Canadian Journal of
Forest Research

Research Article

Variation in Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) and red alder (*Alnus rubra*) stem taper across varying stand conditions in the Pacific Northwest

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Abstract

Tree taper has been of interest for over a century, yet questions remain regarding the effects of silvicultural treatments and forest health on recoverable volume. This work utilizes data from Douglas-fir (*Pseudotsuga menziesii* (Mirb.)) ($n = 608$) and red alder (*Alnus rubra* (Bong.)) ($n = 495$) trees to assess the influences of fertilization, pruning, thinning, regeneration origin, and defoliation caused by Swiss Needle Cast (SNC; *Nothophaeocryptopus gaeumannii*), on stem taper in the Pacific Northwest. The Kozak (2004; For. Chor. 80: 507–515) variable-exponent equation was used to test the addition of treatment and crown variables as the model is widely regarded for its flexibility in application. Using a mixed effects framework, results reveal that thinning of Douglas-fir can result in a 3.5% increase in upper stem diameter inside bark, while pruning may lead to a 4.1% decrease. SNC-induced defoliation of Douglas-fir reduced mean diameter above-breast height by 11.5%. Total volume of artificially regenerated red alder was 16% greater than naturally regenerated stems. Overall, thinning of healthy Douglas-fir and planting red alder may increase recoverable volume and C captured in long-term timber products in the region, and the inclusion of crown variables can increase the predictive power of taper estimates for some species.

Key words: taper, volume, variable-exponent taper equation, Oregon, Washington

Introduction

Stem taper equations are widely used for estimating merchantable and total bole volume of commercial tree species in North America (McTague and Weiskittel 2021), offering greater predictive power and application when compared with the original Girard form class approach developed in the 1940s (Mesavage and Girard 1946) or standard volume equations. Several general theories have been proposed to explain stem taper variation in trees, with the uniform stress framework (Dean et al. 2002) perhaps the most logical explanation. Mäkelä (2002) used the pipe model theory of Shinozaki et al. (1964) to predict stem taper and suggested that combining the mechanical properties and hydrological requirements of trees could be used to estimate stem allometry across a range of conditions. Yet, applying the uniform stress and pipe model theories to predict stem taper requires measurements about the vertical distribution of tree leaf area and cannot be used in a static manner to predict the taper of any measured tree (Mäkelä 2002).

Although crown shape and length have long been considered primary factors determining stem form (Larson 1963), most taper equations are primarily derived from tree diameter at breast height (DBH; 1.37 m) and total height (HT) (McTague and Weiskittel 2021). Conceptually, trees with well-developed crowns taper less and are more neiloid in shape, hence crown variables could theoretically increase predictive performance of taper equations because of their close connection with the amount and vertical distribution of tree leaf area. Yet, the inclusion of crown variables into taper equations has had mixed results to date (McTague and Weiskittel 2021) and may be related to the complexity of the model form (continuous vs. segmented), data source and sample size, or range of stand-, site-, and tree-conditions being evaluated, limited in geographic scope and replication (e.g., Garber and Maguire 2003), or highlighting a single highly-specific silvicultural regime (e.g., Putney and Maguire 2021).

In the Pacific Northwest (PNW) of the United States, coastal Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco) and red alder (*Alnus rubra* (Bong.)) are commonly managed for commodity timber products and grown across a range of environmental conditions and ownership types with intensive silvicultural regimes (Curtis et al. 1998). While both species occur naturally and are planted in artificial regeneration programs, intermediate treatments such as thinning, fertilization, and pruning are commonly applied in efforts to increase individual stem volume and recovered value of

Douglas-fir (Moores et al. 2007) and can have varying impacts on crown shape and branch size (Weiskittel et al. 2007), and stem taper (Weiskittel et al. 2006*b*). While thinning has been shown to lead to a more cylindrical lower bole and greater upper stem taper (Baldwin et al. 2000), the absolute changes are highly dependent upon intensity of thinning treatments (Lennette 1999; Karlsson 2000). Other treatments including pruning (Medhurst et al. 2003; York 2019), and vegetation control (Snowdon et al. 1981), have been evaluated, but overall results of silvicultural treatments on recoverable stem volume have been mixed to date (McTague and Weiskittel 2021).

