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Annualized diameter and height growth equations for Pacific Northwest plantation-grown Douglas-fir, western hemlock, and red alder

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Abstract

Simulating the influence of intensive management and annual weather fluctuations on tree growth requires a shorter time step than currently employed by most regional growth models. High-quality data sets are available for several plantation species in the Pacific Northwest region of the United States, but the growth periods ranged from 2 to 12 years in length. Measurement periods of varying length complicate efforts to fit growth models because observed growth rates must be interpolated to a common length growth period or those growth periods longer or shorter than the desired model time step must be discarded. A variation of the iterative technique suggested by Cao [Cao, Q.V., 2000. Prediction of annual diameter growth and survival for individual trees from periodic measurements. Forest Sci. 46, 127–131] was applied to estimate annualized diameter and height growth equations for pure plantations of Douglas-fir, western hemlock, and red alder. Using this technique, fits were significantly improved for all three species by embedding a multi-level nonlinear mixed-effects framework (likelihood ratio test: $p < 0.0001$). The final models were consistent with expected biological behavior of diameter and height growth over tree, stand, and site variables. The random effects showed some correlation with key physiographic variables such as slope and aspect for Douglas-fir and red alder, but these relationships were not observed for western hemlock. Further, the random effects were more correlated with physiographic variables than actual climate or soils information. Long-term simulations (12–16 years) on an independent dataset using these annualized equations showed that the multi-level mixed effects models were more accurate and precise than those fitted without random effects as mean square error (MSE) was reduced by 13 and 21% for diameter and height growth prediction, respectively. The level of prediction error was also smaller than an existing similar growth model with a longer time step (ORGANON v8) as the annualized equations reduced MSE by 17 and 38% for diameter and height growth prediction, respectively. These models will prove to be quite useful for understanding the interaction of weather and silviculture in the Pacific Northwest and refining the precision of future growth model projections.

Keywords: Douglas-fir; Western hemlock; Red alder; Plantation growth and yield; Pacific Northwest; Empirical growth models; Multi-level mixed effects

1. Introduction

Over the last few decades rotation lengths in plantations of the Pacific Northwest (PNW) have significantly decreased and are currently ranging from 30 to 50 years (Adams et al., 2005). Growth and yield models in the region, however, continue to use a 5–10 year time step. With the shorter rotations, treatment windows for silvicultural activities such as fertilization, thinning, and pruning are also shortening, and are often less than 5 years, especially on more productive sites. The longer model time steps also make it difficult to forecast silvicultural treatment effects accurately or investigate the role of annual climate fluctuations on growth (e.g. Henning and Burk, 2004). For example, Johnson (2005) recently found a very wide range (1.3–2.3-fold difference) of predicted responses to thinning, fertilization, and the combination of these treatment for six commonly used PNW empirical growth models. These large differences among models can partially be attributed to their inability to capture the short-term stand dynamics following intensive treatment. As management practices continue to

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intensify and rotations remain relatively short in this region, the need for annual diameter and height growth equations is apparent.

The primary difficulty in developing annual equations is that most permanent plots are remeasured on a 2–6 year cycle. Shorter measurement cycles are usually not favored because the effect of measurement error can greatly bias results (e.g. Snowdon, 1987). McDill and Amateis (1993) evaluated several different methods to fit annual growth models from periodic measurements and found two interpolation methods to work better than simple averaging. Cao (2000) generalized these conclusions and recently presented a method to simultaneously develop annual individual tree diameter and height growth and survival equations from periodic measurements (Cao et al., 2002). This method has been successfully used for European beech [*Fagus sylvatica* L.] (Nord-Larsen, 2006), loblolly pine [*Pinus taeda* L.] (Cao, 2000, 2004; Cao et al., 2002), longleaf pine [*Pinus palustris* Mill.] (Cao et al., 2002), Norway spruce [*Picea abies* (L.) H. Karst] (Johannsen, 1999), and oak [*Quercus robur* L. and *Quercus petraea* L.] (Johannsen, 1999).

