest growth dynamics in coastal Alaska. fgmod includes a growth and yield model for interior Alaska forests (Liang 2010). Both programs permit forest managers to predict the outcomes of various silvicultural prescriptions and provide information about important stand attributes such as volume, biomass, basal area, trees per acre, and forest diversity. Chapter 3 discusses the purpose of developing cross-platform, easy-to-use software programs. System requirements and how to install both pieces of software is described. The functions,

capabilities and limitations of each program are presented to illustrate which of these two programs a forest researcher or land manager would want to use. Lastly, an application of using both programs is shown. Additional information about the programs and models are found in the appendices.

Chapter 4 presents a summary of the research results described in this thesis. Problems with the presently available models in coastal Alaska are well documented (McClellan 2005; McClellan and Biles 2003; Barnes 1962) along with their potential causes (Farr and Harris 1979; Viereck and Little 1975; Harris and Farr 1974). The matrix growth and yield model developed in Chapter 2 is compared to existing models from the region in terms of accuracy and plausibility. Matrix growth models have been used extensively and effectively in forestry and are well documented (Liang and Picard 2013; Liang 2010; Buongiorno and Mitchie 1980). Matrix growth models can predict the evolution of forests over time and the effects of various management decisions under risk (Buongiorno and Gilless 2003). Computer software is developed so that forest managers can use the new model.

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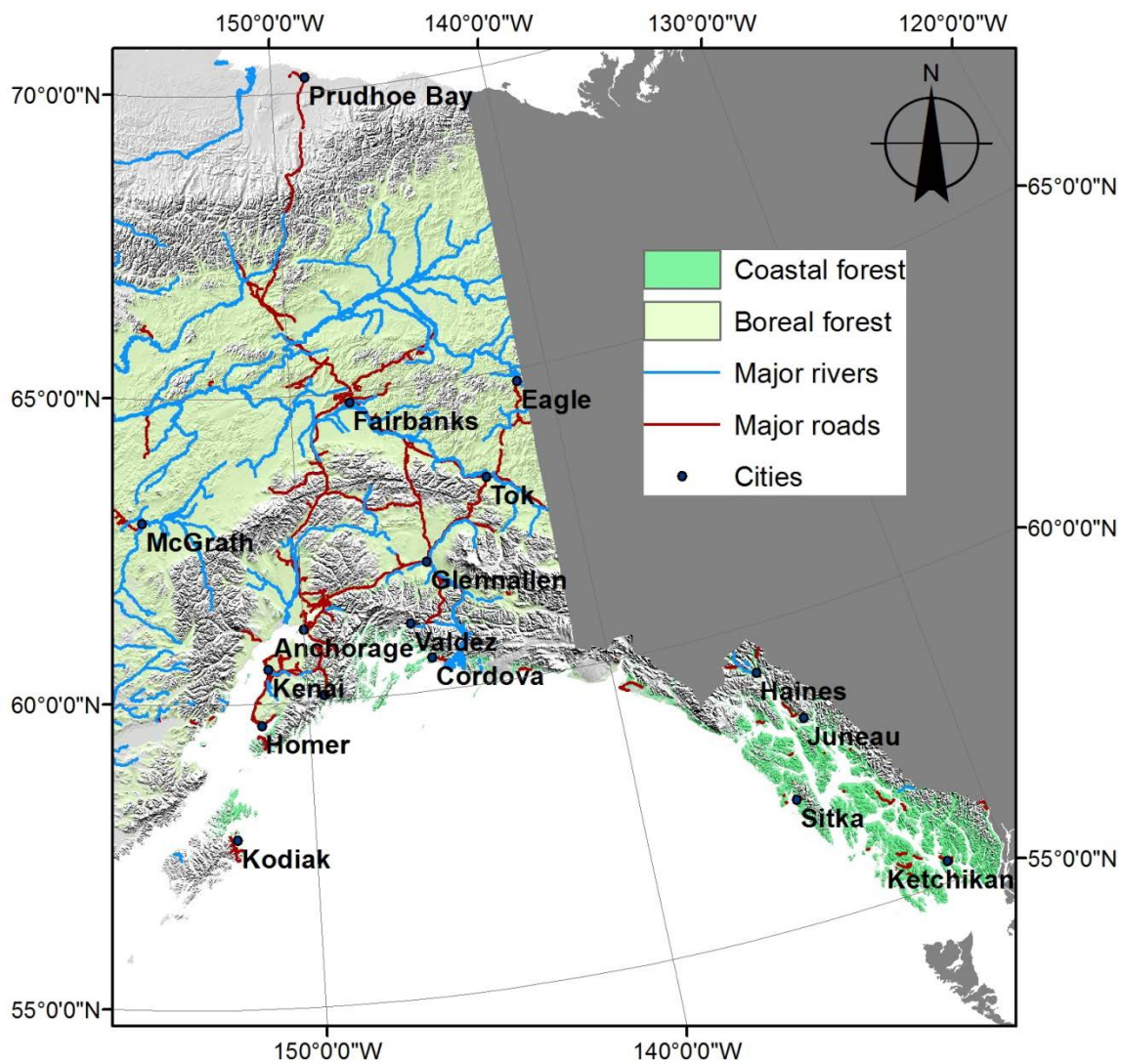


Figure 1.1. Distribution of Alaska's coastal and boreal forests (adapted from Ruefenacht et al. 2008)

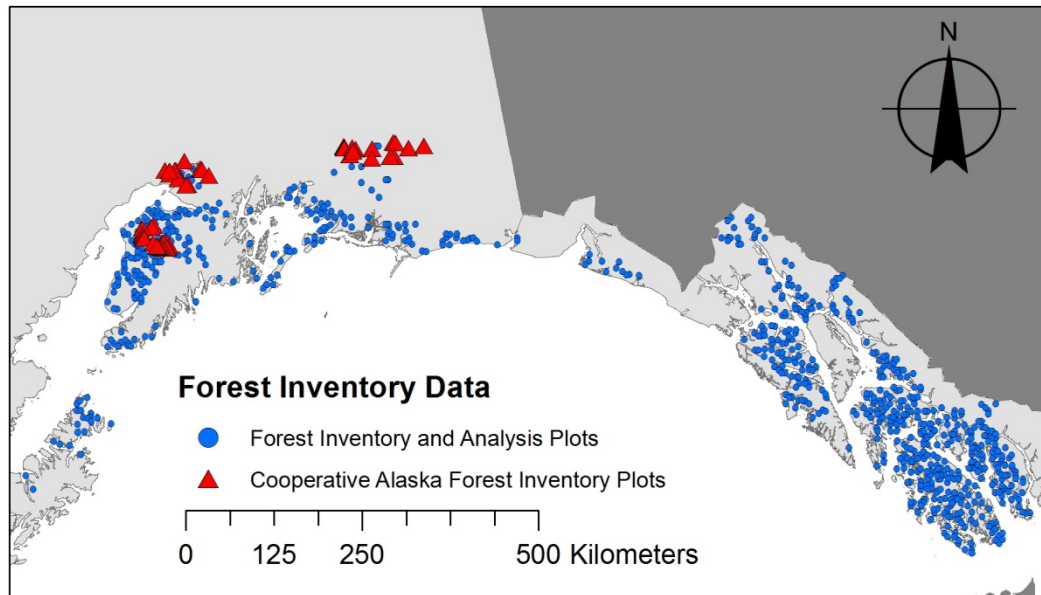


Figure 1.2. Geographic locations of the 788 Forest Inventory and Analysis and 49 Cooperative Alaska Forest Inventory plots located in coastal Alaska and used in this study.

Chapter 2

Modeling Population Dynamics and Woody Biomass in Alaska Coastal Forest¹

Abstract

Alaska coastal forest, 6.2 million ha in size, has been managed in the past mainly through clearcutting. Declining harvest and dwindling commercial forest resources over the past two decades have led to increased interest in management of young-growth stands and utilization of woody biomass for bioenergy. However, existing models to support these new management systems are very limited in number and value. This study develops a density-dependent, size-, and species-specific matrix growth model for forest in coastal Alaska. This model enables short- and long-term predictions of stand basal area, volume, and biomass in a simple and accurate way, and facilitates understanding of the ecological and economic effects of forest management alternatives. Components of forest growth were estimated from tree and stand level attributes from repeated measurements of 544 FIA permanent sample plots located throughout coastal Alaska with a wide range of stand conditions. The model was tested to be of significantly higher accuracy on 293 post-sample validation plots than the Forest Vegetation Simulator (FVS), the only growth model available for the region. Analysis of residuals revealed no spatial autocorrelation, which indicates that this model is able to adequately account for

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the effects of physiographic factors and other differences between Southeast and Southcentral Alaska.

Keywords: Matrix model, forest management, population structure, spatial autocorrelation

Introduction

Alaska coastal forest is 6.2 million ha in size, with 2.6 million ha of timberland (Barrett and Christensen 2011). Geographically, the region spans roughly 25 degrees longitude and 8 degrees latitude across seven ecoregions and numerous forest types (Nowacki et al. 2002). The region is composed of two distinct parts, Southeast and Southcentral Alaska (Viereck and Little 1975). Shade tolerant conifers dominate the maritime Southeast Alaska landscape that is often characterized by steep slopes and temperate climate. Coastal and boreal tree species occupy different niches across the transitional ecoregion zone in Southcentral Alaska, where climatic conditions are a mixture of maritime and continental and vary by location (Nowacki et al. 2002).

Alaska's coastal forest is dominated by seven conifers of moderate to high shade tolerance —*Tsuga heterophylla* (Raf.) Sarg. (western hemlock), *Picea sitchensis* (Bong.) Carr. (Sitka spruce), *Tsuga mertensiana* (Bong.) Carr. (mountain hemlock), *Chamaecyparis nootkatensis* (D. Don) Spach (Alaska cedar), *Thuja plicata* Donn ex D. Don (western red cedar), *Picea glauca* (Moench) Voss (white spruce), *Picea mariana* (Mill.) B. S. P. (black spruce)—that comprise more than 90 percent of total basal area (Table 2.1). Deciduous *Betula papyrifera* Marsh. (paper birch), *Populus trichocarpa* Torr. & Gray (black cottonwood), *Populus tremuloides* Michx. (quaking aspen), *Alnus*

rubra Bong. (red alder) and shade-intolerant *Pinus contorta* Dougl. ex. Loud. (lodgepole pine), most of which are distributed in Southcentral Alaska (Burns and Honkala 1990; Nowacki et al. 2002), account for less than 10 percent of total basal area.

Forest management in the region has been dominated by harvesting old-growth forests using clearcutting (Deal 2007; Halbrog et al. 2009). Declining harvest and dwindling commercial forest resources over the past two decades (Brackley et al. 2009) have led to a new era of forest management that is characteristic of various efforts to stimulate the industry through efforts such as the alternatives to clearcutting (ATC) program (McClellan et al. 2000), managing young-growth stands (Barbour et al. 2005; TLMP 2008), and utilizing woody biomass for bioenergy (Alexander et al. 2010). Presently, there is little information available regarding the effects of uneven-aged forest management on coastal Alaska forests, despite its wide prescription in the region (TLMP 2008), and experimental results are still a long way off (Deal 2007).

The existing growth and yield models are of limited value for these new management systems for several reasons. The Forest Vegetation Simulator (FVS) Southeast Alaska variant (FVS-SEAPROG) lacks sufficient observations in model calibration for *Picea* species (Keyser 2008; Ritchie 1999) and has been found problematic when used to predict outcomes of silviculture treatments other than clearcutting (McClellan 2005; McClellan and Biles 2003). The three growth and yield-tables (Barnes 1962; Meyer 1937; Taylor 1934) for the region are designed for even-age stands and do not provide the details demanded by current resource managers (Ritchie 1999).

In order to better understand the ecological and economic effects of various ATC systems on Alaska coastal forest, this study developed a matrix model of forest dynamics and linear models of stem volume and biomass based on permanent sample plot data collected throughout the region. Prediction accuracy of the present model in comparison with that of existing growth and yield models for the region was evaluated with an independent validation dataset. Spatial autocorrelation was investigated to determine if the present model could be reliable in large-scale applications.

Data and methods

Data

Data used to calibrate the matrix model of forest dynamics came from the Alaska Forest Inventory and Analysis (FIA) database (Grimm and Railsback 2005). FIA field data is from a systematic sample of forested areas across all private and public lands (excluding wilderness) in the coastal Alaska region and consist of four circular .017-ha (0.042-acre) subplots. Permanent sample plots (PSP) selected for model calibration in this study met the following criteria: 1) a selected PSP must be classified as forested land (O'Connell et al. 2013) and remeasured at least once, 2) there was at least one live tree at time of both measurements, and 3) there was no evidence of silvicultural treatments or any other forms of vegetation manipulation in a selected PSP. A total of 788 PSP across the Alaska coastal region were selected with these criteria. In order to test model accuracy and spatial autocorrelation, we took a simple random sample of the modeling data and held 244 FIA PSP for validation. This was combined with an independent sample dataset of 49 Cooperative Alaska Forest Inventory (CAFI, Malone et al. 2009)

PSP located in the boreal-coastal transition zone of Southcentral Alaska, which made a total of 293 validation plots (Figure 2.1). CAFI plots were established and measured similarly to FIA plots, with an exception that each CAFI plot consists of three 0.04-ha (0.1-acre) subplots.

The 13 tree species in Alaska coastal forest were integrated into six species categories (Table 2.1). Western hemlock, mountain hemlock, and Sitka spruce each constitutes an independent species category due to their abundance and commercial importance in the region. Western red cedar and Alaska cedar were grouped as Alaska cedars due to similar growth characteristics and geographic distributions (Viereck and Little 1975). Similarly, black spruce and white spruce were combined into boreal spruce because of similar growth patterns and natural range (see Liang 2010). All the remaining species account for less than 7 percent of the total stocking, and were combined into one category labeled as other species.

All variables and their units are defined in Table 2.2. Stand diversity measures (H_d , H_s) were calculated by Shannon's formula:

$$H_d = -\sum_{j=1}^n \frac{B_j}{B} \ln\left(\frac{B_j}{B}\right), \quad H_s = -\sum_{i=1}^k \frac{B_i}{B} \ln\left(\frac{B_i}{B}\right) \quad (2.1)$$

where B_j , B_i , and B were, respectively, the basal area of size-class $j=1, \dots, n$, species group $i=1, \dots, k$, and total basal area. According to the summary statistics of plot level variables (Table 2.3), the average and maximum stand basal area of Alaska coastal forest was higher than those of the productive Douglas-fir/western hemlock forests in the U.S. Pacific Northwest (Liang et al. 2005), which together with the domination of climax

species in terms of stem density (Table 2.3) are indicative of the large amount of Alaska coastal forest that maintains old-growth characteristics. Western hemlock has the highest recruitment (R) and total stem density (N), whereas Alaska cedars have the lowest recruitment but are medium in total stem density. Average stand basal area is $32.05 \text{ m}^2 \cdot \text{ha}^{-1}$ and gross above-ground timber volume is $271.29 \text{ m}^3 \cdot \text{ha}^{-1}$ (Table 2.3). High correlations between some plot level variables, the highest being 71.2% between basal area (B) and tree size diversity (H_d), suggest that multicollinearity needs to be addressed in model development.

At the individual tree level (Table 2.4), Sitka spruce had the largest dbh (D) and highest average annual diameter growth (g). Boreal spruce had the highest mortality rate (m) and the second highest g , which was nearly twice the growth rate of the same species in Interior Alaska (Liang 2010). The lowest diameter growth belongs to western hemlock, mountain hemlock, and Alaska cedars. The high standard deviation observed in all plot (Table 2.3) and tree level (Table 2.4) variables reflects the wide variety of site and structural conditions represented by this data set.

Matrix model structure

A matrix model of forest dynamics (hereafter, matrix model) was developed to study ecological and economic effects of various ATC systems. Using transition or probability matrices to predict future plant and animal population structures, matrix models have been employed to study the dynamics of forests all over the world (see a review by Liang and Picard In Press). We chose to develop a matrix model in this study for three major reasons. First, matrix models primarily deal with temporal changes of structured forest

populations and can be directly coupled with a diameter-biomass model to predict the dynamics of woody biomass and above-ground carbon (e.g. Picard et al. 2009); matrix models, due to the demographic nature, have been extensively used to study the outcomes of a broad range of forest management regimes and silvicultural treatments (e.g. Buongiorno et al. 1995); and last but not least, matrix models can be easily incorporated into user-friendly computer simulation programs to facilitate forest management planning and education (e.g. Liang et al. 2006; Schulte et al. 1998).