Along the coastal range of Oregon and Washington, defoliation of Douglas-fir from infestation with Swiss Needle Cast (SNC—*Nothophaeocryptopus gaeumannii*) can result in a reduction in a decline in diameter growth (Zhao et al. 2015) and change in both the amount and vertical distribution of foliage and crown shape (Weiskittel et al. 2006*a*). Younger et al. (2008)found that fertilization of SNC infested trees could effectively decrease stem taper, yet the patterns of these results are difficult to extrapolate beyond the sampling area. As such, and with the increasing trends of SNC outbreak in the PNW (Ritóková et al. 2016), additional testing of the inclusion of crown variables to predict taper may enhance model quality and predictive power. This is especially important as the total losses in profits for current Douglas-fir plantations affected by SNC are estimated to be around $206.5–430 M with an average decline of 50% ($2643/ha) in economic revenues compared with a healthy stand (Susaeta et al. 2024), even without accounting for the potential influence of SNC on stem form and merchantable volume, which could increase forecasted losses.

The effects of varying stand conditions imposed by alternative intensive silvicultural practices and SNC on recoverable volume of Douglas-fir and red alder have been of interest to foresters in the PNW for decades (Curtis et al. 2007). Cooperative research programs, comprised of industrial landowners, state and federal scientists, and sovereign Tribal Nations, facilitate collaborative projects in applied research and technical development in the PNW region. Among several research networks, the Type I series was installed by the Stand Management Cooperative (SMC) at the University of Washington in the 1980s to quantify long-term thinning and fertilization treatments on residual tree growth and volume over time across the PNW (Maguire et al. 1991). The effects of SNC-induced defoliation on Douglas-fir growth have been tracked over time through recurring measurements of stem dimensions and crown dynamics as part of the Swiss Needle Cast Cooperative (SNCC) program housed at Oregon State University (Shaw et al. 2011). In parallel, silvicultural systems for red alder have been an attractive option to produce commodity hardwood products. The Hardwood Silviculture Cooperative (HSC) at Oregon State University has maintained a regional network of silvicultural treatment plots since the late 1980s to track the effects of artificial regeneration, thinning, and stem pruning on long-term recoverable yield.

Considering the increased pressure on managed forest lands to meet evolving objectives of C sequestration and storage in addition to traditional timber commodities (Van Deusen et al. 2012), continued investigation of silvicultural practices and stand conditions on recoverable volume is warranted, especially in areas impacted by pest outbreaks. Given the noted trends in silvicultural treatments and SNC on crown shape of Douglas-fir (Weiskittel et al. 2006*a*, 2007), the inclusion of crown variables in static equations may be the best approach for making accurate predictions across a wide range of applications. Thus, the overall goal of this work was to quantify stem taper of Douglas-fir and red alder under a variety of stand conditions created by contrasting silvicultural treatments common to the region and impacted by SNC in the PNW utilizing the cooperative regional research networks of the SMC, SNCC, and HSC. The specific objectives were to: (1) evaluate the influence of various crown variables on stem taper across varied stand conditions; (2) quantify the effects of various silvicultural treatments (pruning, thinning, and fertilization), stand origin (limited to red alder—natural vs. planted), and stand health (Swiss needle cast disease) in the case of Douglas-fir on stem taper; and (3) examine the influence of these factors on bark thickness.

Methods

Study area

The 92 unique study installations cover a range of environmental conditions near the Pacific Ocean. The general climate of the study area is classified as Oceanic and Warm-Summer Mediterranean, and temperatures span from 4.9 to 15.1 °C in the winter and summer, respectively, with most of the annual precipitation (219–350 cm) occurring in the winter season. Geologic provinces include the Southern Olympic Mountains and Willapa Hills, parent materials include alluvium over unconsolidated glacial deposits, and residuum from weathered basalt and sandstone, that result in in high variability of soil chemistry, texture, and drainage class (McKee 1972; NRCS 1999). Across the study sites, elevation ranges from 54 to 237 m above sea level on gentle to moderate slopes of 0%–15% (Fig. 1).