However, these previous analyses have not accounted for the sampling structure of these types of data. In addition to having multiple measurements made on trees over varying time periods, these trees are often nested within plots and perhaps more grouping levels. The repeated measures and hierarchical nature of these data result in autocorrelation violating the assumptions of least squares. One approach to remedying this is to directly model the covariance structure via a continuous autoregressive process (Gregoire, 1987). This approach adequately accounts for spatial and temporal correlation among measurements but may not represent the hierarchical nature of the data. A second approach is to introduce one or more random effects on a subset of parameters at each level of nesting. Each approach has been effective in reducing the impact of autocorrelation on hypothesis testing (Hall and Bailey, 2001; Hibbs et al., 2007). However, the latter approach may better account for the complex covariance structure and provide better predictions (Hall and Bailey, 2001). Moreover, the random effects approach has the additional appeal of permitting the evaluation of plot and site covariates not typically included within the models.

The primary objective of this study was to extend Cao's (2000) approach to hierarchical data in developing annualized diameter and height growth equations from periodic measurements in pure, untreated plantations of coastal Douglas-fir [*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco], western hemlock [*Tsuga heterophylla* (Raf.) Sarg], and red alder [*Alnus rubra* Bong.]. Specific objectives were to: (i) determine whether the combination of Cao's (2000) technique and hierarchical approaches produce biologically consistent parameters estimates; (ii) compare fits and predictions with generalized nonlinear least squares (GNLS) and multi-level nonlinear mixed effects (NLME); (iii) test the physiographic variables on diameter and height growth of these three species by regressing the installation random effects on these variables; and (iv) evaluate these annualized equations against a commonly used regional growth model.

2. Methodology

2.1. Data sets

Data for this study came from existing permanent plots established by three PNW research cooperatives. The Douglas-fir growth data were from the Stand Management Cooperative (SMC; University of Washington) and the Swiss Needle Cast Cooperative (SNCC; Oregon State University). The western hemlock data were obtained solely from the SMC database. The red alder growth data came from the SMC and the Hardwood Silviculture Cooperative (HSC; Oregon State University). In all cases, only pure, untreated plots with at least 10% of the sampled trees having breast-height age, height (HT), and height to crown base (HCB) measurements were used. A brief description of each database is given below.

2.1.1. Stand Management Cooperative (SMC)

Since its establishment in 1985, the SMC (http://www.cfr.washington.edu/research.smc/) has maintained a database representing 435 installations in British Columbia, Washington, and Oregon (Maguire et al., 1991). The primary sampling population was from plantation-grown Douglas-fir in western Oregon, Washington, and British Columbia, but some work was also done in western hemlock and red alder plantations. For this analysis, Douglas-fir and western hemlock data were extracted from the Type I and III installations. Type I installations were established as square 0.2-ha plots in existing plantations and have received designed sets of silvicultural treatments since plot establishment in the late 1980s and early 1990s. Type III installations were established as initial spacing trials with six densities ranging from 247 to 3048 trees per ha. Plot size varied from 0.086 ha at the highest density to 0.202 ha at the lowest density. In addition, plots from four western hemlock installations were included in the analysis. These plots were established in 1980 during Phase IV of the Regional Forest Nutrition Research Project (RFNRP; University of Washington) and were designed to test growth responses to fertilization in precommercially thinned plantations. The red alder data were collected from two installations established in 1980 as part of a Department of Energy project to examine the implications of whole tree harvesting on nutrient capital.

2.1.2. Swiss Needle Cast Cooperative (SNCC)

The SNCC established 76 permanent plots (0.08 ha) in 1998 to represent relatively young, e.g. 10–30-year-old, Douglas-fir plantations, with varying levels of SNC (Maguire et al., 2002) (http://www.cof.orst.edu/coops/sncc/). In addition, 22 untreated plots (0.08 ha) from a precommercial thinning study and 30 untreated plots (0.2-ha) from a commercial thinning study were also included. The former