Similar to the matrix models developed for Douglas-fir/western hemlock forest in the Pacific Northwest (Liang et al. 2005) and for Alaska boreal forest (Liang 2010), the matrix model presented here is stand-specific, *i.e.* the transition matrices and projections are derived not only from the structure and composition of forest populations, but also from the site productivity and/or physiographic conditions at specific locations. A stem volume and a stem biomass model were also developed and incorporated into the matrix model to enable an analysis on the volume and biomass output of ATC systems.

A forest matrix model predicts the structured population dynamics of forest stands from time t to $t+1$:

$$\mathbf{y}_{t+1} = \mathbf{G} \cdot \mathbf{y}_t + \mathbf{R} + \boldsymbol{\varepsilon} \quad (2.2)$$

where $\mathbf{y}_t = [y_{ijt}]$ is a vector of live trees at time t of size-class $j=1, \dots, n$ and specie-group $i=1, \dots, k$. $\boldsymbol{\varepsilon}$ is the error term. \mathbf{G} and \mathbf{R} are respectively the growth and recruitment matrices which are defined as:

$$\mathbf{G} = \begin{bmatrix} \mathbf{G}_1 & & & \\ & \mathbf{G}_2 & & \\ & & \ddots & \\ & & & \mathbf{G}_k \end{bmatrix}, \quad \mathbf{G}_i = \begin{bmatrix} s_{i,1} & & & & \\ g_{i,1} & s_{i,2} & & & \\ & \ddots & \ddots & & \\ & & g_{i,n-2} & s_{i,n-1} & \\ & & & g_{i,n-1} & s_{i,n} \end{bmatrix}, \quad (2.3)$$

$$\mathbf{R} = \begin{bmatrix} \mathbf{R}_1 \\ \mathbf{R}_2 \\ \vdots \\ \mathbf{R}_k \end{bmatrix}, \quad \mathbf{R}_i = \begin{bmatrix} R_i \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

where \mathbf{G} is the transition matrix of live trees of size j and specie group i that stay alive ($s_{i,j}$ denotes the annual stasis rate) or grow into the next size-class ($g_{i,j}$ denotes the annual upgrowth rate), and \mathbf{R} is the recruitment of trees for specie group $i=1, \dots, k$ that enter the smallest size-class. $s_{i,j}$ is calculated using the following relationship:

$$s_{i,j} = 1 - g_{i,j} - m_{i,j} \quad (2.4)$$

where $m_{i,j}$ is the annual mortality rate. Trees in this study were sorted into nineteen 5.08cm (2-in) diameter at breast height (dbh) classes. The smallest size class consisted of trees 12.7–17.8 cm (5–7 in) in dbh and the largest consisted of trees 104.1cm (41 in) and above.

The components of forest dynamics, diameter growth, mortality, and recruitment, were modeled with the tree- and plot-level variables listed in Table 2.2, and so were volume and biomass models. More specifically, diameter and its square (D, D^2) were employed in individual tree models (diameter growth, mortality, volume, and biomass) to capture the nonlinear effect of diameter on growth (e.g. Liang et al. 2005). To estimate stand level recruitment of a species, R_i , we employed the number of trees of that species

and its square (N_i, N_i^2) to represent the size of the seed bank. Basal area (B) and site productivity (C) are considered as key predictors in many existing matrix models, due to their prominent effect on forest dynamics (e.g. Namaalwa et al. 2005). Physiographic variables—elevation (E), slope (S), and aspect ($\cos(a), \sin(a)$)—were also included in the present matrix model, as it was hypothesized that each variable could individually affect forest dynamics. In addition, stand diversity measures (H_d, H_s), metrics of size and species diversity, were also employed in the model to explicitly account for the effects of diversity on forest dynamics (Liang et al. 2007).

Upgrowth rate ($g_{i,j}$), the probability that a live tree in size class $j=1, \dots, n$ at time t would move into size class $j+1$ a time $t+1$, was calculated as the annual diameter increment ($d_{i,j}$), divided by 5.08 cm, the width of each size-class, assuming that $g_{i,j}$ stays constant within each diameter class. $d_{i,j}$ was estimated with ordinary least squares (OLS) and the residuals (ψ_{ij}) were assumed to be independent $N(0, \sigma^2)$. The following equation represented the full model of diameter growth:

$$d_{ij} = \alpha_{i1} + \alpha_{i2}D_j + \alpha_{i3}D_j^2 + \alpha_{i4}B + \alpha_{i5}C + \alpha_{i6}E + \alpha_{i7}S + \alpha_{i8}\cos(a) + \alpha_{i9}\sin(a) + \alpha_{i10}H_d + \alpha_{i11}H_s + \psi_{ij} \quad (2.5)$$

The average annual mortality, m_{ij} , was estimated from M_{ij} , a binary variable representing whether a tree of species i and diameter class j died ($M_{ij}=1$) or not ($M_{ij}=0$) between the two inventories over an elapsed time of T years:

$$m_{ij} = \frac{P(M_{ij} = 1 | \mathbf{x})}{T} \quad (2.6)$$

where $P(M_{ij}=1|\mathbf{x})$ was estimated with a Probit model and its full model was represented by the following equation:

$$P(M_{ij} = 1|\mathbf{x}) = \Phi(\delta_{i1} + \delta_{i2}D_j + \delta_{i3}D_j^2 + \delta_{i4}B + \delta_{i5}C + \delta_{i6}E + \delta_{i7}S + \delta_{i8} \cos(a) + \delta_{i9} \sin(a) + \delta_{i10}H_d + \delta_{i11}H_s + \xi_{ij}) \quad (2.7)$$

Recruitment of species i , R_i was estimated with a Tobit model (Tobin 1958) to explicitly account for total stand recruitment that is left truncated at zero:

$$E(R_i | x_i) = \Phi(x_i\beta_i\sigma_i^{-1})x_i\beta_i + \sigma_i\varphi(x_i\beta_i\sigma_i^{-1}) \quad (2.8)$$

with the full model:

$$x_i\beta_i = \beta_{i1} + \beta_{i2}N + \beta_{i3}N^2 + \beta_{i4}B + \beta_{i5}C + \beta_{i6}E + \beta_{i7}S + \beta_{i8} \cos(a) + \beta_{i9} \sin(a) + \beta_{i10}H_d + \beta_{i11}H_s + \mu_{ij} \quad (2.9)$$

where Φ was the standard normal cumulative distribution function and φ was the standard normal probability density function.

Total stand volume and biomass are calculated with the following equation:

$$\mathbf{v}_i = \mathbf{v}' \mathbf{y}_i \quad (2.10)$$

where \mathbf{v} was a vector of single-stem volume and biomass by size and species (v_{ij}),

which was represented by the following full model:

$$v_{ij} = \theta_{i1} + \theta_{i2}D_j + \theta_{i3}D_j^2 + \theta_{i4}B + \theta_{i5}C + \theta_{i6}E + \theta_{i7}S + \theta_{i8} \cos(a) + \theta_{i9} \sin(a) + \theta_{i10}H_d + \theta_{i11}H_s + \omega_{ij} \quad (2.11)$$

Model estimation and quality control

We aimed at developing a matrix model that is parsimonious and accurate. Parsimony of the present model was achieved by keeping only those explanatory variables that contributed significantly to the goodness of fit as determined through hierarchical

partitioning (HP) and met the expected biological response. To avoid compromised type-I error rates and severe artifacts commonly associated with model selection procedures, HP (Mac Nally 2000) was used for the screening of explanatory variables by decomposing the goodness-of-fit of this model through incremental partitioning to determine the average independent contribution of each variable. The HP analysis was conducted with the hier.part package of the R program (Mac Nally and Walsh 2004).

Accuracy of the present model was evaluated through short-term prediction errors. Short-term prediction error was defined as the difference between the observed and the predicted stand states on 293 independent validation plots. Predicted stand states were obtained by setting the stand states of the initial inventory as the initial states, and applying Eq. 2.2 iteratively over the elapsed period between the two inventories. For comparison, we also calculated prediction errors of the Forest Vegetation Simulator (FVS) model (Keyser 2008) on the same validation plots. FIA data were imported into FVS using the procedures outlined by Shaw (2008), and predictions were estimated for each plot using its database extension software (Crookston et al. 2003).

Spatial autocorrelation

Large-scale spatial trends are a common ecological phenomenon that often cause spatial autocorrelation in biotic and abiotic variables (Legendre 1993). In coastal Alaska for example, Farr and Harris (1979) confirm a latitudinal effect on site index, and Harris and Farr (1974) show that average stand height and total stand volume are correlated with elevation. Barnes (1962) traces inaccuracies in a yield table to uncontrolled geographic locations. McClellan and Biles (2003) report that the current Prognosis growth and yield

model is subject to unrealistic results due to its recruitment function that predicts a uniform mixture of Sitka spruce and western hemlock recruitment everywhere in the region. Since the coastal Alaska region is composed of two distinct parts—Southeast and Southcentral Alaska (Viereck and Little 1975)— and each area has distinctive climatic conditions and species composition (Figure 2.1), testing for spatial autocorrelation is an important step in examining the accuracy of the matrix model presented here.

A key hypothesis then behind this matrix model was that when physiographic factors such as aspect, elevation, and slope are controlled for adequately the models' predictions would exhibit no spatial autocorrelation. Spatial autocorrelation was tested via an analysis of annual prediction errors, ϵ , of Eq. 2,2 using the validation data set errors. If large-scale spatial trends were accounted for, ϵ should be spatially independent. If not, it could imply that spatially dependent factors, such as soil attributes, temperature, or precipitation were not appropriately controlled (Bivand et al. 2008). Annual prediction error was calculated by taking the difference of observed and predicted total basal area B , by species, and dividing it by the remeasurement interval.

We employed three non-parametric tests, *Viz.* variograms and envelopes, Moran's I, Geary's C, to test for spatial autocorrelation. Empirical variograms and envelopes based on permutations were estimated using the *geoR* package in R (Ribeiro Jr and Diggle 2010). Permutation tests of the Moran's I and Geary's C statistics were estimated using the *spdep* package in R (Bivand et al. 2010). Spatial autocorrelation of the annual prediction error was significant if there was agreement between the tests.

Results

Parameter estimates

Parameter estimates for the full and reduced diameter growth models are presented in Table 2.5 and the accompanying contribution of each variable to the goodness-of-fit of the model in Table 2.10. Trees on more productive sites and steeper slopes grew faster, regardless of species. Diameter growth was negatively associated with stand basal area, except for mountain hemlock, of which basal area was insignificant for diameter growth. In general, site productivity contributed most to the goodness-of-fit. Structural and species diversity effects on diameter growth varied highly, but were generally found significant with the HP method.

The parsimonious mortality models, in general, consisted of fewer variables than the parsimonious diameter growth models (Table 2.6). Mortality of western hemlock was found to be independent from any explanatory variable, and was therefore set as a constant. Mortality of Alaskan cedars was only subject to a positive effect of slope, and mortality of other non-major species was only subject to a positive effect of basal area and structural diversity.

Recruitment of all the species was consistently higher if there were more trees of that species (N) on the stand, and basal area (B) reduced recruitment of western hemlock, Sitka spruce, and boreal spruce, but was insignificant for the other species (Table 2.7). In general, N and N^2 contributed considerably (70 - 90 percent) to the goodness-of-fit of recruitment of all the species, while the contribution of all other variables was inconsistent (Table 2.10).

Parameter estimates for the full and reduced volume and biomass models were presented in Tables 2.8 and 2.9. The coefficient of determination was greater than 90 percent for all the models suggesting that the models explained a large amount of the variability. Diameter and diameter squared were the most important variables and contributed over 99 percent to the goodness-of-fit of stem volume and biomass models. Site productivity (C), although providing much less to the overall goodness-of-fit of each model, had consistent positive effects on volume and biomass in the reduced models.

Prediction errors

Short-term prediction errors were calculated using the 293 post-sample validation plots in terms of basal area by diameter class and species predicted by the present model, and all fell within the 95% confidence intervals of the observed mean and had an overall root mean square error (RMSE) of $4.48 \text{ m}^2 \cdot \text{ha}^{-1}$ (Figure 2.2). In general, the stand state at the second inventory predicted by the present model were close to the observed stand state, and there was no systematic under- or over-estimation. Most prediction errors occurred in the smallest size classes, and the model was more accurate for large trees.

In comparison, predictions made by FVS frequently fell outside the 95% confidence intervals of the observed mean. FVS under-estimated the basal area of the smallest trees, and systematically over-estimated the basal area of trees larger than 20 cm in diameter (Figure 2.2). The present model (RMSE = $4.48 \text{ m}^2 \cdot \text{ha}^{-1}$) reduced the root-mean-square error by 36 percent from FVS (RMSE = $6.98 \text{ m}^2 \cdot \text{ha}^{-1}$).

Residual spatial autocorrelation

Annual prediction errors from the present model and FVS were analyzed with three metrics: empirical variograms and tests of Moran's I and Geary's C. The present model was generally free of spatial autocorrelation according to the three metrics, except that Moran's I value indicated that prediction errors for mountain hemlock were spatially dependent (Figure 2.3). In contrast, both Moran's I and Geary's C values indicated that FVS was subject to strong spatial autocorrelation for mountain hemlock, Sitka spruce, and boreal spruce, and variogram plots also displayed the presence of spatial autocorrelation in mountain hemlock and Sitka spruce, as the variograms of both species fell outside of their empirical envelopes.

Ecological inference

Due to numerous confounding factors, ecological inference from empirical forest dynamics models is admittedly a difficult task (Liang et al. 2005; Monserud 2003). For the dynamics components of this matrix model, namely diameter growth, mortality, and recruitment, the physiographic variables (E , S , and a) had mixed significance and effects (Tables 2.5-2.7) across species, which reinforces the ecological consensus that influence of physiographic conditions varies by species (e.g. Stage and Salas 2007). The effects of tree species diversity (H_s) and tree size diversity (H_d) were also inconsistent across different species.

It is noteworthy that several key explanatory variables were of significant and consistent effects in the present model. For diameter growth, site productivity (C) had a positive effect across all species, which suggests that secondary growth of all the tree

species in Alaska coastal forest is governed by site productivity. Total stand basal area (B) was negatively impacted for all the species but mountain hemlock (Table 2.5), implying that secondary growth of most species slows down as stocking goes up; mountain hemlock may be an exception due to its occurrence in muskegs and near treeline (Viereck and Little 1975), where the competition effect is less limiting than environmental constraints. Higher growth as slope increases is likely a result of better drainage, as flat areas often develop into bogs and muskegs given the very high precipitation in Southeast Alaska. Stand basal area (B) also had a negative impact on the recruitment of western hemlock, Sitka spruce, and boreal spruce, indicating that competition may hinder the recruitment of both shade-tolerant (western hemlock) and less tolerant (Sitka spruce, white spruce) species, and the effect of stocking on recruitment was not only decided by shade-tolerance, but also by the size of seed bank (represented by the total number of mature trees N), site productivity (C), and physiographic conditions (Table 2.7).

Discussion and conclusion

A density-dependent, size-, and species-specific matrix model was developed to study dynamics of Alaska coastal forests. The present model was tested on 293 post-sample validation plots and the predicted stand states all fell within the 95 percent confidence intervals of the observed means. In comparison, the Forest Vegetation Simulator (FVS SEAPROG) systematically underestimated stem density of small trees and overestimated stem density of large trees, and the present model is generally more accurate than FVS with 36 percent less root-mean-square error. Analysis of the present models' residuals

revealed no spatial autocorrelation, which indicated that the model was able to adequately account for the effects of physiographic factors.

Differences between species groups are numerous and difficult to quantify, especially in large regions with many different climatic and physiographic conditions. Large- and fine-scale spatial patterning is known to cause problems in individual tree growth-and-yield models (Fox et al. 2007a, 2007b, Liang and Zhou 2010), but our results support the finding by Liang (2012) that if exogenous variables such as physiographic variables and site productivity are appropriately accounted for, the matrix growth model predictions can be a stationary process. Spatial autocorrelation in a growth model's prediction errors, by species, would inform us that the prediction errors are generally more similar at shorter distances than further apart, implying either that a model did not account for a variable (e.g., localized climatic conditions) or that an error was introduced (e.g., recruitment of species in a region where it is not present). The present model illustrates that the inclusion of physiographic variables in nonspatial models, applied via a matrix growth model, can control for these large- and micro-scale spatial variations in regions having numerous varied climate conditions, consisting of a mixture of tree species that reach the extent of their range, while still being able to provide an adequate level of prediction accuracy.