Data curation

Stem taper datasets and tree lists were compiled from the SMC, HSC, and SNCC and analyzed separately due to the unique nature of each dataset with associated species and treatments. The SMC dataset consists of taper data collected on trees felled during thinning treatments and climbed tree data collected during the summer of 2004 (Weiskittel et al. 2007). A total of 503 trees were measured across 23 separate installations, including plots fertilized with N in the form of urea, thinned to various residual densities, thinned and fertilized, and pruned to 20%, 40%, or 60% live crown ratio (LCR) (Maguire et al. 1991). Prior to felling, each sample tree was measured for DBH, total height, and height to crown base (HCB) (Table 1). Once cut, disks were sampled ($n = 7853$) along the main stem at 1 m along internodal intervals and measured for both inside (dib)- and outside bark diameter (dob). Time since thinning was based on years since the first thinning entry, while thinning intensities were not reconstructed as it was assumed that the combination of DBH, HT, and HCB implicitly capture the influence of current stand density on

Can. J. For. Res. **55:** 1–10 (2025) | dx.doi.org/10.1139/cjfr-2025-0018

Fig. 1. Locations of the Hardwood Silviculture Cooperative (HSC—red dots), Stand Management Cooperative (SMC—green dots) and Swiss Needle Cast Cooperative (SNCC—blue dots) plot networks in Oregon and Washington, USA. Figs was created using the ggmap package (Kahle and Wickham 2013) in the R software environment (version 4.4.0—R Core Team 2024). Background image provided by Google in 1984 WGS coordinates.

