Biomass and Bioenergy 84 (2016) 118–123

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: http://www.elsevier.com/locate/biombioe

Research paper

# Evaluation of predictive models for Douglas-fir bark thickness at breast height following 12 biomass harvest treatments

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ARTICLE INFO

*Article history:*
Received 25 June 2015
Received in revised form
12 November 2015
Accepted 17 November 2015
Available online 7 December 2015

*Keywords:*
Interior Douglas-fir
Bark thickness
Segmented linear regression
Biomass harvesting
Northern Rocky Mountains

ABSTRACT

Foresters often require an estimation of bark thickness from a reference height (typically breast height) to accurately estimate the bark or wood volume of a tree. Various models for estimating the bark thickness of interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) from measured dbh (diameter at breast height) were evaluated. Sample trees were from northern Rocky Mountain mixed conifer stands that had been subjected to four levels of experimental woody biomass harvesting. Among simple linear, nonlinear, and segmented linear mixed effects models, the segmented linear model performed best. A join point (where the linear equations are linked) for the segmentation was statistically detected at approximately 19.0 cm dbh. The join point seems to indicate the size at which juvenile Douglas-fir trees boost the production of bark tissue, perhaps as those trees express dominance over competing understory vegetation. Woody biomass utilization level had no impact on bark thickness, indicating that the bark:dbh relationship does not depend on biomass utilization intensity. The study results enable accurate bark thickness estimation for interior Douglas-fir in this region, and suggest several silvicultural applications for juvenile Douglas-fir stand management.



## 1. Introduction

Estimations of tree bark volume have long been pursued because foresters must know merchantable log volumes, and subtracting bark volume from outside bark volume provides the most convenient calculation method [1]. Numerous mathematical equations accounting for each species' bark thickness have been developed over the past decades (e.g., [2–4]). They generally predict the bark thickness at any given tree height from bark thickness at a certain reference height (typically, diameter at breast height, or dbh; 1.4 m). Accurate prediction of whole tree bark and log volumes are predicated upon the accurate estimate of bark thickness from measured diameter at the reference height, because error in that estimate is expressed and thereby amplified throughout the log.

In an ongoing study of biomass utilization at Montana's Coram Experimental Forest [5,6], we have been quantifying forest vegetation and productivity responses to a variety of biomass harvest treatments. In that work, determining accurate estimates of forest biomass by segregated components is a primary objective, and one that requires a robust bark predictive model, particularly for Rocky Mountain Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *glauca* (Beissn.) Franco). Previous research has produced a variety of models to predict the bark thickness of Douglas-fir using diameter at breast height. For coastal Douglas-fir, Johnson [7] developed a segmented linear equation for the estimation of bark thickness from dbh. Larsen and Hann [8] formulated a nonlinear equation for bark thickness in a similar region. For interior Douglas-fir, Spada [9], Monserud [10], and Dolph [11] each constructed simple linear regression models. Monserud [10] and Dolph [11] found different results among linear models across the regions, implying the necessity of locally-constructed equations for the best predictive performance.

During field surveys at Coram Experimental Forest, we observed an apparent difference in the ratio of bark thickness to tree size between small and large Douglas-fir trees. We theorized that the simple linear approach might be inappropriate, and that segmented linear regression analysis might yield a better predictive model for Douglas-fir in the northern Rocky Mountains. Segmented linear regression has been used to construct stem taper equations (e.g., [2,12,13]). In contrast to more complex models, it provides a simpler method by producing different equations within different

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http://dx.doi.org/10.1016/j.biombioe.2015.11.015
0961-9534/

regions of the explanatory variable space [14]. Two (or more) different linear equations are fitted simultaneously under a constraint: the "join point," where the linear equations are linked. If it is possible to estimate the join point, then the model can be constructed as multiple linear forms with simplicity and robustness. This study considered segmented, simple linear and nonlinear mixed effects regression to determine the best model for predicting the bark thickness of Douglas-fir from breast-height diameter (dbh) in northern Rocky Mountain forests, and to evaluate whether the relationship of bark thickness to dbh differs significantly among biomass utilization treatments and regeneration harvests.

## 2. Methods and materials

### 2.1. Study site

This study was conducted at the site of the interdisciplinary Forest Residues Utilization Research and Development Program at western Montana's Coram Experimental Forest (Flathead National Forest). Established in 1974, a primary purpose of the research program was to evaluate the effects of varying biomass removal levels (and associated post-harvest burning treatments) for each of three common regeneration harvest methods. The present study is one aspect of an ongoing comprehensive analysis of that experiment, focused on the relatively long-term responses of vegetation and site productivity to biomass harvesting in northern Rocky Mountain forests [5].