Users should be aware of the present models' limitations. There is no distinction between forest types and old- or young-growth stands, and a number of species had to be grouped due to data availability and model complexity issues. Long-term predictions can be unstable because of the present models' recruitment equations; e.g. predicting white

spruce regeneration in a western hemlock-Sitka spruce forest. Although the error of annual predicted recruitment is negligible, it can aggregate over time and confound predictions in long-term projection. It is recommended that simulation results over 100 years be taken cautiously. Predictions are limited to trees >12.7cm (5in) at DBH and its recommended that users define their management objectives prior to using the present model if users want to know about growth of trees <12.7cm.

As interest in the region changes from old-growth to young-growth timber management (Alexander et al. 2010), there is increasing need for a model that can accurately predict management effects of both clearcutting and ATC systems (McClellan 2005). Land managers and forest researchers interested in the use of silvicultural systems (i.e. partial cutting and thinning) to achieve structural old-growth characteristics, or to harvest biomass and biofuel, should find the present model useful, as the model was calibrated with an unbiased, representative data set that includes old-growth, young-growth, productive, non-productive, even-aged, and multi-aged stands, and the simple structure and associated computer simulation programs under development will make model application an easy and quick process.

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Table 2.1. Percent basal area of live trees in all the sample plots.

Common name	Scientific name	Basal area (%)
Western hemlock	<i>Tsuga heterophylla</i>	35.11
Sitka spruce	<i>Picea sitchensis</i>	21.29
Mountain hemlock	<i>Tsuga mertensiana</i>	15.36
	Alaska Cedars	19.47
Alaska cedar	<i>Chamaecyparis nootkatensis</i>	11.22
Western red cedar	<i>Thuja plicata</i>	8.25
	Boreal spruce	2.21
White spruce	<i>Picea glauca</i>	1.72
Black spruce	<i>Picea mariana</i>	0.49
	Other species	6.56
Lodgepole pine	<i>Pinus contorta</i>	2.67
Paper birch	<i>Betula papyrifera</i>	1.97
Black cottonwood	<i>Populus trichocarpa</i>	1.15
Quaking aspen	<i>Populus tremuloides</i>	0.54
Red alder	<i>Alnus rubra</i>	0.22
Subalpine fir	<i>Abies lasiocarpa</i>	0.02
	All Species	100.00

¹Nomenclature per Viereck and Little (2007)

Table 2.2. Definition and units of variables used in this study.

Variable	Units	Definition/explanation
<i>a</i>	°	plot slope aspect
<i>B</i>	$\text{m}^2 \cdot \text{ha}^{-1}$	total stand basal area
<i>C</i>	$\text{m}^3 \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$	site productivity
<i>D</i>	cm	diameter at breast height
<i>E</i>	km	plot elevation
<i>g</i>	$\text{mm} \cdot \text{yr}^{-1}$	annual diameter growth
<i>H_d</i>		tree size diversity
<i>H_s</i>		tree species diversity
<i>m</i>	yr^{-1}	average annual mortality rate
<i>Q</i>	$\text{kg} \cdot \text{ha}^{-1}$	total stand gross biomass (oven-dry weight including top, stem, and limbs, except foliage)
<i>N</i>	$\text{trees} \cdot \text{ha}^{-1}$	number of trees per hectare
<i>R</i>	$\text{trees} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$	total stand recruitment, the number of trees per hectare that grew into the smallest diameter class (12.70-18cm) in a year
<i>S</i>	°	average slope of each subplot
<i>T</i>	yrs	elapsed time between inventories
<i>V</i>	$\text{m}^3 \cdot \text{ha}^{-1}$	total stand gross above-ground timber volume

Table 2.3. Summary statistics of plot level variables.

Variables	Mean	SD	Max	Min
$B(\text{m}^2 \cdot \text{ha}^{-1})$	32.05	23.08	138.09	0.19
$C(\text{m}^3 \cdot \text{ha}^{-1} \cdot \text{yr}^{-1})$	2.89	2.45	17.02	0.66
H_d	1.66	0.57	2.50	0.00
H_s	0.59	0.40	1.45	0.00
Q (kg·ha ⁻¹)	182,597	184,749	1,545,519	357
T (years)	8.03	2.64	13.10	1.00
V (m ³ ·ha ⁻¹)	271.29	277.06	2,338.49	0.39
N (trees·ha ⁻¹)				
Western hemlock	134.03	168.65	1,323.51	0.00
Mountain hemlock	75.80	161.50	1,397.87	0.00
Sitka spruce	60.50	143.64	1,457.35	0.00
Alaska cedars	72.00	131.60	951.74	0.00
Boreal spruce	25.42	83.21	654.32	0.00
Other species	41.22	80.99	490.74	0.00
R (trees·ha ⁻¹ ·yr ⁻¹)				
Western hemlock	1.30	2.96	28.09	0.00
Mountain hemlock	0.59	1.96	24.78	0.00
Sitka spruce	0.93	3.74	40.78	0.00
Alaska cedars	0.48	1.41	13.64	0.00
Boreal spruce	0.93	3.23	26.77	0.00
Other species	0.59	3.62	69.98	0.00

Note:

T and R are between the two inventories, and all the remaining variables are at the time of the first inventory.

SD: standard deviation.

Table 2.4. Summary statistics for tree level variables.

	Species					
	Western hemlock	Mountain hemlock	Sitka spruce	Alaska cedars	Boreal spruce	Other species
	<i>D</i> (cm)					
Mean	28.03	25.74	31.28	28.56	17.74	23.66
SD	16.38	12.99	19.48	16.46	5.28	9.32
Max	116.33	107.69	147.32	141.47	47.49	67.31
Min	12.70	12.70	12.70	12.70	12.70	12.70
<i>n</i>	4521	2573	2066	2483	826	1366
	<i>g</i> (cm·year ⁻¹)					
Mean	0.12	0.09	0.22	0.09	0.21	0.17
SD	0.11	0.10	0.22	0.11	0.16	0.19
Max	0.64	0.51	1.21	0.58	0.74	0.95
Min	-0.18	-0.24	-0.16	-0.35	-0.24	-0.27
<i>n</i>	4521	2573	2066	2483	826	1366
	<i>m</i> (year ⁻¹)					
Mean	0.005	0.005	0.006	0.003	0.018	0.009
SD	0.024	0.025	0.027	0.017	0.060	0.034
Max	0.476	1.000	1.000	0.169	0.476	0.476
Min	0.000	0.000	0.000	0.000	0.000	0.000
<i>n</i>	4858	2727	2197	2596	922	1483

Note:

D is calculated at the first inventory, *g* and *m* are between the two inventories.

n: number of observations.

Table 2.5. Estimated parameters of the diameter growth model.

		Model
Western hemlock		
Full		$1.7546^{***} + 2.2310D^{***} - 2.2513D^2^{***} - 0.0064B^{***} + 0.1354C^{***} - 0.5952H_d^{***} - 0.2741H_s^{***} + 0.6753E^{***} + 0.0033S^{***} + 0.0054\cos(a) - 0.1050\sin(a)^{***}$
Reduced		$1.7585^{***} + 2.2342D^{***} - 2.2541D^2^{***} - 0.0065B^{***} + 0.1353C^{***} - 0.5949H_d^{***} - 0.2738H_s^{***} + 0.6747E^{***} + 0.0032S^{***} - 0.1044\sin(a)^{***}$
Mountain hemlock		
Full		$1.8709^{***} - 0.0827D - 0.4595D^2 - 0.0003B + 0.0828C^{***} - 0.4512H_d^{***} - 0.5680H_s^{***} - 0.2919E^{**} + 0.0054S^{***} - 0.0550\cos(a)^* - 0.0082\sin(a)$
Reduced		$1.8490^{***} + 0.0753D^{***} - 0.4672D^2^{***} + 0.0798C^{**} - 0.4483H_d^{***} - 0.5674H_s^{***} - 0.2739E^{***} + 0.0053S^{***}$
Sitka spruce		
Full		$3.1770^{***} + 4.8461D^{***} - 3.2500D^2^{***} - 0.0327B^{***} + 0.2370C^{***} - 1.1379H_d^{***} + 0.1720H_s^{***} + 1.0926E^{**} + 0.0029S - 0.1886\cos(a)^* - 0.0411\sin(a)$
Reduced		$3.1779^{***} + 4.8652D^{***} - 3.2700D^2^{***} - 0.0328B^{***} + 0.2375C^{***} - 1.1374H_d^{***} + 0.1674H_s^* + 1.0497E^{***} + 0.0031S^{***} - 0.1895\cos(a)^{***}$
Alaska cedars		
Full		$0.6783^{**} - 0.1229D + 0.3669D^2 - 0.0035B + 0.1385C^{***} + 0.3485H_d^* - 0.5262H_s^{***} - 1.1643E^{***} + 0.0049S^{***} + 0.1209\cos(a)^{***} + 0.0706\sin(a)^*$
Reduced		$0.7351^{**} - 0.1248D^{***} + 0.3698D^2^{***} - 0.0025B^{**} + 0.1342C^{***} + 0.2986H_d^{***} - 0.5168H_s^{***} - 1.1017E^{***} + 0.0048S^{***} + 0.1234\cos(a)^{***}$
Boreal spruce		
Full		$1.6224^{**} - 9.5702D + 28.6283D^2^{**} - 0.0448B^{***} + 0.2841C^{***} + 0.8035H_d^{***} + 0.1309H_s + 1.4934E^{***} + 0.0003S - 0.2967\cos(a)^{**} + 0.3583\sin(a)^{***}$
Reduced		$1.6312^{**} - 9.4605D^{***} + 28.442D^2^{***} - 0.0451B^{***} + 0.2825C^{***} + 0.8411H_d^{***} + 1.4047E^{***} + 0.0006S^{**} - 0.2866\cos(a)^{**} + 0.3647\sin(a)^{***}$
Other species		
Full		$3.4441^{***} - 1.7078D + 4.5096D^2 - 0.0042B + 0.2272C^{***} - 1.3176H_d^{***} - 0.6592H_s^{***} - 0.7719E + 0.0143S^{***} - 0.0096\cos(a) + 0.0508\sin(a)$
Reduced		$3.0086^{***} + 0.9709D^* - 0.0024B^{***} + 0.2309C^{***} - 1.3518H_d^{***} - 0.6210H_s^{***} + 0.0129S^{***}$

Note:

Significance levels: * <0.05 ; ** <0.01 ; *** <0.001

Table 2.6. Estimated parameters of the mortality models.

Model	
Western hemlock	
Full	$-1.255^{***} - 0.972D + 0.815D^2 + 0.002B - 0.025C - 0.068H_d - 0.100H_s - 0.534E^* + 0.001S - 0.009\cos(a) + 0.036\sin(a)$
Reduced	-1.641^{***}
Mountain hemlock	
Full	$-1.705^{***} + 0.269D - 0.425D^2 - 0.013B^{***} + 0.027C - 0.082H_d + 0.457H_s^{**} + 4.686E + 0.003S - 0.034\cos(a) + 0.004\sin(a)$
Reduced	$-1.564^{***} - 0.013B^{***} - 0.029H_d^* + 0.409H_s^*$
Sitka spruce	
Full	$-1.984^{***} - 1.397D^{**} + 0.702D^{2*} + 0.004B + 0.008C + 0.167H_d + 0.074H_s - 1.355E^* + 0.005S^* - 0.005\cos(a) + 0.018\sin(a)$
Reduced	$-1.840^{***} - 0.454D^* + 0.007B^{**} - 0.640E^{**}$
Alaska cedars	
Full	$-1.467^{**} - 1.167D + 0.926D^2 + 0.004B + 0.048C - 0.308H_d + 0.268H_s + 0.329E - 0.006S^* - 0.021\cos(a) + 0.008\sin(a)$
Reduced	$-1.756^{***} - 0.005S^{**}$
Boreal spruce	
Full	$-2.466^{***} + 13.847D^* - 22.459D^2 + 0.022B^* - 0.054C - 0.475H_d^* + 0.181H_s + 0.350E - 0.021S^{***} - 0.162\cos(a) - 0.059\sin(a)$
Reduced	$-2.718^{***} + 13.021D^{***} - 21.211D^{2***} - 0.016S^{***} - 0.038\cos(a)^*$
Other species	
Full	$-2.407^{***} + 2.201D - 5.087D^2 + 0.011B^* - 0.014C + 0.399H_d - 0.162H_s - 0.082E - 0.003S + 0.031\cos(a) + 0.119\sin(a)$
Reduced	$-2.207^{***} + 0.012B^{***} + 0.246H_d^{***}$

Note:

Probit mortality equations were estimated by maximum likelihood.

Significance levels: * <0.05 ; ** <0.01 ; *** <0.001

Table 2.7. Estimated parameters of the recruitment model.

	Model	Scale
Western hemlock		
Full	$-6.066^{***} + 0.039N^{***} - 0.027N^{2***} - 0.044B^* + 0.342C^{**} - 1.222H_d + 2.597H_s^{**} - 0.134E + 0.003S - 0.661\cos(a) - 0.215\sin(a)$	5.238 ^{***}
Reduced	$-6.109^{***} + 0.040N^{***} - 0.028N^{2***} - 0.056B^{***} + 0.271C^{***} - 0.002S^* - 0.659\cos(a)^*$	5.308 ^{***}
Mountain hemlock		
Full	$-9.863^{***} + 0.018N^{***} - 0.006N^2 - 0.026B - 0.731C^{**} + 1.364H_d + 2.118H_s^* + 0.586E^{**} + 0.026S + 0.468\cos(a) + 0.383\sin(a)$	4.422 ^{***}
Reduced	$-6.227^{***} + 0.021N^{***} - 0.010N^{2***} - 0.892C^{**} + 0.395E^{***} + 0.030S^*$	4.462 ^{***}
Sitka spruce		
Full	$-8.145^{**} + 0.050N^{***} - 0.021N^{2*} - 0.124B^* + 0.565C^* - 3.718H_d^* + 1.383H_s - 0.500E + 0.081S^* - 0.773\cos(a) + 1.930\sin(a)$	9.780 ^{***}
Reduced	$-7.408^{**} + 0.048N^{***} - 0.021N^{2***} - 0.094B^{***} + 0.532C^{***} - 2.919H_d^{***}$	9.981 ^{***}
Alaska cedars		
Full	$-7.843^{***} + 0.036N^{***} - 0.034N^{2***} - 0.041B - 0.001C - 0.465H_d + 3.392H_s^{**} - 0.219E + 0.022S + 0.179\cos(a) + 0.207\sin(a)$	3.756 ^{***}
Reduced	$-9.100^{***} + 0.035N^{***} - 0.036N^{2***} - 0.129C^{**} + 3.310H_s^{***}$	3.878 ^{***}
Boreal spruce		
Full	$-5.834^* + 0.138N^{***} - 0.183N^{2***} - 0.341B^{***} + 0.386C - 1.247H_d - 3.125H_s - 0.140E + 0.034S + 0.661\cos(a) - 0.026\sin(a)$	6.828 ^{***}
Reduced	$-4.333^{**} + 0.136N^{***} - 0.180N^{2***} - 0.312B^{***} - 1.433H_d^{***} - 2.934H_s^*$	6.945 ^{***}
Other species		
Full	$-10.354^{**} + 0.073N^{**} - 0.016N^2 - 0.159B + 0.511C - 5.844H_d^* + 8.541H_s^{**} - 0.503E - 0.011S - 2.088\cos(a) - 0.746\sin(a)$	10.308 ^{***}
Reduced	$-10.538^{***} + 0.108N^{***} - 0.106N^{2***} - 5.797H_d^{***}$	10.727 ^{***}

Note:

Tobit recruitment equations were estimated by maximum likelihood

Significance levels: *<0.05; **<0.01; ***<0.001

Table 2.8. Estimated parameters of the stem volume model.

