Development of a hybrid modeling approach for predicting intensively managed Douglas-fir growth at multiple scales

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Introduction

Hybrid models offer the opportunity to improve future growth projections by combining advantages of both empirical and process-based modeling approaches. Hybrid models have been constructed in several regions and their performance relative to a purely empirical approach has varied. A hybrid model was constructed for intensively managed Douglas-fir plantations in the Pacific Northwest by embedding a hierarchy of components representing fundamental processes into a spatially implicit individual-tree model.

Model Overview

The modeling approach emphasized a hierarchical treatment of multiscale processes with predictions made at the individual branch-, tree-, and stand-levels. Three primary components comprise the model, corresponding to characterization of crown structure (BCACS), estimation of annual net primary production (NPP), and allocation of carbon and growth to different parts of the tree (ALOGRO).

BCACS

This submodel contains a set of empirical equations that predict the location, diameter, and biomass of every branch on each tree on the sample plot being simulated. The input is a tree list containing diameter at breast height (DBH), height (HT), height to crown base (HCB; lowest live branch), and expansion factor (EXPF, in trees per ha) as well as estimates of total age and site index (base age 50 years). Past height growth is reconstructed from the dominant height curves developed by Bruce (1981) to determine the location of annual whorls of branches. These attributes were then summed to estimate biomass and surface area at the tree- and stand-levels.

Total stem and sapwood volume were estimated at the tree-level from existing stem volume and sapwood taper equations (Maguire and Batista 1996; Walters et al. 1985). Volumes were converted to biomass by applying regional values for total and sapwood density (530 and 455 kg m^{-3}, respectively). Belowground biomass at the stand level was estimated from total aboveground biomass assuming the relationship presented by Ranger and Gelhaye (2001).

Net Primary Production (NPP)

Inputs for this submodel were kept as simple as possible to capture the fundamental physiological processes, and so included: (1) daily climate obtained from DAYMET (http://www.daymet.org); (2) site physiographic features (elevation, slope, aspect); (3) stand structural attributes from BCACS (LAI, biomass, canopy cover, etc.); (4) basic soils information (rooting depth, texture, rock content), and (5) foliar nitrogen concentration. The model estimates gross primary production (GPP) five times daily. The model contains all the necessary components for accurately estimating GPP, which include: (1) daily time step; (2)

separation of direct and diffuse radiation; (3) light extinction coefficients dependent on solar geometry, canopy structure, and type of radiation; (4) separation of sunlit and shaded leaf area; (5) photosynthesis estimates based on the Farquhar *et al.* (1980) biochemical equation and modified by foliar nitrogen levels, (6) site slope and aspect effects on diurnal distribution of radiation and fraction of sunlit leaf area (particularly in areas with complex terrain); (7) estimates of stomatal conductance as a function of vapor pressure deficit and soil water availability; and (8) canopy gas exchange linked to soil water and nutrition availability. Net primary production was estimated as constant fraction of GPP (Waring et al. 1998).

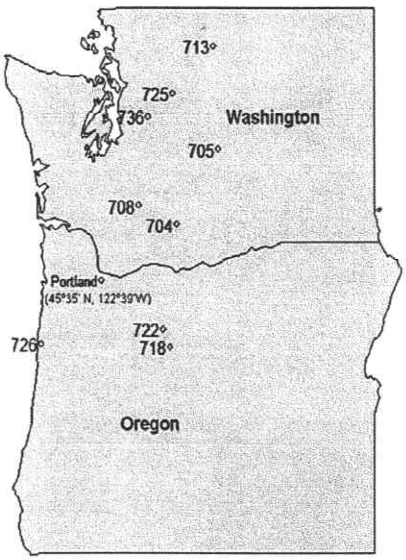

Figure 1. Location of SMC installations from which the verification data were collected.