The site is located in the experimental forest's Upper Abbot Creek basin (48°25′N, 113°59′W), about 20 km east of Columbia Falls, and 9 km south of Glacier National Park. Elevation ranges from 1195 m to 1615 m with 16.7°–38.7° slopes. Mean annual precipitation is 1076 mm (range: 890–1270 mm), occurring primarily in the form of snow [15]. Mean annual temperatures during summer and winter months are about 16 °C, and −7 °C, respectively [16].

The site is characterized by the western larch (*Larix occidentalis* Nutt.) forest cover type (Society of American Foresters Cover Type No. 212; [17]), mixed with Douglas-fir, subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), and Engelmann spruce (*Picea engelmannii* Parry ex Engelm.). At the lower elevations, broadleaf species such as paper birch (*Betula papyrifera* Marshall), black cottonwood (*Populus balsamifera* L. ssp. *trichocarpa* (Torr. & A. Gray ex Hook.) Brayshaw), and quaking aspen (*P. tremuloides* Michx.) are also present. The subalpine fir – queen's cup (*Clintonia uniflora* (Menzies ex Schult. & Schult. f.) Kunth) (ABLA/CLUN) habitat type is dominant [18,19].

### 2.2. Experimental design

The experiment was established as a split-plot design with two replicates, three whole-plots, and four sub-plots. The three whole-plots consisted of shelterwood, group selection, and clearcut harvest units. Within each whole-plot harvest unit, four biomass utilization treatment combinations were imposed as sub-plots. Each sub-plot treatment consisted of a combination of biomass utilization level (high, medium, and low) and post-harvest prescribed burning (burned, unburned) (details in Table 1). Burning was prescribed for reduction of fire hazard; it was performed only at the medium and low utilization levels, because the high utilization level produced woody fuels loads that were insufficient to either warrant or permit burning. The four combinations of biomass utilization levels and post-harvesting treatments (burning treatment) were: 1) High-Unburned, 2) Medium-Unburned, 3) Medium-Burned, and 4) Low-Burned. In each of the clearcut and shelterwood harvest units, the four biomass utilization treatments were oriented longitudinally downslope and adjacent to each other. In the group selection units, eight patches were harvested, and two patches were randomly assigned to each of the four biomass utilization treatments. The experiment was replicated at two elevations (low, high).

Harvesting was conducted via skyline yarder in 1974, and prescribed burning treatment followed in 1975. In the lower shelterwood unit, burning was not achievable (fuel moisture contents exceeded the prescription limits; [21]), resulting in an imbalance in the experimental design and the addition of a Low-Unburned treatment in that unit. The Low-Unburned treatment was excluded for data analyses.

Douglas-fir bare-root seedlings (2-0; two-year-old in the seedbed without transplantation) were planted during 1976–1979. Except for the Medium-Unburned treatment (understory protected treatment), 25 seedlings were planted at 1.8 m spacing on the middle-top area of each sub-plot during each of 4 consecutive years. Within each biomass utilization treatment (sub-plot) of the clearcut and shelterwood units, 10 permanent sampling points were installed (two columns × five rows) spaced at 30.5 m. Five permanent sampling points were located within each cut patch of the group selection harvest units.

### 2.3. Data collection

From 2012 to 2013, cores were taken with an increment borer from a total 393 trees (Table 2). The sampling procedure was selected according to tree layer and regeneration type. For overwood trees in the shelterwood units, 20 Douglas-fir trees in each biomass utilization treatment were selected, avoiding the edge effect of neighbor sub-plot. Among naturally regenerated trees, 1–2 damage-free crop trees were selected within a 15 m radius of each historical permanent sampling point in all units. Sampling for the planted trees was conducted only in clearcut units. At each tree's breast height (1.37 m), diameter was recorded and two core samples (at right angles) were taken. Bark thickness per core was measured through either a bark gauge inserted at the coring spot, or a digital caliper measurement of the removed core. The average of the two measurements was calculated as the bark thickness per tree.

### 2.4. Data analysis

Since the data were collected from an experiment with a split-

**Table 1**
Design of the utilization treatments within harvesting units (from Refs. [19,20]).

| Treatment | Cut trees[a] | Max. Size of retained woody materials[b] | Post-harvest treatment |
|---|---|---|---|
| Medium-Unburned | >17.8 cm dbh | 7.6 cm × 2.4 m | Understory protected/unburned |
| High-Unburned | All trees | 2.5 cm × 2.4 m | Slashed/unburned |
| Low-Burned | All trees | 14.0 cm × 2.4 m | Slashed/broadcast burned |
| Medium-Burned | All trees | 7.6 cm × 2.4 m | Slashed/broadcast burned |

[a] Except designated overstory shelterwood trees.
[b] Live and dead down logs (small-end diameter × length); for dead down logs, they were removed if sound enough to yard.