	Model	R^2
Alaska cedars		
Full	$-0.4193^{***} + 1.5965D^{***} + 2.4582D^{2***} - 0.0047B + 0.0835C^{***} + 0.047H_d + 0.0911H_s^{***} + 0.0434E^* + 0.0028S + 0.0091\cos(a) + 0.0038\sin(a)$	0.95
Reduced	$-0.292^{***} + 1.6253D^{***} + 2.4015D^{2***} - 0.003B^{***} + 0.084C^{***}$	0.95
Boreal spruce		
Full	$-0.0362^{**} - 0.3256D^{**} + 6.2675D^{2***} + 0.0052B^{**} + 0.0013C + 0.0116H_d + 0.0035H_s - 0.0971E^{***} - 0.0006S + 0.005\cos(a) + 0.0093\sin(a)^{**}$	0.94
Reduced	$-0.0123^{***} - 0.2632D^{***} + 6.1993D^{2***} - 0.1153E^{***} + 0.0067\sin(a)^{***}$	0.94
Other species		
Full	$-0.1833^{***} + 0.4255D^{***} + 4.8037D^{2***} + 0.015B^{***} + 0.0347C^{***} - 0.0281H_d^* + 0.0361H_s^{***} - 0.0891E^{***} + 0.0032S^* - 0.0004\cos(a) + 0.0115\sin(a)^*$	0.93
Reduced	$-0.1322^{***} + 0.3291D^{***} + 4.969D^{2***} + 0.0276H_d^* + 0.0167\sin(a)^*$	0.92

Note:

Stem volume equations were estimated by ordinary least squares

Significance levels: * <0.05 ; ** <0.01 ; *** <0.001

R^2 : adjusted R-squared value

Independent and response variables are $\ln + 1$ transformed. $\sin(a)$ and $\cos(a)$ are $\ln + 2$ transformed

Species-specific volume equations are from 13 published sources, as documented in Barrett and Christensen (2011)

Table 2.9. Estimated parameters of the stem biomass model.

	Model	R^2
Alaska cedars		
Full	$0.638^{***} + 17.302D^{***} - 10.925D^{2***} - 0.018B + 0.162C^{***} + 0.404H_d^{***} + 0.621H_s^{***} + 0.318E^{***} - 0.002S + 0.013\cos(a) - 0.029\sin(a)$	0.95
Reduced	$1.447^{***} + 17.509D^{***} - 11.318D^{2***} + 0.162C^{***} - 0.014\sin(a)^*$	0.95
Boreal spruce		
Full	$1.068^{***} + 25.220D^{***} - 28.061D^{2***} + 0.093B^{***} - 0.091C^{***} - 0.096H_d^* + 0.014H_s - 1.074E^{***} - 0.018S^{**} + 0.024\cos(a) + 0.053\sin(a)^*$	0.91
Reduced	$0.991^{***} + 24.841D^{***} - 27.496D^{2***} + 0.066B^{***} - 1.172E^{***} + 0.084\sin(a)^{***}$	0.90
Other species		
Full	$0.603^{***} + 24.717D^{***} - 24.418D^{2***} + 0.094B^{***} + 0.259C^{***} - 0.394H_d^{***} + 0.167H_s^{***} - 0.363E^{***} + 0.017S^{**} + 0.005\cos(a) - 0.003\sin(a)$	0.92
Reduced	$0.664^{***} + 24.215D^{***} - 23.616D^{2***} + 0.252C^{***}$	0.91

Note:

Significance levels: * <0.05 ; ** <0.01 ; *** <0.001

R^2 : adjusted R-squared value

Independent and response variables are $\ln + 1$ transformed. $\sin(a)$ and $\cos(a)$ are $\ln + 2$ transformed

Species-specific biomass equations are from 13 published sources, as documented in Barrett and Christensen (2011)

Table 2.10. Independent contribution (%) of each explanatory variable to the goodness-of-fit of the response variables.

	Western hemlock	Mountain hemlock	Sitka spruce	Alaskan cedars	Boreal spruce	Other species
Diameter growth						
<i>D</i>	2.6 ***	2.4 ***	2.4 ***	5.9 ***	5.6 ***	0.9 *
<i>D</i> ²	1.6 ***	2.4 ***	1.4 ***	5.7 ***	7.1 ***	0.7
<i>B</i>	5.4 ***	1.3	28.2 ***	7.6 ***	15.5 ***	6.5 ***
<i>C</i>	49.9 ***	2.4 **	34.1 ***	32.2 ***	28.8 ***	34.7 ***
<i>H_d</i>	20.2 ***	18.3 ***	29.7 ***	6.4 ***	7.0 ***	29.2 ***
<i>H_s</i>	10.0 ***	54.6 ***	0.4 *	13.0 ***	0.5	24.4 ***
<i>E</i>	1.5 ***	3.4 ***	0.9 ***	16.7 ***	9.1 ***	0.2
<i>S</i>	1.7 ***	11.9 ***	1.2 ***	6.8 ***	2.4 **	2.7 ***
cos(<i>a</i>)	0.3	1.0	0.9 ***	4.2 ***	17.1 ***	0.5
sin(<i>a</i>)	6.8 ***	2.2	0.8	1.4	6.9	0.2
Mortality						
<i>D</i>	15.9	0.6	18.3 *	8.3	20.0 ***	2.1
<i>D</i> ²	8.8	0.7	6.2	4.1	13.8 ***	2.9
<i>B</i>	9.6	52.5 ***	18.8 **	4.6	4.7	40.6 ***
<i>C</i>	14.4	0.9	4.8	9.8	0.7	0.8
<i>H_d</i>	0.8	9.7	13.4 *	15.8	2.4	32.4 ***
<i>H_s</i>	7.1	31.8 ***	0.8	7.3	0.1	2.2
<i>E</i>	22.8	1.8	20.9 **	1.8	1.5	2.1
<i>S</i>	5.5	1.3	13.7	46.9 **	48.0 ***	3.3
cos(<i>a</i>)	1.7	0.6	2.0	0.4	8.5 *	2.6
sin(<i>a</i>)	13.3	0.2	1.0	0.9	0.4	11.1
Recruitment						
<i>N</i>	52.5 ***	50.4 ***	39.1 ***	57.8 ***	63.7 ***	33.1 ***
<i>N</i> ²	18.4 ***	39.8 ***	42.6 ***	22.8 ***	27.4 ***	57.4 ***
<i>B</i>	4.1 ***	-1.1	3.1 ***	-0.5	4.8 ***	1.5
<i>C</i>	12.6 ***	2.1 **	4.7 ***	3.0 **	-1.2	-0.2
<i>H_d</i>	1.7	-1.3	9.4 ***	0.2	6.2 ***	6.0 ***
<i>H_s</i>	1.9	-1.5	1.0	16.7 ***	1.2 *	0.0
<i>E</i>	1.7	10.7 ***	0.4	-0.1	-1.4	0.1
<i>S</i>	2.5 *	1.7 **	-0.1	-0.7	0.5	-0.1
cos(<i>a</i>)	2.3 *	-1.5	-0.9	-1.3	-1.4	-0.1
sin(<i>a</i>)	2.2	0.8	0.7	2.1	0.3	2.4

Note:

Significance levels: *<0.05; **<0.01; ***<0.001

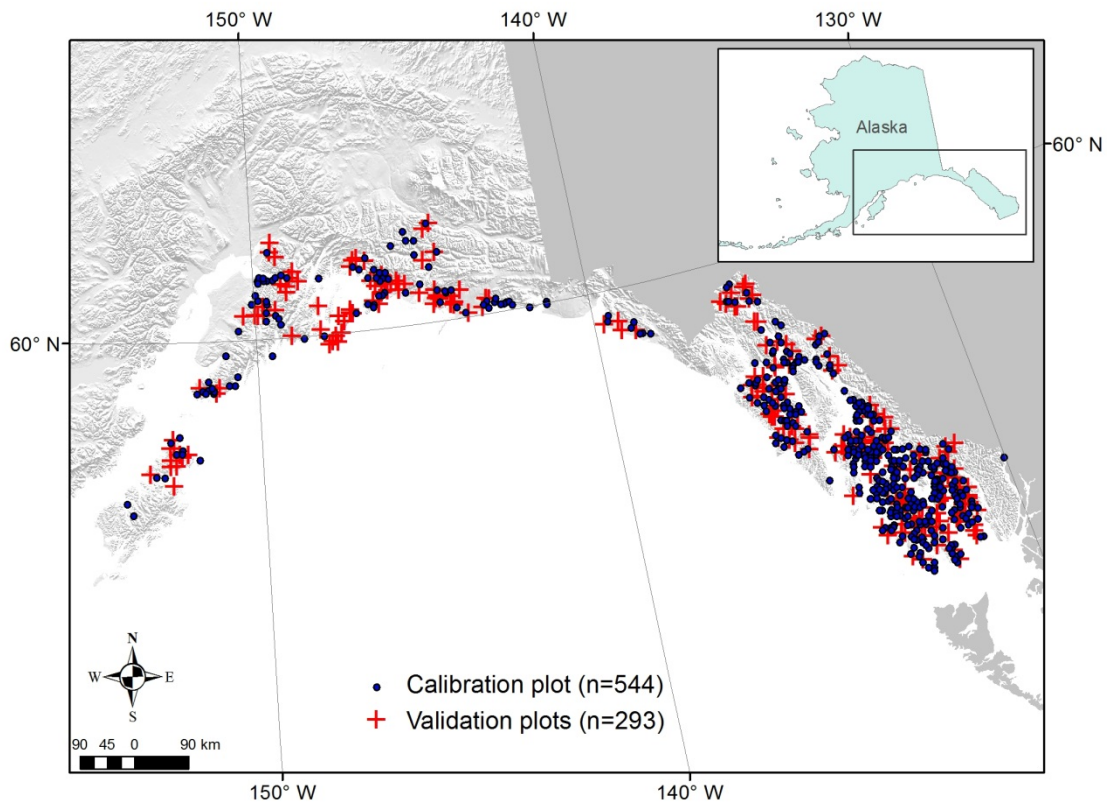


Figure 2.1. Location of sample plots used to calibrate and validate the matrix growth model.

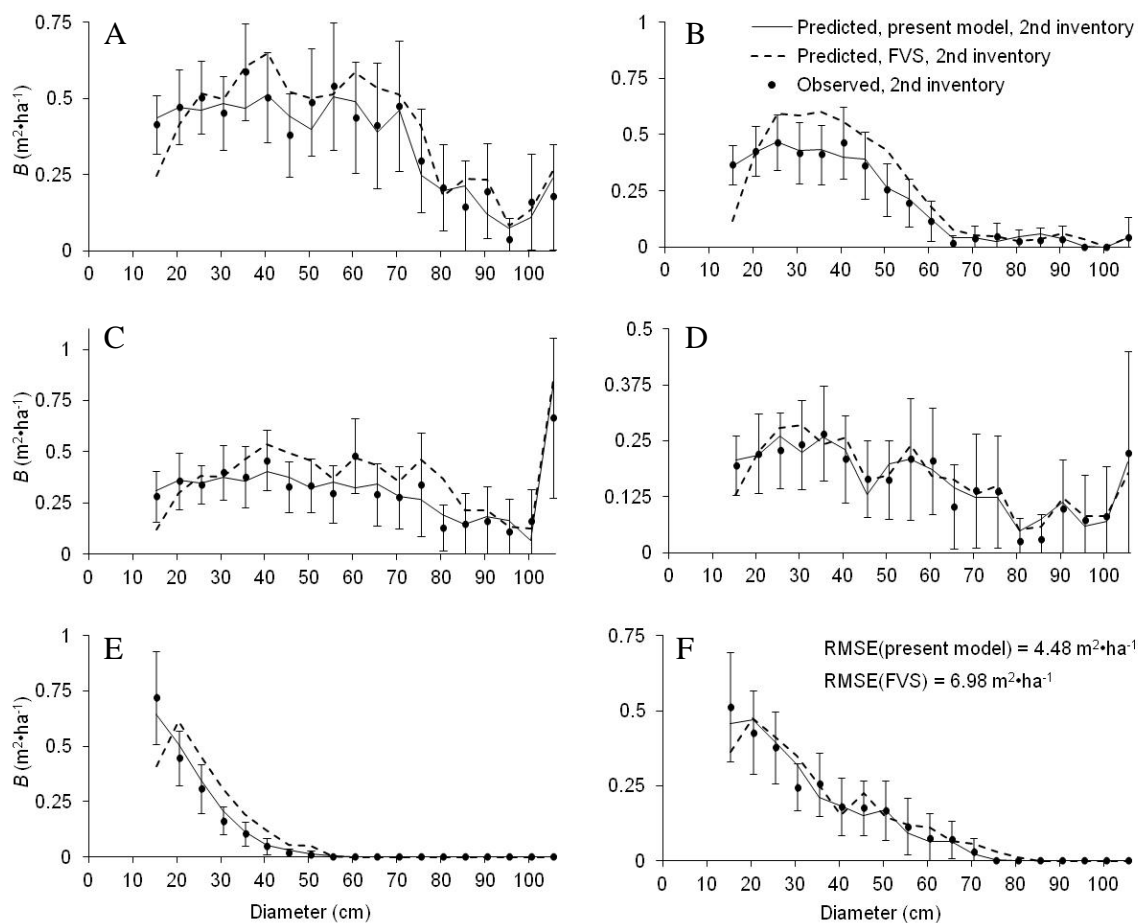


Figure 2.2. Average predicted and observed stand states at the second inventory for the present model and FVS on the 293 post-sample validation plots, with the 95% confidence interval of the observed mean, for (A) western hemlock; (B) mountain hemlock; (C) Sitka spruce; (D) Alaska cedars; (E) black spruce and white spruce; (F) other species.

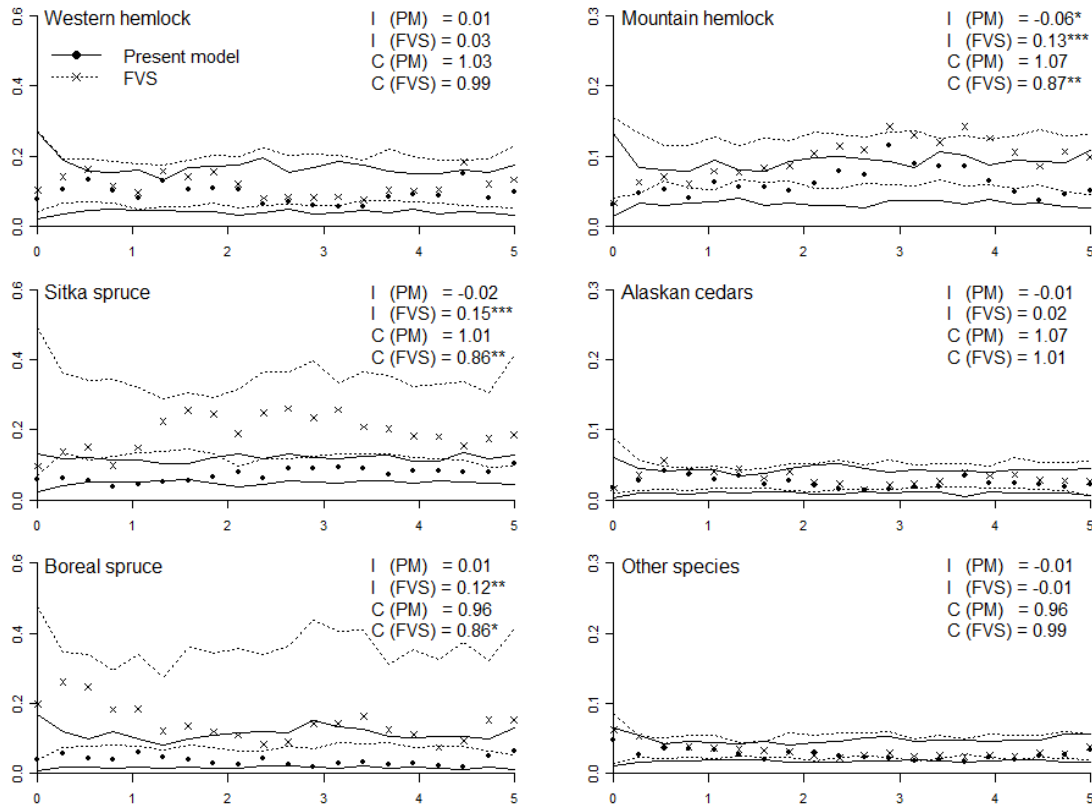


Figure 2.3. Empirical variograms and envelopes based on permutations of the annual prediction errors of the present model (PM) and FVS. The vertical axis is the semi-variance and the horizontal axis represents the distance between plots in WGS84 degrees. I and C, respectively.