Allocation and Growth (ALOGRO)

A modified 3-PG (Landsberg and Waring 1997) carbon allocation approach resulted in the highest correlation between simulated above-ground NPP and observed stem volume growth. The modifications to the 3-PG allocation approach involved estimation of the site fertility rating from canopy N percentage (Swenson et al. 2005) and applying Duursma's and Robinson's (2003) correction for inherent bias when estimating stand-level biomass (or its allocation in this case) from stand-level mean tree size. Disaggregating of stand volume growth to individual trees was based on weighted leaf areas estimated by a regression model developed from the data of Brunner and Nigh (2003). Individual tree diameter and height growth were predicted using differentiated allometric equations (Kirschbaum 1999), pipe-model theory (Valentine and Mäkelä 2005), and transport resistance model (Thornley 1999). For comparison, predictions were also made with purely empirical equations (Weiskittel et al. 2007) and the following hybridized form of these equations:

$$[1] \qquad \Delta Y_{adj} = \Delta Y_{EMP} * (\beta_{ij} + \beta_{ij}*NPP + \beta_{ij}*\ln(NPP))$$

where ΔY_{adj} is the adjusted growth rate (diameter or height), ΔY_{EMP} is the predicted growth from the empirical equation, and the β_{ij}'s are annualized parameters to be estimated from an independent dataset. Mortality in ALOGRO was assumed to occur when individual tree growth efficiency (stem biomass increment/tree leaf area) fell below 0.10 kg $m^{-2} yr^{-1}$. Performance of this approach was compared to that from an empirical model for estimating annual probability of individual tree mortality (Flewelling and Monserud 2002).

Model Simulations

Data from nine SMC installations in Oregon and Washington comprised the verification and testing dataset (Figure 1). These installations covered a wide range of growing conditions that are typical for the region. The plantations were established between 1971 and 1982 at varying densities (905 to 1575 stems per ha) and levels of vegetation control. Several sets of 0.2-ha permanent plots were established by the SMC at each installation between 1986 and 1992. Since establishment, the 56 plots have received a variety of silvicultural regimes that have involved thinning, pruning, and nitrogen fertilization.

The model assembled from BCACS, NPP, and ALOGRO was evaluated by simulating leaf area index (LAI) and growth on each of the 56 SMC plots and comparing the predicted stem volume growth to observed current annual increment (CAI). The same plots were also simulated in 3-PG after parameterizing for Douglas-fir with information presented by Waring and McDowell (2002). To estimate the subjective soil fertility index for 3-PG, the measured soil nitrogen percentage was converted to nitrogen content based on soil depth and estimated bulk density (Kaur et al. 2002). This value for total nitrogen was then converted to the soil fertility index with the equation developed by (Swenson et al. 2005). Climate information for the growth periods represented on the SMC plots was obtained from DAYMET (http://www.daymet.org).

Results

At the stand-level the NPP algorithm described in this study performed significantly better than 3-PG when LAI was estimated by BCACS (Figure 2). For individual trees, the hybrid approach developed in this study produced a level of bias comparable to the empirical approach, in large part due to its empirical basis (Table 1). The hybrid model predictions modified empirical estimates as follows:

[2] $$\Delta DBH_{adj} = \Delta DBH_{EMP} * (0.5999 - 0.0149*NPP + 0.1742*\ln(NPP))$$

[3] $$\Delta HT_{adj} = \Delta HT_{EMP} * (1.4197 + 0.0199*NPP - 0.3229*\ln(NPP))$$

where ΔDBH_{EMP} and ΔHT_{EMP} are predicted diameter and height growing using the equations of Weiskittel et al. (2007). Tree mortality imposed when growth efficiency fell below the threshold produced final stand basal areas that were comparable to predictions with an empirical mortality equation (Figure 3); however, both approaches underpredicted mortality in stands with higher density.

Discussion

Hybrid models have been proclaimed as the next step forward for improving growth projections for managed stands (e.g. Landsberg, 2003b). The hybrid modeling framework combines the strengths of both empirical and process-based models. The hybrid model constructed here for intensively managed Douglas-fir plantations in the Pacific Northwest significantly improved predictions of LAI and CAI compared to other modeling approaches. At the individual tree-level, disaggregation of NPP and prediction of stem diameter and height growth were improved. In addition, imposing mortality when growth efficiency fell below a threshold value predicted mortality at a level of accuracy comparable to empirical approaches. These improvements resulted directly from: (1) more detailed representation of crown structure and dynamics; (2) inclusion of key physiological mechanisms at an appropriate spatial and temporal resolution; and (3) application of empirical equations modified by simulated NPP to predict diameter and height growth of individual trees rather than relying on allometric or theoretical equations. Areas of future improvement for these types of models include: (1) components that simulate the effects of soil water and nutrients on physiological processes, particularly respiration and carbon allocation, in a simple yet mechanistic manner; (2) components that account for the effects of silvicultural treatment and environmental conditions on foliage age class dynamics, so that seasonal variation in LAI and net photosynthesis can be simulated more accurately; and (3) rigorous assessment of the relationship between growth efficiency and probability of individual tree mortality.