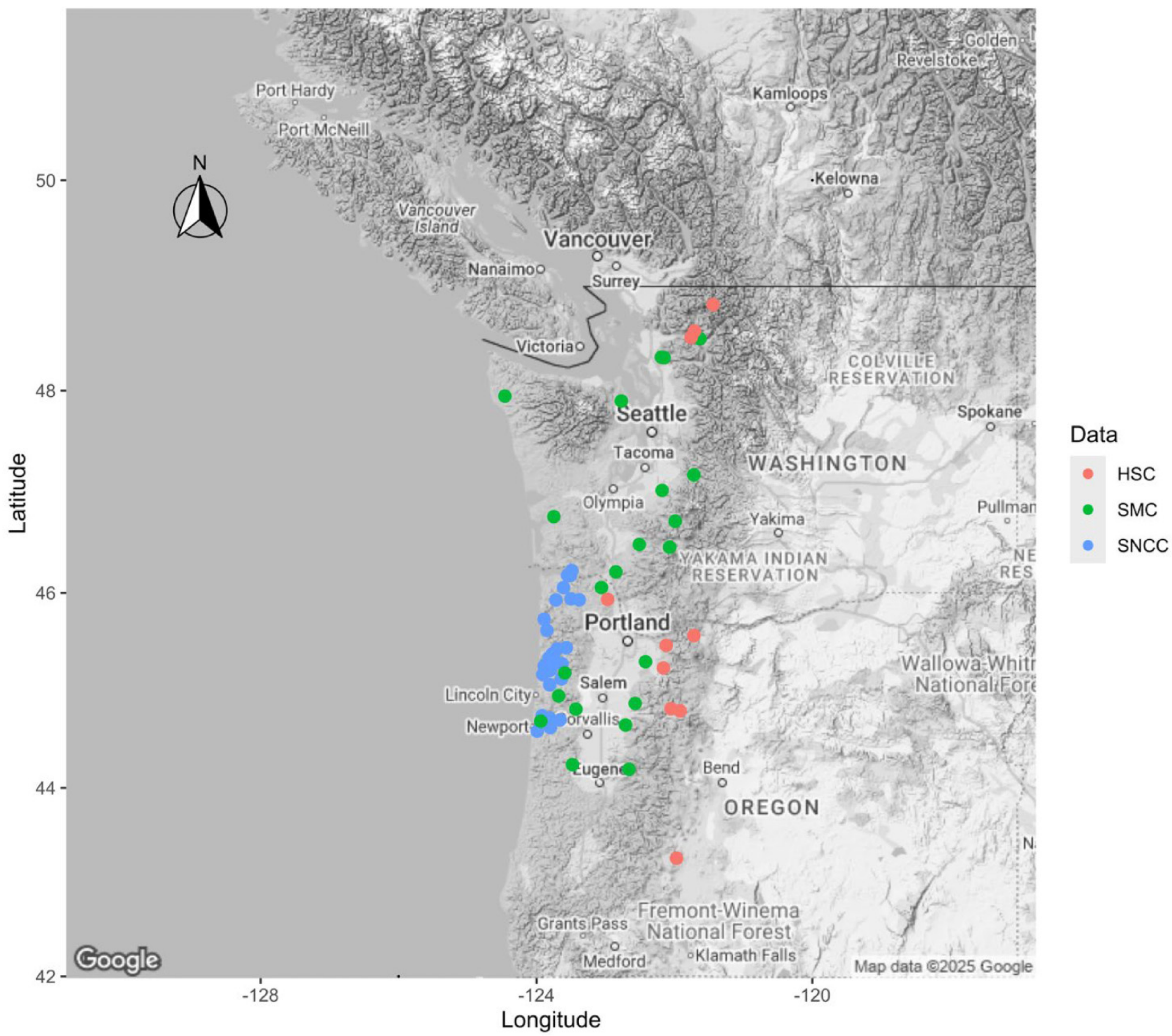


Table 1. Mean and range (in parentheses) of tree attributes from the SMC, SNCC, and HSC plot network used in this analysis corresponds to the standard deviation.

	DBH (cm)	DIB (cm)	DOB (cm)	HT (m)	HCB (m)
Douglas-fir					
SMC installations = 23; trees = 503	19.5 (4.7–43.8)	11.2 (0.0–48.2)	13.0 (0.0–54.6)	16.3 (5.1–27.8)	7.4 (0.3–18.7)
SNCC installations = 31, trees = 105	32.6 (12.5–66.6)	18.7 (0.4–67.2)	28.3 (0.6–73.2)	25.5 (11.9–45.8)	11.0 (0.5–28.3)
red alder					
HSC installations = 81, trees = 495	21.6 (3.1–46.0)	14.9 (0.5–53.6)	15.9 (0.5–55.5)	18.8 (4.9–37.8)	10.8 (0.1–28.5)

Note: SMC, Stand Management Cooperative; SNCC, Swiss Needle Cast Cooperative; HSC, Hardwood Silviculture Cooperative; DBH, diameter at breast height; DIB, inside bark diameter; DOB, outside bark diameter; HT, total height; HCB, height to crown base.

crown form and stem taper. The SNCC dataset includes measurements from 105 individual tree across 31 installations collected between 2002 and 2004 (Weiskittel et al. 2006*a*). The sites ranged from low to high SNC defoliation rates (1.2–4.4 years) (Zhao et al. 2012) and plantation age varied between 10 and 60 years. Standing trees were measured for DBH, HT, and HCB, with 10 to 15 discs per tree (n = 1375 total) sampled along the stem at fixed intervals of 1 m. Trees were divided into 100 equal sections for numerical integration for volume estimation using Smalian's equation given the small distance between measurements. The red alder dataset from the HSC includes standing tree and felled stem measurement data from 495 red alder trees at 81 plots across 23 distinct study sites in Washington, Oregon, USA, and British Columbia, Canada. Silvicultural treatments included natural regeneration, planted stock, pruning treatments, and control plot reference areas. Like both the SMC and SNCC, trees were felled trees and systematically sectioned into discs at 1 m and measured for dib/dob (Table 1).

Statistical analysis

Preliminary data processing required imputation of dib for the SNCC dataset since standing trees were only measured for dob. A preliminary bark thickness model specifying silvicultural treatment, stand origin (planted/natural), and/or health parameters was fit with a power function dib $= \beta_0 + \text{dob}^{\beta 1}$ revealed no detectable effect of silvicultural treatment for Douglas-fir when compared to a base model given likelihood ratio tests ($p < 0.001$; $\Delta\text{AIC} = 121$), in line with findings from Li and Weiskittel (2011). Once values were imputed, a variable exponent function (Kozak 2004) was selected as a base model form given its flexibility in testing the effect of silvicultural treatments, tree crown attributes, and stand conditions, on stem shape. The general model form was:

$$(1) \qquad \widehat{\text{dib}} = \beta_0 \text{DBH}^{\beta_1} \text{HT}^{\beta_2} \times X_i^{\left[\beta_3 Z_i^4 + \beta_4 \left(1/e^{\text{DBH}/\text{HT}}\right) + \beta_5 X_i^{0.1} + \beta_6 \left(\frac{1}{\text{DBH}}\right) + \beta_7 \text{HT}^{Q_i} + \beta_8 X_i\right)\right]}$$