Chapter 3

AlaskaPro and Forest Growth Modeler (fgmod): Computer Software to Simulate Growth, Yield and Management of Alaska Forest²

Abstract

AlaskaPro and the forest growth modeler (fgmod) are both cross-platform software applications designed to implement and display the results of matrix forest growth and yield models. AlaskaPro is a macro-enabled Microsoft Excel application. fgmod is a program developed in the R programming language. Both programs are easy to use, but have different intended audiences: AlaskaPro is intended for forest resource managers who don't want to spend time learning a new programming language and fgmod is intended for forest researchers who want to quickly manipulate the output. AlaskaPro enables the prediction of forest growth dynamics in coastal Alaska and fgmod has growth models for both Interior and coastal Alaska. Both programs are free, but require different procedures to operate. This manual describes how to install and use these programs and provides an example to help users get started. AlaskaPro and fgmod implements matrix growth and yield models and is intended for use on all of Alaska's forestland.

Keywords: fgmod, AlaskaPro, simulation, growth model, forest management, economics, ecology, diversity, risk, boreal forest, coastal forest, western hemlock, mountain hemlock, Sitka spruce, Alaska cedar, western red cedar, black spruce, white spruce, aspen, birch.

² Peterson, R.L., Liang, J., Barrett, T.M. Prepared for submission as a Forest Service General Technical Report.

Introduction

AlaskaPro and forest growth modeler (fgmod) are both cross-platform software that facilitate the use of growth and yield models developed for Alaska forests. AlaskaPro and fgmod enable forest managers to predict the effects of various management decisions on stand attributes such as growth, productivity, income, and diversity. At the moment, there are two variants available: coastal Alaska (Peterson et al. 2014) and Interior Alaska (Liang et al. 2010). The following chapter is separated into three parts; 1) a background discussion of AlaskaPro and fgmod, 2) how to install each program and 3) how to use the programs to simulate forest growth. Part 1 provides the necessary background information needed to use the models and explains what motivated AlaskaPro and fgmod's development. Part 2 lists the system requirements and explains how to install AlaskaPro and fgmod. Part 3 shows how to run simulations using AlaskaPro and fgmod. Additional information about the data used to calibrate the models, matrix models and diversity metrics can be found in the appendices. Appendix 3.1 describes the data used in the calibration of the coastal and interior models. Appendix 3.2 outlines how matrix growth models work. Appendix 3.3 discusses the three diversity metrics used in the models.

AlaskaPro and fgmod software and other documentation can be obtained by contacting the author or by referring to the supplemental files (fgmod.tar.gz; Alaska Pro – Coastal.xlsm).

Background

What are AlaskaPro and fgmod?

AlaskaPro is an Excel spreadsheet program that can be used to simulate forest growth (Figure 3.1). The coastal Alaska variant is currently the only model available for use in AlaskaPro. Excel is a user-friendly environment and is easily learned and widely available. Excel's usefulness is its simplicity, but this simplicity comes with a cost. Changing the Excel program is a time consuming activity and can be fraught with errors that are not easy to troubleshoot or even identify! A quicker, more flexible programming environment such as R is an appealing alternative (R Core Team 2014). fgmod is a R program that, like AlaskaPro, can be used to simulate forest growth and because of its flexibility, both coastal and interior variants are available. fgmod is also user-friendly, but R does have a learning curve and is not as readily accessible as AlaskaPro.

Users can quickly determine the impact of numerous forest management decisions on a variety of tree species (Table 3.1). The coastal Alaska variant of AlaskaPro and fgmod is calibrated for use with the following tree species: *Abies lasiocarpa* (subalpine fir), *Alnus rubra* (red alder), *Betula papyrifera* (paper birch), *Chamaecyparis nootkatensis* (Alaska cedar), *Picea glauca* (white spruce), *Picea mariana* (black spruce), *Picea sitchensis* (Sitka spruce), *Pinus contorta* (lodgepole pine), *Populus trichocarpa* (black cottonwood), *Populus tremuloides* (quaking aspen), *Thuja plicata* (western red cedar), *Tsugua heterophylla* (western hemlock), and *Tsuga mertensiana* (mountain hemlock). The Interior Alaska variant of fgmod is calibrated for use with black spruce, *Betula*

neopalaskana (Alaska paper birch), quaking aspen, and white spruce (Liang 2010).

Important features of AlaskaPro include:

- Data used in the calibration of the coastal and interior models are from two independent databases consisting of 544 and 446 plots, respectively (O'Connell et al. 2013; Malone et. al 2009). Data represent a wide variety of forest types and site conditions (Appendix 3.1).
- Tree species with individual models is variant specific. In the coastal Alaska variant, individual specie models are available for western hemlock, mountain hemlock, Sitka spruce and specie group models are available for Alaska cedars (western red cedar and Alaska cedar), boreal spruce (black and white spruce), and other species (black cottonwood, lodgepole pine, paper birch, red alder , and subalpine fir). In the Interior Alaska variant, individual specie models are available for Alaska paper birch, black spruce, white spruce, and quaking aspen.
- Growth models explicitly control for the impact of forest diversity on stand development.
- Inclusion of physiographic variables such as elevation, slope, aspect, and permafrost tailor model predictions to local site conditions.

Spreadsheet programs similar to AlaskaPro include CalPro, NorthPro, SouthPro, WestPro, and WestProPlus (Liang et al. 2004a, Liang et al. 2004b, 2006, Ralson et al. 2003, Schulte et al. 1998). Users who are interested in additional information and examples are encouraged to consult the aforementioned programs' user manuals.

Why do we need models for this area?

Alaska contains 17 percent of all forested land in the United States (Smith et al., 2009). The forested area spans roughly 33 degrees longitude and 14 degrees latitude and numerous forest types (Ruefenacht et al., 2008), though it is predominantly separated into two broad ecoregion zones; coastal and Interior (Viereck and Little, 1975). Commercial timber harvest occurs primarily in Southeast and Southcentral Alaska (Brackley et al., 2009). Timber is primarily utilized as saw logs (Halbrook et al., 2009), however rising energy costs in the state has generated a lot of interest about wood-based energy (Alexander et al. 2010; TLMP 2008). Since 35% of Alaska is forested land (Smith *et al.*, 2009), non-timber forest products are also of great importance; these products include hunting, tourism, and recreation (Clason et al. 2008; Pilz et al. 2006). Management of Alaska's forests requires accurate growth and yield models that are applicable to a wide array of forest types and site conditions.

Even-aged forest management is the dominant form of silviculture practiced in Alaska (Deal et al. 2010), but despite this, managers are increasingly prescribing uneven-aged systems (TLMP 2008). Concerns that uneven-aged forestry can result in reduced stand vigor, structural diversity, and species composition along with increased mortality, wounding, and windthrow have been shown to be mostly unfounded (Deal 2009). AlaskaPro and fgmod are tools that provide researchers the ability to predict a stand's development into the future and evaluate the outcome of even- and uneven-aged management decisions.

How does AlaskaPro and fgmod work?

AlaskaPro and fgmod make deterministic predictions of forest dynamics using a matrix growth model (Appendix 3.2). The two variants included are stand specific, meaning that users need to enter the number of trees by size- and species (Table 3.1). In addition to specifying the initial stem distribution, each variant requires additional but slightly different information (Table 3.2). Users of the coastal variant need to specify elevation, slope, aspect, and site productivity class. Users of the Interior variant need to specify elevation, slope, aspect, and permafrost. Users should check that all of their data fall within the range of data used to calibrate both variants (Tables 3.3-3.5). Once all of the necessary input is provided, deterministic predictions of forest growth are made by applying the appropriate matrix growth models (Tables 3.6-3.10).

Getting started

AlaskaPro and fgmod are both cross-platform software meaning that both can be used on Windows, Macintosh, and Linux operating systems. Each has minimal, albeit different, software requirements. They are easily installed and uninstalled and do not require administrative privileges to use.

AlaskaPro system requirements

To operate AlaskaPro you will need a computer that has the following software and hardware specifications:

- A personal computer with Microsoft Excel 2007 or newer installed
- At least 6 megabytes (MB) of hard disk space

- A free copy of AlaskaPro

Installing and removing AlaskaPro

AlaskaPro is a macro-enabled spreadsheet program. It is designed and implemented in the simplest possible way to facilitate the programs use. AlaskaPro is installed with the following directions:

1. Insert the disk with AlaskaPro.xlsm or download it online. If you have downloaded AlaskaPro.xlsm online go to step 3.
2. Select the AlaskaPro.xlsm file and copy it onto your hard disk.
3. Open AlaskaPro.xlsm and enable macros.
4. To remove AlaskaPro.xlsm from your computer simply close and delete the file.

fgmod system requirements

To operate fgmod you will need a computer that has the following software and hardware specifications:

- A personal computer with R (≥ 3.10) installed
- At least 1 megabytes (MB) of hard disk space
- A free copy of fgmod

Installing and removing fgmod

fgmod is a R package and is currently only available as a binary package. It is designed to be user friendly and comes with a help file that describes how to use the program. fgmod is installed with the following directions:

1. Insert the disk with fgmod_1.0.tar.gz or download it online. If you have downloaded AlaskaPro.xlsm online go to step 3.
2. Select the AlaskaPro.xlsm file and copy it onto your hard disk.
3. Open R and enter the following command into the command prompt:

```
install.packages(file.choose(), repos=NULL, type="binary")
```
4. Step 3 will prompt you to select a file. Navigate to where fgmod_1.0.tar.gz is stored on your hard disk and select the file. This will install fgmod on your computer.
5. To remove fgmod_1.0.tar.gz from your computer enter the following code into R:

```
remove.packages("fgmod")
```

Using AlaskaPro and fgmod

Target distribution

Both AlaskaPro and fgmod ask users to enter the initial and target stand distribution as the number of trees per hectare by species and size. The target distribution is the distribution of trees, after harvest, the user wants to remain on the stand. An entry of 0 would remove all trees of that size and species. Entering a large value, such as 999, would result in no harvest for that particular size and species. Specifying a target distribution such as a diameter limit cut can be achieved by setting the target distribution of trees greater than a specified size as 999 for all species (Liang et al. 2006). The target distribution can be used to represent thinning by setting the target distribution to a pre-determined fraction of the initial stand distribution. Removal of a specific tree or group of trees can be simulated by setting the year of first harvest to 1 and setting the associated

size and species target distribution as the initial stand distribution minus the trees to be removed.

AlaskaPro input

To enter data into AlaskaPro, navigate to the Input tab (Figure 3.2). Enter the following: 1) stem distribution of trees by species, 2) target distribution of trees by species, 3) variant-specific model parameters (elevation, slope, aspect, site productivity), and 4) simulation parameters (simulation length, year of first harvest, rotation length).

Running and saving simulations in AlaskaPro

To run a simulation in AlaskaPro, navigate to View Macros, select Predict and press run (Figure 3.3). Running a simulation may take some time depending on the simulation length and computer speed. The output of the simulation is stored in the following tabs: PredictedTPHA (stores the predicted trees per hectare by species, size and year), PredictedBA (stores the predicted basal area per hectare by species, size and year), HarvestTPHA (if harvest is specified, stores predicted harvest in terms of trees per hectare by species, size and harvest year), PredictedOther (stores predicted species diversity metrics, volume and biomass by species and year), and Figures (Figure 3.4). To store output from a simulation, navigate to File, Save As, enter a new File name, and press save.

fgmod input

Prior to running any simulation, make sure that fgmod is loaded into R: `library(fgmod)`. To enter data into fgmod run the following code: `mydata = fgdata()`. This

command will prompt users to enter stand-specific information and store it into the object `mydata` (Figure 3.5). Users enter the data in the following sequence: 1) stem distribution of trees by species, 2) target distribution of trees by species and 3) variant-specific model parameters (elevation, slope, aspect, site productivity). To look at or obtain summary statistics of the data entered, run the code `print(mydata)` or `summary(mydata)`. If users want to change any elements of input, they can do so by running the following code: `mydata = edit(mydata)`.

Running and saving simulations in fgmod

Since two variants are available in `fgmod`, users must load the variant-specific model prior to running a simulation in R. To do so, enter the following commands: `data(akinterior)` or `data(akcoastal)` depending on the variant and `mymod = fgmodel()`. The last command will prompt users to specify the variant and store that model into the object `mymod`. Then to run a simulation, enter the following code: `mypred = fgpred(fgmodel=mymod, fgdata=mydata, SimLength=100, T=8)`, where `SimLength` corresponds to the length of simulation in years and `T` is the time average time elapsed between inventories and is variant specific (Figure 3.6; Table 3.7). Output is stored in the object `mypred` in this instance. Users can inspect the output with a variety of commands: `print(mypred)` displays the number of trees per acre by species and size, `summary(mypred)` displays various stand attributes, and `plot(mypred)` graphically displays the number of trees by species and size (Figure 3.7). If running multiple simulations, users can easily store the output of each simulation into a new object (e.g.

mypred2, mypred3, etc.). A help manual is included with fgmod that provides additional information about the programs functions as well as examples.

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Table 3.1. Percent of live trees by basal area and species in all sample plots in both coastal and Interior variants.

Common name	Scientific name ¹	Species code	Percent basal area (%)
Coastal variant			
Western hemlock	<i>Tsuga heterophylla</i>	1	35.11
Sitka spruce	<i>Picea sitchensis</i>	3	21.29
Mountain hemlock	<i>Tsuga mertensiana</i>	2	15.36
Alaska cedars		4	
Alaska cedar	<i>Chamaecyparis nootkatensis</i>		19.47
Western red cedar	<i>Thuja plicata</i>		11.22
Boreal spruce		5	
White spruce	<i>Picea glauca</i>		8.25
Black spruce	<i>Picea mariana</i>		2.21
Other species		6	
Lodgepole pine	<i>Pinus contorta</i>		1.72
Paper birch	<i>Betula papyrifera</i>		0.49
Black cottonwood	<i>Populus trichocarpa</i>		6.56
Quaking aspen	<i>Populus tremuloides</i>		2.67
Red alder	<i>Alnus rubra</i>		1.97
Subalpine fir	<i>Abies lasiocarpa</i>		1.15
All species			100
Interior variant ²			
Alaska paper birch	<i>Betula neoalaskana</i>	1	28
Quaking aspen	<i>Populus tremuloides</i>	2	20
White spruce	<i>Picea glauca</i>	3	37
Black spruce	<i>Picea mariana</i>	4	5
All species			90

¹Nomenclature per Viereck and Little (2007)²Interior variant information adapted from Liang 2010

Table 3.2. Definition and units of variables used in the variants.

Variable	Units	Definition/explanation
<i>a</i>	°	plot slope aspect
<i>B</i>	m ² ·ha ⁻¹	total stand basal area
<i>C</i>	m ³ ·ha ⁻¹ ·yr ⁻¹	site productivity
<i>D</i>	cm	diameter at breast height
<i>E</i>	1000m	plot elevation
<i>g</i>	mm·yr ⁻¹	annual diameter growth
<i>H</i>		number of trees species on plot
<i>H_d</i>		tree size diversity (19 size-classes)
<i>H_s</i>		tree species diversity (6 specie groups)
<i>m</i>	yr ⁻¹	annual tree mortality
<i>M</i>	kg·ha ⁻¹	oven-dried single-tree gross biomass (including top, stem, and limbs), does not include foliage.
<i>N</i>	trees·ha ⁻¹	number of trees per hectare
<i>P</i>		categorical variable indicting the amount of permafrost present, with 1 being most likely and 4 being not likely at all
<i>R</i>	trees·ha ⁻¹ ·yr ⁻¹	recruitment, the number of trees per hectare that grew into the smallest diameter class (12.70-18cm) in a year
<i>S</i>	°	slope of plot in degrees
<i>s</i>	%	percent slope
<i>T</i>	yr	elapsed time between inventories
<i>V</i>	m ³ ·ha ⁻¹	gross single-tree volume outside of bark

Table 3.3. Summary statistics of plot level variables.