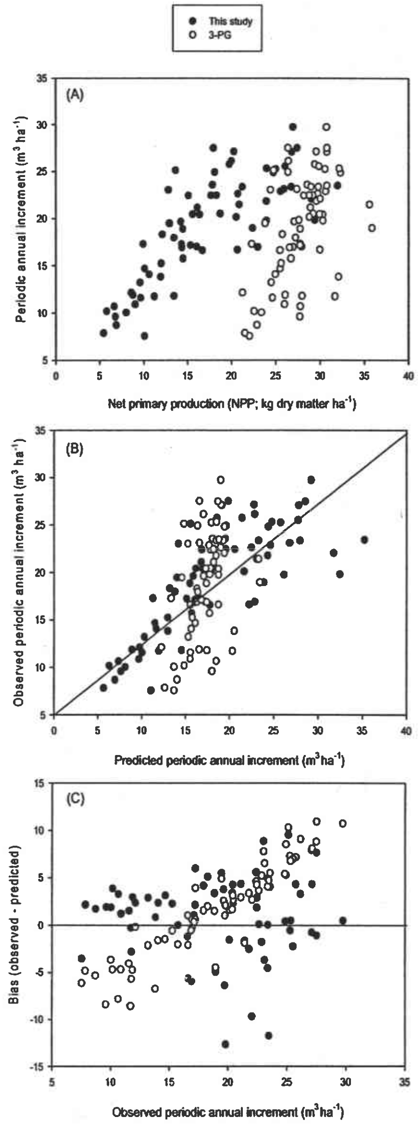

Figure 2. Relationships between observed growth and predictions from both the hybrid model and 3-PG: (A) observed current annual increment (CAI; m^3 ha^{-1}) over simulated net primary production (NPP); (B) observed over predicted and CAI; and (C) bias (observed – predicted) over observed CAI.

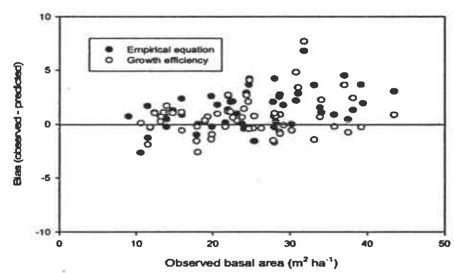

Figure 3. Bias (observed – predicted) in final stand basal area (m^2 ha^{-1}) after four years of simulated growth on 56 Stand Management Cooperative plots. Predictions were made with two alternative tree mortality models, the first an empirical mortality equation and the second a threshold growth efficiency.

Approach	DBH (n = 8860)			HT (n = 2805)		
	Mean bias	MSE	% bias	Mean bias	MSE	% bias
1. Empirical	-0.01	1.22	-0.61	-0.59	0.97	-3.84
2. Allometric	1.24	1.63	4.97	-0.42	1.30	-3.87
3. Pipe-model	3.07	3.25	13.04	-2.52	3.43	-19.78
4. Thornley (1999)	-3.75	3.91	-20.63	-0.06	1.28	-1.41
5. Hybrid	0.53	1.18	1.99	0.15	0.85	1.04

Table 1. Mean bias, percent (%) bias, and mean square error (MSE)for individual-tree predictions of diameter and height growth on 56 Stand Management Cooperative plots with thinning and fertilization treatments. Growth was estimated with: (1) an empirical model (Weiskittel et al. 2007); (2) an allometric equation (Kirschbaum (1999); (3) equations based on pipe-model theory (Valentine and Mäkelä 2005); (4) a transport resistance model (Thornley 1999); and (5) hybrid equations developed in this study.

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