where DBH = outside bark diameter at breast height (cm), HT = total tree height (m), h_i = height from ground (m), $Z_i = h_i/\text{HT}$, proportional height from ground, $p = 1.3/\text{HT}$, $X_i = ((1 - Z_i^{(1/3)})/(1 - p^{(1/3)}))$, $Q_i = 1 - Z_i^{(1/3)}$. Due to the hierarchical nature of the data and multiple measurements on an individual stem, the models were fit using maximum likelihood with multiple-level random effects at the tree, plot, and installation levels with a specified autoregressive error structure (Garber and Maguire 2003). Specifically, the parameters β_0 and β_7 were found to vary the most from tree to tree so were selected to be random parameters and in the case of the overall model, they were allowed to vary by study, installation, plot, and tree, with parameter estimates weighted by a power variance function to adjust for heteroscedasticity.

To analyze the effects of various silvicultural treatments and SNC on stem taper of Douglas-fir and planting stock on red alder, additional parameters β_9–β_{14} were added to the base model to account for the inclusion of crown ratio, time since thinning, and site-specific estimates of foliage retention (Zhao et al. 2012) as continuous variables, while thinning, pruning, fertilization treatments (DF), and planting stock (RA) were included as categorical variables, taking a value of 1 if treated, and 0 otherwise, with the modified form,

$$(2) \qquad \widehat{dib} = \beta_0 \text{DBH}^{\beta_1} \text{HT}^{\beta_2} X_i \left[\beta_3 Z_i^4 + \beta_4 \left(\frac{1}{e}^{\frac{\text{DBH}}{\text{HT}}}\right) + \beta_5 X_i^{0.1} + \beta 6 \left(\frac{1}{\text{DBH}}\right) + \beta_7 HT^{Qi} \beta_8 X_i + \beta_9 CR \right.$$
$$+ \beta_{10} \log(\text{TST} * \text{THIN} * \text{CL} + 0.1) + \beta_{11} \log(TST * PRUNE * CL + 0.1) + \beta_{12} \log(\text{TST} * \text{FERT} * \text{CL} + 0.1)$$
$$\left. + \beta_{13} \log(FLRET * DBH) + \beta_{14} \log(\text{TST} * \text{PLANTED} * \text{CL} + 0.1) \right]$$

where TST is time since treatment, CL is crown length (m), CR is crown ratio, FLRET is years of foliage retention (lower values equate to higher SNC defoliation; Zhao et al. 2012), and other variables have been previously defined. For RA, data from the HSC was used to generate a model of similar form as eq. 2, but with the inclusion of stand origin (planted vs. natural origin) and without a fertilization indicator or SNC modifier. For SNC, alternatives to foliage retention were tested and included categorical variables for defoliation severity and the crown spareness index (Maguire and Kanaskie 2002). For RA, a pruning term was included in the model to test for potential effects despite less than 5% of trees in the dataset being pruned. Model performance was compared with likelihood ratio tests used to assess improvements over the base approach in eq. 1. Comparison of the model performance with treatment and SNC modifiers was conducted through assessment of Akaike Information Criterion (AIC), and goodness of fit tests including root mean square error (RMSE), mean absolute error (MAE), and mean absolute bias (MAB).

To assess relative model performance, eq. 2 was compared to Kozak's original regionalized equation for British Columbia commercial species (Kozak 1997—hereinafter Kozak BC), and the Walters and Hann (1986) segmented regional taper equation. Although the Walters and Hann (1986) equation was originally parameterized for Douglas-fir in southwest Oregon (SWO), it is the taper function used in the ORGANON forest growth and yield model, while the SWO bark thickness equation has been shown to produce better results than its Northwest Oregon (NWO) counterpart (D.W. Hann, personal communication). For RA, the model generated by Bluhm et al. (2011) for plantations across the PNW was used for comparison. For additional assessment, total volume inside bark was calculated by integrating the taper equations for each treatment group for the range of observed tree sizes in the dataset, and three example defoliation level groups (foliage retention 4.5, 2.5, and 1.5 years, indicating healthy, moderately healthy, and unhealthy trees, respectively).

 Can. J. For. Res. 55: 1–10 (2025) | dx.doi.org/10.1139/cjfr-2025-0018

Table 2. Uncertainty and goodness of fit metrics of the tested models.