Variable	Mean	SD	Max	Min
Coastal variant				
$B(\text{m}^2 \cdot \text{ha}^{-1})$	32.05	23.08	138.09	0.19
$C(\text{m}^3 \cdot \text{ha}^{-1} \cdot \text{yr}^{-1})$	2.89	2.45	17.02	0.66
H_d	1.66	0.57	2.50	0.00
H_s	0.59	0.40	1.45	0.00
$M(\text{kg} \cdot \text{ha}^{-1})$	182,597	184,749	1,545,519	357
$T(\text{years})$	8.03	2.64	13.10	1.00
$V(\text{m}^3 \cdot \text{ha}^{-1})$	271.29	277.06	2,338.49	0.39
E	0.20	0.17	0.82	0.03
S	37.77	25.35	80.60	0.00
$\cos(a)$	0.19	0.75	1.00	-1.00
$\sin(a)$	0.01	0.63	1.00	-1.00
Interior variant ¹				
$B(\text{m}^2 \cdot \text{ha}^{-1})$	22.91	0.49	63.43	0.00
P	3.33	0.04	4.00	1.00
H	2.32	0.04	5.00	0.00
E	0.36	0.01	0.96	0.02
S	10.17	0.60	77.00	0.00
$\cos(a)$	-0.25	0.03	1.00	-1.00
$\sin(a)$	0.00	0.03	1.00	-1.00

Note: T and R are between the two inventories and all the remaining variables are at the time of the first inventory.

SD: standard deviation.

¹Interior variant information adapted from Liang 2010

Table 3.4. Summary statistics of plot level variables.

	Coastal variant						Interior variant ¹			
	Western hemlock	Mountain hemlock	Sitka spruce	Alaska cedars	Boreal spruce	Other species	Alaska birch	Quaking aspen	White spruce	Black spruce
	<i>N</i> (trees·ha ⁻¹)									
Mean	134.03	75.80	60.50	72.00	25.42	41.22	336.35	286.82	651.20	281.56
SD	168.65	161.50	143.64	131.60	83.21	80.99	31.73	32.13	44.36	51.69
Max	1323.51	1397.87	1457.35	951.74	654.32	490.74	5955.03	4867.80	8771.93	12700.77
Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	<i>R</i> (trees·ha ⁻¹ ·yr ⁻¹)									
Mean	1.30	0.59	0.93	0.48	0.93	0.59	5.60	2.49	27.92	32.30
SD	2.96	1.96	3.74	1.41	3.23	3.62	0.97	0.69	2.63	6.48
Max	28.09	24.78	40.78	13.64	26.77	69.98	197.68	222.39	444.77	1161.35
Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: *N* is calculated at the first inventory, *R* is between the two inventories.

¹Interior variant information adapted from Liang 2010

Table 3.5. Summary statistics for tree level variables.

	Coastal variant					Interior variant ¹				
	Western hemlock	Mountain hemlock	Sitka spruce	Alaska cedars	Boreal spruce	Other species	Alaska birch	Quaking aspen	White spruce	Black spruce
<i>D</i> (cm)										
Mean	28.03	25.74	31.28	28.56	17.74	23.66	13.13	12.30	10.52	6.12
SD	16.38	12.99	19.48	16.46	5.28	9.32	7.57	6.03	7.23	3.90
Max	116.33	107.69	147.32	141.47	47.49	67.31	59.49	53.29	85.39	30.71
Min	12.70	12.70	12.70	12.70	12.70	12.70	1.30	1.30	1.30	1.30
<i>n</i>	4521	2573	2066	2483	826	1366	6080	5206	11677	4862
<i>g</i> (cm·year ⁻¹)										
Mean	0.12	0.09	0.22	0.09	0.21	0.17	0.10	0.08	0.11	0.09
SD	0.11	0.10	0.22	0.11	0.16	0.19	0.12	0.08	0.12	0.11
Max	0.64	0.51	1.21	0.58	0.74	0.95	1.55	0.81	2.50	1.82
Min	-0.18	-0.24	-0.16	-0.35	-0.24	-0.27	-3.99	-0.62	-2.27	-2.20
<i>n</i>	4521	2573	2066	2483	826	1366	6080	5206	11677	4862
<i>m</i> (year ⁻¹)										
Mean	0.005	0.005	0.006	0.003	0.018	0.009	0.02	0.03	0.01	0.01
SD	0.024	0.025	0.027	0.017	0.060	0.034	0.06	0.07	0.04	0.03
Max	0.476	1.000	1.000	0.169	0.476	0.476	0.20	0.20	0.20	0.20
Min	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.00	0.00
<i>n</i>	4858	2727	2197	2596	922	1483	6885	6011	12161	5014

Note: *D* is calculated at the first inventory, *g* and *m* are between the two inventories.

n: number of observations.

¹Interior variant information adapted from Liang 2010

Table 3.6. Parameters of the diameter growth model.

Diameter growth models
Coastal variant
$g_{1j} = 1.7585 + 2.2342D - 2.2541D^2 - 0.0065B + 0.1353C - 0.5949H_d - 0.2738H_s + 0.6747E + 0.0032S - 0.1044\sin(\alpha)$
$g_{2j} = 1.8490 + 0.0753D - 0.4672D^2 + 0.0798C - 0.4483H_d - 0.5674H_s - 0.2739E + 0.0053S$
$g_{3j} = 3.1779 + 4.8652D - 3.2700D^2 - 0.0328B + 0.2375C - 1.1374H_d + 0.1674H_s + 1.0497E + 0.0031S - 0.1895\cos(\alpha)$
$g_{4j} = 0.7351 - 0.1248D + 0.3698D^2 - 0.0025B + 0.1342C + 0.2986H_d - 0.5168H_s - 1.1017E + 0.0048S + 0.1234\cos(\alpha)$
$g_{5j} = 1.6312 - 9.4605D + 28.442D^2 - 0.0451B + 0.2825C + 0.8411H_d + 1.4047E + 0.0006S - 0.2866\cos(\alpha) + 0.3647\sin(\alpha)$
$g_{6j} = 3.0086 + 0.9709D - 0.0024B + 0.2309C - 1.3518H_d - 0.6210H_s + 0.0129S$
Interior variant ¹
$g_{1j} = 0.0159 + 0.0196D - 0.6653D^2 + 7.4747D^3 - 0.0034B + 0.0131P - 0.0040H + s[0.0011 - 0.0023\cos(\alpha) + 0.0012\sin(\alpha)] + \ln(z + 1) \cdot s[-0.0145 - 0.0076\cos(\alpha) + 0.0047\sin(\alpha)] + (z^2) \cdot s[0.0120 + 0.0083\cos(\alpha) + 0.0013\sin(\alpha)] + 0.0446z - 0.0632z^2$
$g_{2j} = 0.0125 + 0.0143D - 0.3204D^2 + 3.2381D^3 - 0.0006B + 0.0024P + 0.0004H + s[-0.0010 - 0.0011\cos(\alpha) + 0.0002\sin(\alpha)] + \ln(z + 1) \cdot s[0.0096 - 0.0066\cos(\alpha) + 0.0082\sin(\alpha)] + (z^2) \cdot s[-0.0090 + 0.0095\cos(\alpha) - 0.0054\sin(\alpha)] - 0.2751z + 0.3269z^2$
$g_{3j} = -0.0065 + 0.0139D - 0.3891D^2 + 3.2980D^3 - 0.0025B + 0.0308P + 0.0004H + s[-0.0024 - 0.0017\cos(\alpha) - 0.0001\sin(\alpha)] + \ln(z + 1) \cdot s[0.0079 + 0.0021\cos(\alpha) + 0.0028\sin(\alpha)] + (z^2) \cdot s[-0.0020 - 0.0017\cos(\alpha) - 0.0020\sin(\alpha)] + 0.0976z - 0.2275z^2$
$g_{4j} = -0.0170 - 0.0092D - 0.9223D^2 + 20.8142D^3 - 0.0017B + 0.0208P + 0.0188H + s[0.0015 - 0.0013\cos(\alpha) - 0.0050\sin(\alpha)] + \ln(z + 1) \cdot s[-0.0153 + 0.0277\cos(\alpha) - 0.0062\sin(\alpha)] + (z^2) \cdot s[0.0112 - 0.0206\cos(\alpha) + 0.0046\sin(\alpha)] + 0.0766z - 0.1046z^2$

¹Interior variant equations from Liang 2010

Table 3.7. Estimated parameters of the mortality models.

Mortality models
Coastal variant ¹
$m_{1j} = T^{-1}\phi(-1.641)$
$m_{2j} = T^{-1}\phi(-1.564 - 0.013B - 0.029H_d + 0.409H_s)$
$m_{3j} = T^{-1}\phi(-1.840 - 0.454D + 0.007B - 0.640E)$
$m_{4j} = T^{-1}\phi(-1.756 - 0.005S)$
$m_{5j} = T^{-1}\phi(-2.718 + 13.021D - 21.211D^2 - 0.016S - 0.038\cos(\alpha))$
$m_{6j} = T^{-1}\phi(-2.207 + 0.012B + 0.246H_d)$
Interior variant ^{1,2}
$m_{1j} = T^{-1}\phi(0.1476 - 0.3022D + 0.0117D^2 - 0.0001D^3 + 0.0088B + 0.0734P - 0.0028H + s[0.0044 + 0.0123\cos(\alpha) + 0.0048\sin(\alpha)] + \ln(z + 1) \cdot s[0.1171 - 0.0299\cos(\alpha) + 0.0449\sin(\alpha)] + (z^2) \cdot s[-0.2337 + 0.0274\cos(\alpha) - 0.1423\sin(\alpha)] - 1.9943z + 3.4102z^2)$
$m_{2j} = T^{-1}\phi(0.9284 - 0.3241D + 0.0122D^2 - 0.0002D^3 - 0.0064B - 0.1867P + 0.1252H + s[0.0208 + 0.0473\cos(\alpha) - 0.0331\sin(\alpha)] + \ln(z + 1) \cdot s[-0.2761 + 0.1451\cos(\alpha) - 0.4092\sin(\alpha)] + (z^2) \cdot s[0.2361 - 0.1075\cos(\alpha) + 0.3146\sin(\alpha)] + 3.7097z - 4.6599z^2)$
$m_{3j} = T^{-1}\phi(0.1129 - 0.3301D + 0.0197D^2 - 0.0003D^3 + 0.0087B - 0.0653P - 0.0592H + s[0.0016 - 0.0065\cos(\alpha) + 0.0009\sin(\alpha)] + \ln(z + 1) \cdot s[0.0516 - 0.1436\cos(\alpha) + 0.0532\sin(\alpha)] + (z^2) \cdot s[-0.0615 + 0.1892\cos(\alpha) - 0.0397\sin(\alpha)] - 3.0204z + 2.9369z^2)$
$m_{4j} = T^{-1}\phi(-2.3105 + 0.1718D - 0.0171D^2 + 0.0004D^3 - 0.0051B - 0.1236P + 0.2648H + s[-0.0022 - 0.0802\cos(\alpha) + 0.0948\sin(\alpha)] + \ln(z + 1) \cdot s[0.6514 - 0.9346\cos(\alpha) + 0.7119\sin(\alpha)] + (z^2) \cdot s[-1.1050 + 1.3530\cos(\alpha) - 0.8674\sin(\alpha)] - 5.1131z + 6.7714z^2)$

¹T is variant specific and is the average length in years between inventory measurements (T=8 and T=5 for coastal and interior variants, respectively)

²Interior variant equations from Liang 2010

Table 3.8. Estimated parameters of the recruitment model.

Recruitment models	Scale
Coastal variant ¹	
$\beta_1x_1 = -6.109 + 0.040N - 0.028N^2 - 0.056B + 0.271C - 0.002S - 0.659\cos(\alpha)$	$\sigma_1 = 5.308$
$\beta_2x_2 = -6.227 + 0.021N - 0.010N^2 - 0.892C + 0.395E + 0.030S$	$\sigma_2 = 4.462$
$\beta_3x_3 = -7.408 + 0.048N - 0.021N^2 - 0.094B + 0.532C - 2.919H_d$	$\sigma_3 = 9.981$
$\beta_4x_4 = -9.100 + 0.035N - 0.036N^2 - 0.129C + 3.310H_s$	$\sigma_4 = 3.878$
$\beta_5x_5 = -4.333 + 0.136N - 0.180N^2 - 0.312B - 1.433H_d - 2.934H_s$	$\sigma_5 = 6.945$
$\beta_6x_6 = -10.538 + 0.108N - 0.106N^2 - 5.797H_d$	$\sigma_6 = 10.727$
Interior variant ²	
$r_1 = -2.3656 + 0.0104N - 0.3419B + 1.8113P + 2.7166H + s[-0.2948 - 0.5839\cos(\alpha) - 0.2063\sin(\alpha)] + \ln(z + 1) \cdot s[1.2252 + 1.0285\cos(\alpha) + 4.4528\sin(\alpha)] + (z^2) \cdot s[-0.7321 - 0.5492\cos(\alpha) - 3.6575\sin(\alpha)] + 7.4752z - 10.6422z^2$	
$r_2 = 6.5942 + 0.0086N - 0.1415B - 1.0720P + 1.7391H + s[0.0885 - 0.1339\cos(\alpha) - 0.2049\sin(\alpha)] + \ln(z + 1) \cdot s[-0.4877 + 0.5417\cos(\alpha) + 0.8488\sin(\alpha)] + (z^2) \cdot s[0.2304 - 0.1649\cos(\alpha) - 0.7225\sin(\alpha)] - 17.0313z + 13.6958z^2$	
$r_3 = -30.9940 + 0.0330N - 0.6600B + 7.0050P + 2.5150H + s[0.4610 + 0.3160\cos(\alpha) - 1.4010\sin(\alpha)] + \ln(z + 1) \cdot s[-4.0060 + 8.8550\cos(\alpha) - 1.3850\sin(\alpha)] + (z^2) \cdot s[2.3150 - 7.4110\cos(\alpha) + 0.0520\sin(\alpha)] + 145.8990z - 148.3260z^2$	
$r_4 = 3.5110 - 0.1100N - 0.9560B - 1.4120P + 0.7750H + s[1.4120 + 0.2940\cos(\alpha) - 2.2000\sin(\alpha)] + \ln(z + 1) \cdot s[-7.2600 + 10.9670\cos(\alpha) - 0.6360\sin(\alpha)] + (z^2) \cdot s[3.1920 - 7.3680\cos(\alpha) - 1.1870\sin(\alpha)] + 135.4930z - 136.4710z^2$	

¹Coastalvariant equations are parameterized with a Tobit model

²Interior variant equations from Liang 2010

Table 3.9. Estimated parameters of the stem volume model.

Volume models
Coastal variant ¹
$v_{1j} = -0.3844 + 2.0232D + 3.1286D^2 + 0.0603C$
$v_{2j} = -0.2101 + 0.8126D + 4.3478D^2 + 0.0578C$
$v_{3j} = -0.5572 + 2.5699D + 2.3343D^2 + 0.0071B + 0.0714C + 0.0407H_d + 0.0115\sin(\alpha)$
$v_{4j} = -0.292 + 1.6253D + 2.4015D^2 - 0.003B + 0.084C$
$v_{5j} = -0.0123 - 0.2632D + 6.1993D^2 - 0.1153E + 0.0067\sin(\alpha)$
$v_{6j} = -0.1322 + 0.3291D + 4.969D^2 + 0.0276H_d + 0.0167\sin(\alpha)$
Interior variant ²

¹Independent and response variables are $\ln + 1$ transformed. $\sin(\alpha)$ and $\cos(\alpha)$ are $\ln + 2$ transformed

²Volume equations are not yet implemented in the interior variant

Table 3.10. Estimated parameters of the stem biomass model.

