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Modeling top height growth of red alder plantations

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ABSTRACT

Height growth equations for dominant trees are needed for growth and yield projections, to determine appropriate silvicultural regimes, and to estimate site index. Red alder [*Alnus rubra* Bong.] is a fast-growing hardwood species that is widely planted in the Pacific Northwest, USA. However, red alder dominant height growth equations used currently have been determined using stem analysis trees from natural stands rather than repeated measurements of stand-level top height from plantations, which may cause them to be biased. A regional dataset of red alder plantations was complied and used to construct a dynamic base-age invariant top height growth equation. Ten anamorphic and polymorphic Generalized Algebraic Difference Approach (GADA) forms were fit using the forward difference approach. The Chapman–Richards anamorphic and Schumacher anamorphic model forms were the only ones with statistically significant parameters that yielded biologically reasonable predictions across a full range of the available data. The Schumacher model form performed better on three independent datasets and, therefore, was selected as the final model. The resulting top height growth equations differed appreciably from tree-level dominant height growth equations developed using data from natural stands, particularly at the younger ages and on lower site indices. Both the rate and shape parameters of the Schumacher function were not influenced by initial planting density. However, this analysis indicates that the asymptote, which is related to site index, may be reduced for plantations with initial planting density below 500 trees ha^{-1}. The final equation can be used for predictions of top height (and thus) site index for red alder plantations across a range of different growing conditions.

1. Introduction

Although varying definitions of stand dominant height exist, most measures of it are well correlated with site potential productivity (Sharma et al., 2002) and thus, the resulting equations can be used to estimate site index. The three elements of modeling stand dominant height are the choice of a model form, the structure of the modeling data, and the statistical procedures used to estimate model parameters. Dominant height models have taken many different forms and significant differences in performance can exist between them (e.g., Krumland and Eng, 2005; Cieszewski and Strub, 2008). The modeling data can also come from a variety of sources including measurements of top height taken on temporary plots, from stem analysis of individual dominant trees, or from repeated measurements of top height taken on permanent plots. These different methods can have important implications on the resulting site index equation (Raulier et al., 2003). Given a basic model form and a data set, the guide curve method, the parameter prediction method, or the difference equation method can be used to construct a dominant height growth equation (Clutter et al., 1983; Wang et al., 2008a) through the application of alternative statistical procedures such as fixed parameter, dummy variable, or mixed parameter nonlinear regression. The best statistical method for modeling dominant height growth will most likely be species dependent and is still debated in the literature (Cieszewski and Strub, 2007; Wang et al., 2007a, 2008b).

A form of the difference equation method, Generalized Algebraic Difference Approach (GADA; Cieszewski and Bailey, 2000), has become a common means for fitting dominant height growth equations. GADA (for simplicity, we include the simpler Algebraic Difference Approach equations in this class of equations) dominant height growth equations have several desirable properties such as base-age invariance, generally fewer parameters to be estimated, prediction of dominant height forward or backward in age given any initial conditions, and the ability to identify site dependent curve changes from mean height-age trends (Cieszewski and Bailey, 2000).

GADA dominant height growth equations have been developed for several conifer species including interior Douglas-fir [*Pseudotsuga menziesii* var. *glauca* (Mirb.) Franco] (Cieszewski, 2001),

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loblolly pine [*Pinus taeda* L.] (Wang et al., 2008a), radiata pine [*Pinus radiata* D. Don] (Diéguez-Aranda et al., 2005), subalpine fir [*Abies lasiocarpa* (Hook.) Nutt.] (Cieszewski, 2003), Scots pine [*Pinus sylvestris* L.] (Cieszewski et al., 2007), and 10 northern California conifer species or species groups (Krumland and Eng, 2005). This approach has also been used to develop dominant height growth equations for hardwood species such as European beech [*Fagus sylvatica* L.] (Nord-Larsen, 2006), Pyrenean oak [*Quercus pyrenaica* Willd.] (Carvalho and Parresol, 2005), Spanish cork oak [*Quercus suber* L.] (Sánchez-González et al., 2008), and six species or species groups in northern California (Krumland and Eng, 2005). The application of GADA to fast-growing hardwood species has been limited to *Eucalyptus* species (Amaro et al., 1998; Calegario et al., 2005; Wang et al., 2007b) and to naturally regenerated red alder [*Alnus rubra* Bong.] trees (Krumland and Eng, 2005). Development of a dynamic dominant height growth equation for fast-growing plantation hardwood species may be particularly problematic because of their rapid peak in height growth, potentially greater sensitivity of height growth to stand density, and higher variability in annual height growth patterns.