Model	RMSE	MAE	MAB
Douglas-fir silviculture			
Kozak	1.425	0.969	0.046
Kozak BC	1.719	1.348	0.019
Kozak SMC	1.081	0.699	0.054
Walters and Hann	1.152	0.766	0.132
Douglas-fir SNCC			
Kozak	3.821	2.465	0.807
Kozak BC	2.995	2.264	0.174
Kozak SNCC	2.281	1.573	0.181
Walters and Hann	2.521	1.749	0.005
Red alder			
Kozak	2.199	1.452	0.080
Kozak BC	1.884	1.191	0.316
Kozak HSC	1.865	1.214	0.040
Bluhm et al.	5.006	3.995	0.783

Note: RMSE is root mean square error, MB is mean bias (predicted—observed), and MAB is mean absolute bias. The Kozak SMC, Kozak SNCC, and Kozak HSC correspond to the models generated with the cooperative datasets.

Results

Influence of crown variables

Across the various stand conditions and species examined, the inclusion of crown variables consistently improved overall model performance when compared with the corresponding base equations of the Kozak, Kozak BC, Walters and Hann, and Bluhm et al. approaches. The addition of the CR was significant across species, while the CL interaction term with silvicultural treatment and planting origin provided a better fit to the DF and RA datasets, respectively (Tables 2 and 3). While crown dimension metrics (CR and CL) failed to capture the effect of SNC on DF taper, the FLRET term indicated a negative effect on dib.

Douglas-fir—silvicultural treatments

The inclusion of treatment variables for thinning, thinning × fertilization, and pruning was found to perform better than the base model (eq. 1) fitted without treatment indicator variables as indicated by the AIC scores (ΔAIC = 155.73). Model predictions of stem taper for a tree of average diameter, height, and crown ratio reveals greater mean stem dib above DBH by 3.5% in thinned trees, while pruned trees exhibit a smaller dib by approximately 4.1% (Table 2). The fertilization treatment alone had no significant difference in stem taper from the unmanaged treatment group ($p = 0.9913$). Thinned trees were more cylindrical than unmanaged trees, tapering off more toward the tree tip. Pruned trees tapered off quickly with relative height and displayed a narrower upper bole (Fig. 2). The final model with treatment variables exhibited a greater MAB than the Kozak BC approach, but performed comparatively better in the RMSE and MAE, while the Walters and Hann model had low RMSE and MAE values but notably greater bias (Table 3). Douglas-fir from thinned stands that were not fertilized or pruned showed a 4.3% increase in total bole volume inside bark compared to trees of identical DBH, HT, and HCB from unthinned stands. Pruned trees, all from thinned stands, showed a decrease in total volume inside bark from the unmanaged stand of 4.9%, approximately 2.4% lower than the base Kozak model (eq. 2) (Table 4).

Douglas-fir—SNCC

The addition of crown length and foliage retention variables contributed to modest performance improvements, reducing AIC from the base (ΔAIC = 16.71). Stem taper increased with corresponding years of foliage retention (Table 2; Fig. 3), while both individual tree and plot mean crown sparseness index had no effect ($p > 0.683$). For a given tree size, severe SNC reduces mean dib above-breast height by 13.8% when compared to a healthy tree. Reductions in the dib in the upper 10% of the stem; however, averaged 35.5%. Below breast height, severe SNC increased mean dib by 2.3% when compared to a referenced uninfected stand (Table 4). The locally fit SNCC model exhibited the lowest RMSE and MAE when compared with the other approaches, while the Walters and Hann equation had the lowest MAB (Table 3). Healthy, uninfected trees contained 15.7% more total bole volume than unhealthy trees of equal DBH, HT, and HCB (Table 4). Compared to volume estimates of the Kozak equation, healthy trees contained 6.6% greater volume, while unhealthy trees showed a reduced volume of 9.1%.

Red alder—HSC

The combined model of stand origin and pruning did not improve model performance from the base Kozak form; however, a simplified form containing only the stand origin predictor variable exhibited a better overall fit to the data compared with the base model (ΔAIC = 64.31) (Table 2; Fig. 4). The addition of stand origin (Kozak HSC) performed best with the lowest RMSE and MAB, while the Kozak BC had the lowest MAE among the compared models (Table 3). The Bluhm et al. 2011 model generally performed lowest when compared to the various Kozak forms. Predicted total bole volume was 16.1% lower in planted stands for trees of equal diameter, height, and crown ratio due to difference in stem form. The predicted volume of naturally regenerated red alder was nearly identical to both the Kozak and Kozak BC predictions (~1%) (Table 4).