Biomass models
Coastal variant ¹
$biom_{1j} = 0.887 + 21.548D - 15.898D^2 + 0.210C + 0.035\sin(\alpha)$
$biom_{2j} = 0.916 + 21.806D - 16.132D^2$
$biom_{3j} = 1.355 + 16.264D - 9.483D^2 + 0.079B + 0.200C + 0.088H_d - 0.040\sin(\alpha)$
$biom_{4j} = 1.447 + 17.509D - 11.318D^2 + 0.162C - 0.014\sin(\alpha)$
$biom_{5j} = 0.991 + 24.841D - 27.496D^2 + 0.066B - 1.172E + 0.084\sin(\alpha)$
$biom_{6j} = 0.664 + 24.215D - 23.616D^2 + 0.252C$
Interior variant ²
$biom_{1j} = 0.0593D^{2.5026} + 0.0135D^{2.4053} + 0.0135D^{2.5532} + 0.0546D^{1.6351}$
$biom_{2j} = 0.0605D^{2.4750} + 0.0168D^{2.3949} + 0.0080D^{2.5214} + 0.0261D^{1.6304}$
$biom_{3j} = 0.0359D^{2.5775} + 0.0116D^{2.3022} + 0.0283D^{2.0823} + 0.1601D^{1.4670}$
$biom_{4j} = 0.0477D^{2.5147} + 0.0153D^{2.2429} + 0.0278D^{2.0839} + 0.1648D^{1.4143}$

¹Independent and response variables are $\ln + 1$ transformed. $\sin(a)$ and $\cos(a)$ are $\ln + 2$ transformed

²Models from Lambert et al 2005

Table 3.11. English equivalents.

When you know:	Multiply by:	To find:
Centimeters (cm)	0.3937	Inches
Meters (m)	3.2808	Feet
Square meters (m ²)	10.7639	Square feet
Cubic meters (m ³)	35.3147	Cubic feet
Hectares (ha)	2.4711	Acres
Square meters per hectare (m ² ·ha ⁻¹)	4.356	Square feet per acre
Cubic meters per hectare (m ³ ·ha ⁻¹)	14.2913	Cubic feet per acre
Kilograms (kg)	2.2046	Pounds
Kilograms per hectare (kg·ha ⁻¹)	0.0004	Tons per acre

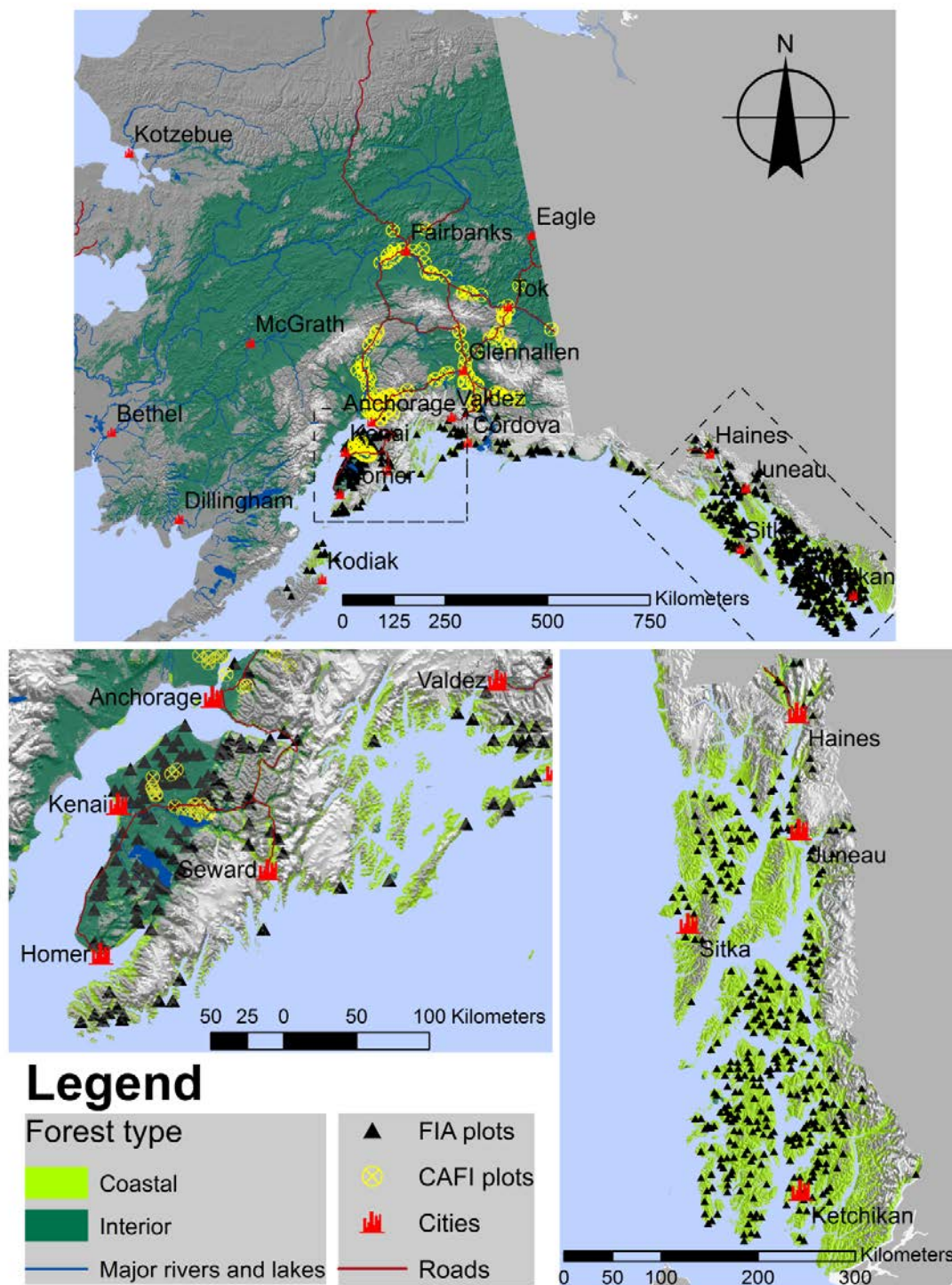


Figure 3.1. Geographic range of AlaskaPro. Coastal variant of AlaskaPro is recommended for use in coastal forest and the interior variant is recommended for use in interior forest. Location of sample plots used to calibrate growth models noted.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1																					
2																					
3	Sitka spruce	AlaskaPro																			
4	DBH Class (cm)	15.35	20.5	25.5	30.5	35.5	40.5	45.5	50.5	55.5	60.5	65.5	70.5	75.5	80.5	85.5	90.5	95.5	100.5	103+	
5	Initial State (trees ha ⁻¹)	18.6	14.2	10.1	7.4	5.1	3.7	2.4	1.7	1.1	0.7	0.5	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.1
6	Target State (trees ha ⁻¹)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	Western hemlock																				
8	DBH Class (cm)	15.35	20.5	25.5	30.5	35.5	40.5	45.5	50.5	55.5	60.5	65.5	70.5	75.5	80.5	85.5	90.5	95.5	100.5	103+	
9	Initial State (trees ha ⁻¹)	17.7	13.2	10.1	6.9	4.0	2.5	1.4	0.8	0.4	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	Target State (trees ha ⁻¹)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	Alaska cedars																				
12	DBH Class (cm)	15.35	20.5	25.5	30.5	35.5	40.5	45.5	50.5	55.5	60.5	65.5	70.5	75.5	80.5	85.5	90.5	95.5	100.5	103+	
13	Initial State (trees ha ⁻¹)	12.8	9.5	6.2	3.9	2.3	1.5	0.9	0.5	0.3	0.2	0.12	0.1	0.05	0.0	0.03	0.0	0.02	0.0	0.0	
14	Target State (trees ha ⁻¹)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
15	Mountain hemlock																				
16	DBH Class (cm)	15.35	20.5	25.5	30.5	35.5	40.5	45.5	50.5	55.5	60.5	65.5	70.5	75.5	80.5	85.5	90.5	95.5	100.5	103+	
17	Initial State (trees ha ⁻¹)	11.8	7.5	4.3	2.9	1.8	1.1	0.8	0.6	0.4	0.3	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.1
18	Target State (trees ha ⁻¹)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
19	Boreal spruce																				
20	DBH Class (cm)	15.35	20.5	25.5	30.5	35.5	40.5	45.5	50.5	55.5	60.5	65.5	70.5	75.5	80.5	85.5	90.5	95.5	100.5	103+	
21	Initial State (trees ha ⁻¹)	11.8	7.5	4.3	2.9	1.8	1.1	0.8	0.6	0.4	0.3	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	
22	Target State (trees ha ⁻¹)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
23	Other species																				
24	DBH Class (cm)	15.35	20.5	25.5	30.5	35.5	40.5	45.5	50.5	55.5	60.5	65.5	70.5	75.5	80.5	85.5	90.5	95.5	100.5	103+	
25	Initial State (trees ha ⁻¹)	11.8	7.5	4.3	2.9	1.8	1.1	0.8	0.6	0.4	0.3	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	
26	Target State (trees ha ⁻¹)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
27																					
28	Year of First Harvest	1																			
29	Rotation Length	20 yr																			
30	Length of Simulation	100 yr																			

Figure 3.2. Data input in AlaskaPro.

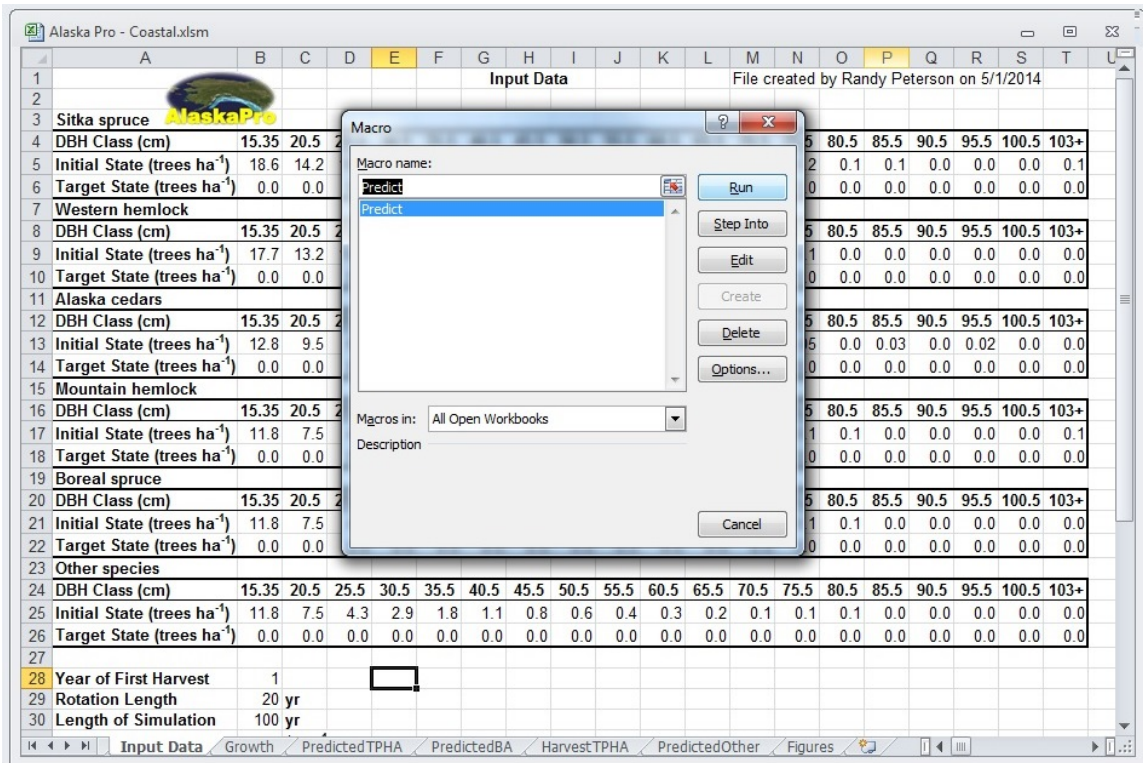


Figure 3.3. Running a simulation in AlaskaPro.

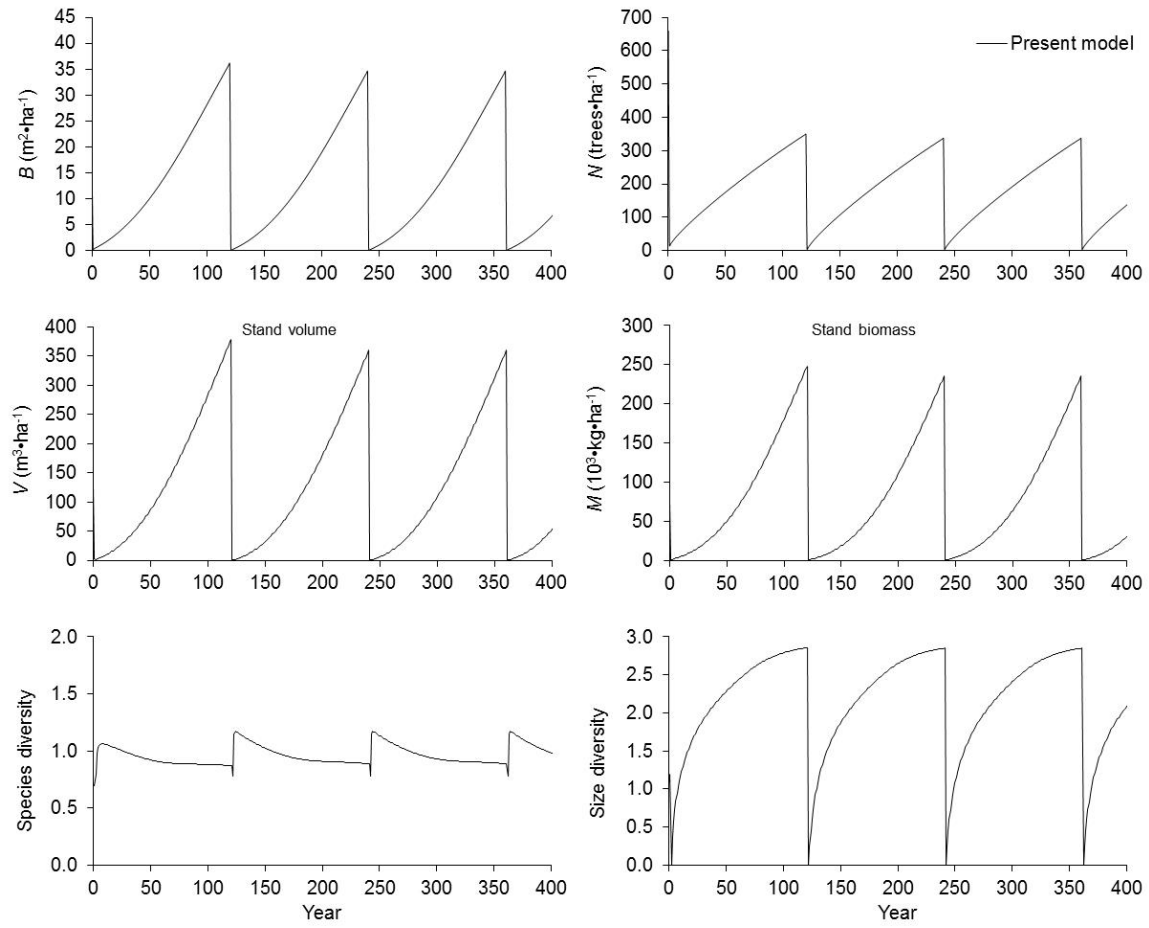


Figure 3.4. Example of simulation output in AlaskaPro.