The *Alnus* genus is comprised of approximately 30 species that are widely distributed throughout the northern temperate zone and several species are of high commercial importance including red, black [*Alnus glutinosa* (L.) Gaertn.], and Italian [*Alnus cordata* (Loisel) Duby] alders. It is our observation that most members of the *Betulaceae* family, such as the *Alnus* species, exhibit common properties of shade intolerance, relatively short lifespans, and fast early growth. In the Pacific Northwest (PNW) region of the United States, planting of red alder has significantly increased in recent years and this trend is expected to continue (Briggs, 2007). On high quality sites, red alder plantations can reach a mean diameter of 30 cm in approximately 22 years and even greater productivities have been reported (Bluhm and Hibbs, 2006). Until about age 30, red alder height growth greatly exceeds the height growth of the other native conifers in the region (Harrington et al., 1994). Several tree-level dominant height growth equations exist for natural, unmanaged red alder stands including those of Porter and Wiant (1965), Worthington et al. (1960), Harrington and Curtis (1986), Nigh and Courtin (1998), and Krumland and Eng (2005). However, a tree-level dominant height growth or a stand-level top height growth equation for managed red alder plantations does not exist and is much needed in the region. In addition, all existing dominant height growth equations for red alder were developed using tree-level stem analysis data as opposed to repeated measurements of stand top height, which can significantly influence the behavior of the site curves.

For example, stand-level top height growth equations often predict taller heights below the base age and shorter heights above the base age when compared to tree-level dominant height growth equations developed from stem analysis (Smith, 1984; Monserud, 1985; Raulier et al., 2003). Raulier et al. (2003) attributed this difference to changes over time in the composition of the dominant trees. Stem analysis studies, such as Harrington and Curtis (1986) and Nigh and Courtin (1998), require actual measurements of site index in their analysis so only dominant trees with ages equal to or greater than the base age are sampled. As a result, their measured heights at younger ages may not be characteristic of the height of true dominants found on the plot at those younger ages due to changes in social status (Oliver and Larson, 1996; Raulier et al., 2003). However, the result of this dynamic behavior would be adequately characterized by using repeated measurements of top height on permanent plots (Raulier et al., 2003).

A key assumption in using dominant height or top height as an index of site productivity potential is that height growth of dominant trees is not influenced by stand density. Several studies have shown this to be generally the case (Skovsgaard and Vanclay, 2008). However, higher levels of stand density has been found to reduce dominant height growth for a number of predominantly intolerant conifer species with strong epinastic control (Gaiser and Merz, 1951; Lynch, 1958; Cieszewski and Bella, 1993; Scott et al., 1998; MacFarlane et al., 2000; Flewelling et al., 2001). As a result, stand density has been incorporated into dominant height growth equations for ponderosa pine (Lynch, 1958), lodgepole pine (Cieszewski and Bella, 1993), and Douglas-fir (Flewelling et al., 2001).

Less attention has been given to hardwood species with weak epinastic control that can reduce dominant height growth at low levels of stand density. In red alder, DeBell and Giordano (1994) reported that the average height growth rate was lower for trees growing on plots with densities below 700 trees ha^{-1}. They also reported that average height growth rate was reduced on plots with a density of over 4000 trees ha^{-1} (DeBell and Giordano, 1994). Maximum height growth of red alder at intermediate densities has also been reported in several additional studies (Bormann and Gordon, 1984; Cole and Newton, 1987; Giordano and Hibbs, 1993). All of these studies were conducted using very young trees on a very limited number of installations.

The overall goal of this research project was to model top height growth of plantation grown red alder using an extensive, regional database. Specific objectives were to: (1) fit several different GADA top height growth model forms using three alternative statistical techniques; (2) compare the predictive performance of the resulting equations on both the fitting data set and an evaluation data set; (3) for the final model, compare predicted development of top height in plantations to the development of dominant height in natural stands; (4) for the final model, assess the influence of planting density on estimated top height growth.

2. Methods

2.1. Study area

Sixty existing research installations of the Hardwood Silviculture Cooperative (HSC; http://www.cof.orst.edu/coops/hsc) and the Weyerhaeuser Company were used in this study. The installations were located in Oregon, Washington, and British Columbia and covered the full range of growing conditions for the species, including sites where commercial plantation management would not be implemented (Table 1). All installations were located between the Pacific Coast and the Cascade Mountains. The overall climate for the region is humid oceanic, with a distinct dry summer and a cool, wet winter. Regional 25-year annual mean rainfall ranged from 125 to 354 cm (http://www.daymet.org). The mean minimum temperature in January ranged from −8.3 to 2.9 °C and the mean maximum temperature in August ranged from 17.9 to 25.9 °C (http://www.daymet.org). Elevation ranged from 38 to 550 m above sea level and all aspects were represented. Soils varied from shallow sandy loams to very deep silty clay loams. The

Table 1
Attributes of the research installations used in this analysis (*n* = 60).

Attribute	Mean	S.D.	Minimum	Maximum
Mean minimum temperature in January (°C)	0.49	1.8	−8.3	2.9
Mean maximum temperature in August (°C)	22.9	1.8	17.9	25.9
Growing degree days (>5 °C)	4185.8	556.5	1885.1	4864.7
Annual precipitation (cm)	214.1	48.3	125.1	354.1
Elevation (m)	238.5	149.8	38.0	550.0
Slope (%)	16.7	17.8	0.0	90.0
Aspect (°)	167.1	101.0	0.0	360.0
Soil water holding capacity (mm)	331.9	152.6	27.5	611.0