Discussion

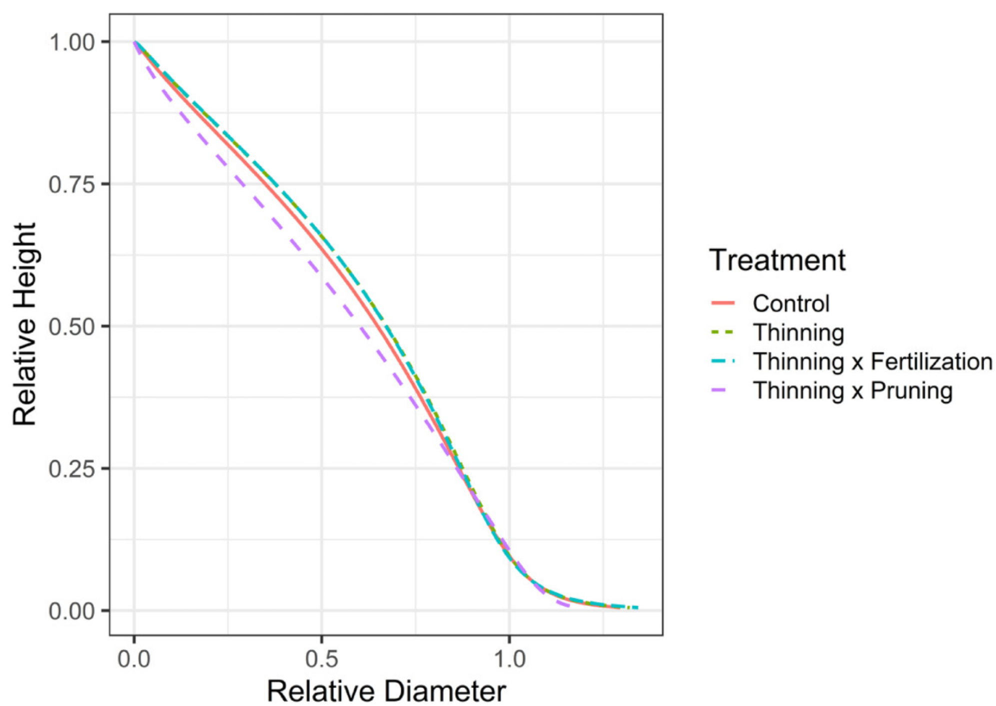
This study represents a modeling approach to determine effects of various stand conditions created by contrasting silvicultural activities, stand origins, and stand health on stem taper of two important commercial species of the PNW, Douglas-fir and red alder. The base model for the study was the widely used Kozak (2004) taper equation. The Kozak (2004) taper equation was chosen as it is flexible, easy to fit, and can provide reliable and accurate predictions for both diameters and tree volume (merchantable volume and total tree volume) across a wide range of settings and species (Li and Weiskittel 2011). Past work has shown that the Kozak

Table 3. Parameter estimates for the locally generated model using the base variable exponent equation (eq. 2).

	SMC		SNCC		HSC	
Parameter	Estimate	SE	Estimate	SE	Estimate	SE
β_0	0.7965	0.0298	1.2734	0.1312	0.3580	0.0333
β_1	0.9835	0.0144	0.8029	0.0642	1.0440	0.0214
β_2	0.1055	0.0204	0.1142	0.0652	0.2830	0.0348
β_3	0.3742	0.0121	0.4382	0.0408	0.3801	0.0220
β_4	0.0354	0.0049	0.0552	0.0140	0.0247	0.0088
β_5	0.2345	0.0434	0.3265	0.2004	0.0161	0.0782
β_6	0.7426	0.2934	9.0439	1.5251	1.3415	0.7088
β_7	0.0929	0.0035	0.0332	0.0044	0.0821	0.0059
β_8	− 0.5304	0.0238	− 0.2807	0.0477	− 0.4432	0.0485
β_9	0.1927	0.0372	0.0132	0.0031	0.0157	0.0023
β_{10}	− 0.0049	0.0022	–	–	–	–
β_{11}	0.0144	0.0049	–	–	–	–
β_{12}	− 0.0001	0.0022	–	–	–	–
β_{13}	–	–	− 0.1281	0.0325	–	–
β_{14}	–	–	–	–	0.0056	0.0012

Note: SMC corresponds to the silvicultural treatment data from the Stand Management Cooperative, SNCC is the defoliation dataset from the Swiss Needle Cast Cooperative, and the HSC is the red alder data from the Hardwood Silviculture Cooperative.