R Console

```
R version 3.0.2 (2013-09-25) -- "Frisbee Sailing"
Copyright (C) 2013 The R Foundation for Statistical Computing
Platform: x86_64-w64-mingw32/x64 (64-bit)

R is free software and comes with ABSOLUTELY NO WARRANTY.
You are welcome to redistribute it under certain conditions.
Type 'license()' or 'licence()' for distribution details.

Natural language support will enable you to use R with no
native language support.

R is a collaborative project with many contributors.
Type 'contributors()' for more information and
'citation()' on how to cite R or R packages in publications.

Type 'demo()' for some demos, 'help()' for on-line help, or
'help.start()' for an HTML browser interface to help.
Type 'q()' to quit R.

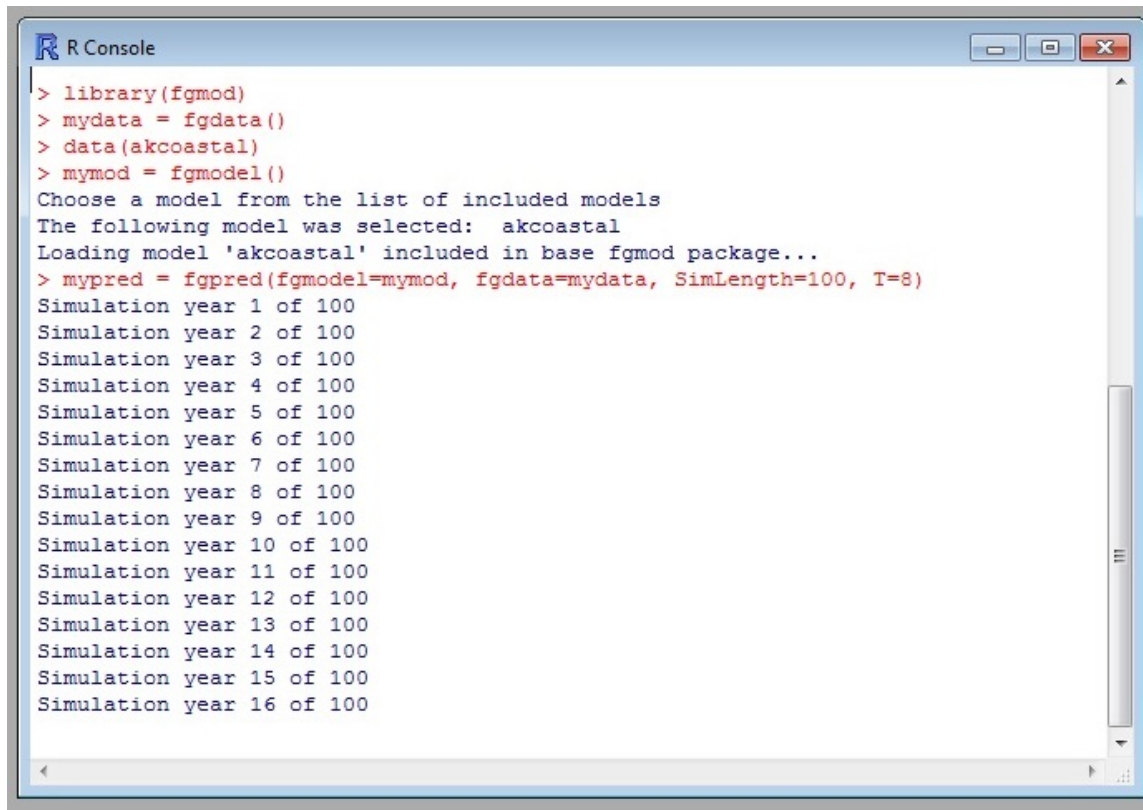
[Previously saved workspace restored]

> library(fgmod)
> mydata = fgdata()
```

Data Editor

	row.names	SPCD1	SPCD2	SPCD3	SPCD4	SPCD5	SPCD6	var8	var9
1	SZCL1	0	0	0	0	0	0		
2	SZCL2	0	0	0	0	0	0		
3	SZCL3	0	0	0	0	0	0		
4	SZCL4	0	0	0	0	0	0		
5	SZCL5	0	0	0	0	0	0		
6	SZCL6	0	0	0	0	0	0		
7	SZCL7	0	0	0	0	0	0		
8	SZCL8	0	0	0	0	0	0		
9	SZCL9	0	0	0	0	0	0		
10	SZCL10	0	0	0	0	0	0		
11	SZCL11	0	0	0	0	0	0		
12	SZCL12	0	0	0	0	0	0		
13	SZCL13	0	0	0	0	0	0		
14	SZCL14	0	0	0	0	0	0		
15	SZCL15	0	0	0	0	0	0		
16	SZCL16	0	0	0	0	0	0		
17	SZCL17	0	0	0	0	0	0		
18	SZCL18	0	0	0	0	0	0		
19	SZCL19	0	0	0	0	0	0		

Figure 3.5. Entering data into fgmod.



```
R Console
> library(fgmod)
> mydata = fgdata()
> data(akcoastal)
> mymod = fgmodel()
Choose a model from the list of included models
The following model was selected: akcoastal
Loading model 'akcoastal' included in base fgmod package...
> mypred = fgpred(fgmodel=mymod, fgdata=mydata, SimLength=100, T=8)
Simulation year 1 of 100
Simulation year 2 of 100
Simulation year 3 of 100
Simulation year 4 of 100
Simulation year 5 of 100
Simulation year 6 of 100
Simulation year 7 of 100
Simulation year 8 of 100
Simulation year 9 of 100
Simulation year 10 of 100
Simulation year 11 of 100
Simulation year 12 of 100
Simulation year 13 of 100
Simulation year 14 of 100
Simulation year 15 of 100
Simulation year 16 of 100
```

Figure 3.6. Running a simulation in fgmod.

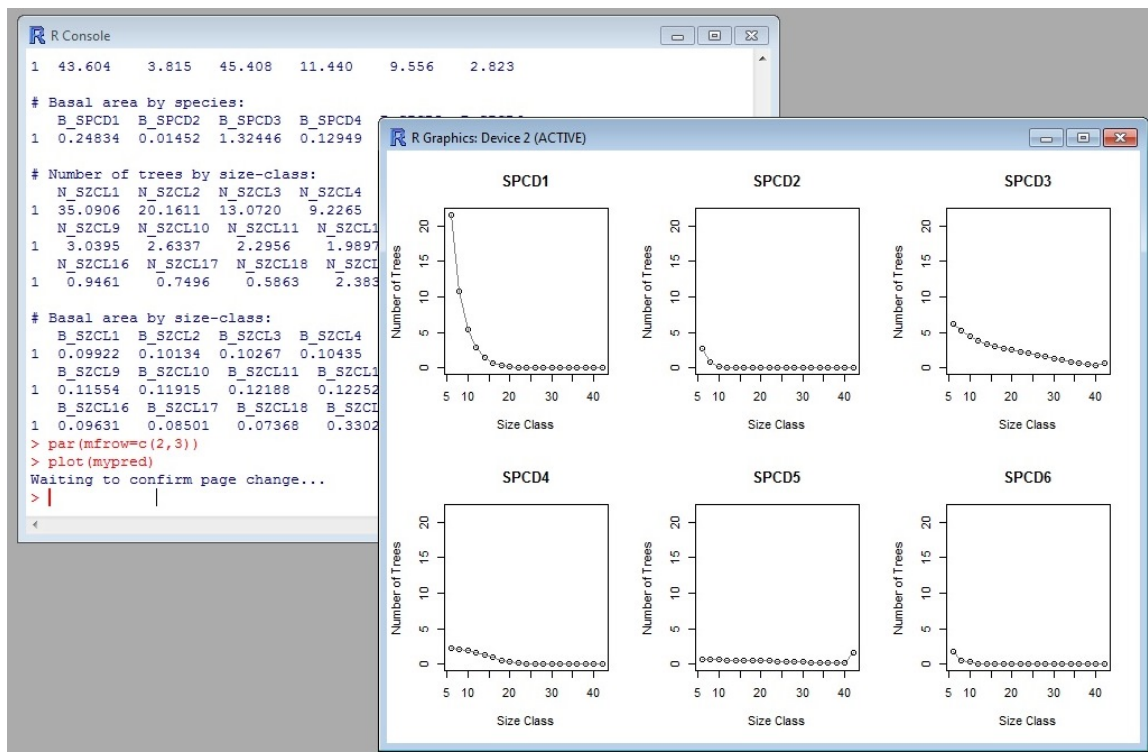


Figure 3.7. Example simulation output in fgmod.

Appendix 3.1. Data used in the development models found in AlaskaPro and fgmod

Data used to the calibrate Interior and coastal variants came from two sources: Alaska Forest Inventory and Analysis (FIA) database (O’Connell 2013) and Cooperative Alaska Forest Inventory (CAFI) database (Malone et al. 2009). Permanent sample plots (PSP) selected for model calibration met the following criteria: 1) a selected PSP must be fully forested and remeasured at least once, 2) there was at least one live tree at time of both measurements, and 3) there was no evidence of silvicultural treatments or any other forms of human interference in a selected PSP. A total of 544 PSP across the Alaska coastal region and 446 PSP spread through interior Alaska were selected using these criterion.

A total of 13 tree species were found on the coastal Alaska PSP and 8 on the Interior Alaska PSP (Table 3.1). Sample size concerns for some tree species limited the number of growth models. Of the 21 tree species, 7 tree species had enough data to form individual growth models; 3 in the coastal variant (Western hemlock, mountain hemlock, and Sitka spruce) and 4 in the Interior variant (Alaska paper birch, quacking aspen, white spruce, and black spruce). In the coastal variant, there were three species groups: Alaska cedars (western red cedar and Alaska cedar), boreal spruce (black and white spruce) and other species (lodgepole pine, paper birch, black cottonwood, quacking aspen, red alder, and subalpine fir).

Appendix 3.2. Matrix growth and yield models

AlaskaPro and fgmod uses a matrix growth model to predict forest dynamics from time t to $t+1$:

$$\mathbf{y}_{t+1} = \mathbf{G} \cdot (\mathbf{y}_t - \mathbf{h}_t) + \mathbf{R} + \boldsymbol{\varepsilon} \quad (\text{A3.2.1})$$

where $\mathbf{y}_t = [y_{ijt}]$ and $\mathbf{h}_t = [h_{ijt}]$ are vectors of live trees at time t of size-class j and specie-group i . $\boldsymbol{\varepsilon}$ is the error term. \mathbf{G} and \mathbf{R} are respectively the growth and recruitment matrices which are defined as:

$$\mathbf{G} = \begin{bmatrix} \mathbf{G}_1 & & & & \\ & \mathbf{G}_2 & & & \\ & & \ddots & & \\ & & & \ddots & \\ & & & & \mathbf{G}_m \end{bmatrix} \quad \mathbf{G}_i = \begin{bmatrix} s_{i,1} & & & & \\ g_{i,1} & s_{i,2} & & & \\ & \ddots & \ddots & & \\ & & & g_{i,n-2} & s_{i,n-1} \\ & & & g_{i,n-1} & s_{i,n} \end{bmatrix} \quad (\text{A3.2.2})$$

$$\mathbf{R} = \begin{bmatrix} \mathbf{R}_1 \\ \mathbf{R}_2 \\ \vdots \\ \mathbf{R}_m \end{bmatrix} \quad \mathbf{R}_i = \begin{bmatrix} R_i \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

where \mathbf{G} is the transition matrix of live trees of size j and specie group i that stays alive ($s_{i,j}$) or grow into the next size-class ($g_{i,j}$), and \mathbf{R} is the recruitment of trees for specie group i that enter the smallest size-class. $s_{i,j}$ is calculated using the following relationship:

$$s_{i,j} = 1 - g_{i,j} - m_{i,j} \quad (\text{A3.3.3})$$

where $m_{i,j}$ is the annual mortality rate.

Diameter growth, mortality, recruitment, volume, and biomass equations are variant specific and presented in Tables 3.6-3.10.

Appendix 3.3. Definition of forest size, species, and composite stand diversity

AlaskaPro and fgmod uses three measures of forest diversity. Forest diversity measures explicitly account for the independent effect that forest size (H_d), species (H_s), and composite stand (H_{ds}) diversity have on forest growth dynamics (Lei and Lu, 2004; Liang et al. 2007). H_d is a measure of how uniformly distributed the basal area in a stand is spread across all size classes. Similarly, H_s is a measure of uniformity across species groups and H_{ds} is a joint measure of uniformity across size and specie groups.

Both coastal and interior variants use Shannon's formula (Pielou 1977). The coastal variant uses the following equation to calculate size and species diversity:

$$H_d = -\sum_{j=1}^n \frac{B_j}{B} \ln\left(\frac{B_j}{B}\right) \quad (\text{A3.3.1})$$

and

$$H_s = -\sum_{i=1}^m \frac{B_i}{B} \ln\left(\frac{B_i}{B}\right) \quad (\text{A3.3.2})$$

where B_j , B_i , and B were, respectively, the basal area of size-class j , species group i , and total stand basal area. The coastal variant has a total of $n = 19$ size-classes and $m = 6$ species and thus the theoretical range of these variables are $(0, \ln(19) = 2.94)$ and $(0, \ln(6) = 1.79)$, respectively. Theoretical maximums would be achieved if the basal area is equally distributed across all 6 specie groups or 19 size-classes. The Interior variant uses the following equation to calculate composite stand diversity:

$$H_{ds} = -\sum_{j=1}^n \sum_{i=1}^m \frac{B_{ij}}{B} \ln\left(\frac{B_{ij}}{B}\right) \quad (\text{A3.3.3})$$

where B_{ij} and B were respectively the basal area of size-class j and species i and total stand basal area. The Interior variant has a total of $n = 19$ size-classes and $m=4$ species and thus the theoretical range of this variable is $(0, \ln(76) = 4.33)$. Theoretical maximum would be achieved if the basal area is equally distributed across all 4 specie groups and 19 size-classes.

Chapter 4

General Conclusion

“Essentially all models are wrong, but some are useful” – George Box

Coastal Alaska forest dynamics were modelled using a distance-independent, density-dependent, size-, and species-specific matrix growth and yield model. Data used in model calibration came from two independent databases (O’Connell 2013; Malone et al. 2009). Chapter 1 introduced the need for a growth and yield model as well as potential applications. A growth model was formulated in Chapter 2 and was found to be more accurate than existing models. Software which allows forest managers and researchers to implement the new model was developed and its use is described in Chapter 3. The model and programs described in Chapters 2 and 3 provide insight into Alaska forest dynamics, but challenges remain in terms of understanding and application.

Ecological inferences made from the component of growth models-diameter growth, mortality, recruitment-identified key variables that describe coastal forest dynamics. In general, diameter growth was 1) greater on sites with higher productivity, 2) higher on sites with increasing slopes and 3) declined with increasing stand density. Mortality was difficult to predict; a complication likely related to the fact that large- and small-scale wind disturbances are an important aspect of the coastal forest ecosystem (Nowacki and Kramer 1998). Developing regional mortality models or utilizing more complex statistical models such as generalized linear mixed effects models might be solutions, but inference about mortality from the current models was limited. Recruitment of a species

increased with the number of trees of that species at a particular stand, but was otherwise difficult to predict. Not all recruitment models included basal area, which is often included to limit the number of trees recruited into the smallest size-class of dense stands, but a non-linear transformation of the number of trees was used instead and found to be sufficient.

Growth and yield predictions from the new model were extensively tested and found to be both accurate and plausible. A comparison of the new model to existing models indicated that the new model was an improvement, which is great news for resource managers interested in making short-term predictions or comparing the outcomes of various forest management activities. Spatial autocorrelation in the prediction errors was tested for and not significant, indicating the new model is capable of capturing large- and small-scale spatial trends, which are known to confound yield predictions across the region (Barnes 1962; Farr and Harris 1979). Volume and biomass equations were also formulated.

Software to implement the models was developed to simulate the growth and yield for Alaska forest. These programs, AlaskaPro and fgmod, were developed with accessibility in mind and are both cross-platform meaning that the software is not operating system specific. The Excel program, AlaskaPro, was developed to be a simple, yet powerful, program which is both easy to use and understand. The R program, fgmod, was developed to provide an environment that can quickly create, validate and apply forest growth and yield models. An advantage to using R was that it can be easily updated to include additional matrix growth models. A coastal and Interior variant were made

available in fgmod (Liang 2010; Peterson et al. 2014). fgmod also facilitated rapid prototyping (Haefner 2005) of various component of growth model equations and model form.

Model and software limitations, although not discussed in great detail in Chapters 2 and 3, should be recognized; indeed, no forest modelling project would be complete without it (Weiskittel et al. 2011). A model is a purposeful representation (Starfield 1991) and the new growth model was shown capable of representing coastal forest dynamics; however, due to the empirically calibrated component of the growth models it will not be able to depict the forest dynamics of forest types such as red alder. Data to calibrate the models was remeasured on an average time interval of 8 years; short-term predictions (extrapolations) of forest dynamics using a similar time interval (simulation length) will be reasonable but long-term predictions should be interpreted with care. Recruitment by species into the smallest size-class was always positive, meaning that the model will predict boreal species in Southeast Alaska and coastal species in Southcentral Alaska. An ad hoc procedure to correct recruitment errors was established (setting the target stand state to 0), but a more statistically robust solution is needed. An interior variant of AlaskaPro has yet to be developed and the AlaskaPro coastal variant can be further improved. fgmod remains under development, but its core functionality was created. Despite the limitations, the newly developed growth and yield model and adjoining software will be useful to forest research in coastal Alaska.

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