Fig. 2. Effects of silvicultural treatment on stem taper of Douglas-fir. Treatment-level average trees are used to highlight stem form differences.



(2004) equation is less biased than other widely used taper equations, such as the segmented equation (Clark et al. 1991), the volume compatible equation (Fang et al. 2000), and the cubic taper equation (Goodwin 2009), and several volume equation forms (e.g., Honer 1965, 1967; Li et al. 2012). Moreover, the Kozak (2004) equation has the merits of being flexible and easy to fit, which is an attractive solution when experimenting with the addition of management, health, and origin indicator variables. Yet, it should be noted that the Kozak (2004) approach can still result in bias at the base and the tip of a tree due to the rapid changes in stem taper at these locations (Li et al. 2012).

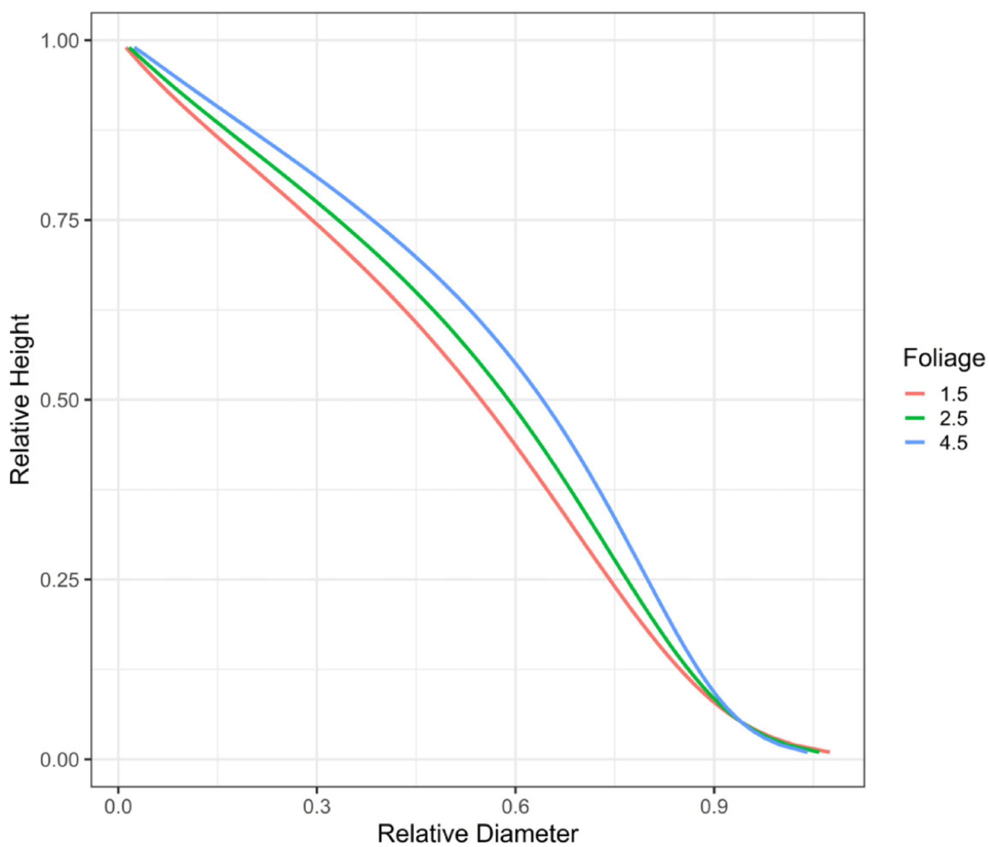
While silvicultural treatment effects were tested for both Douglas-fir and red alder, the only significant effects found in the study were a positive effect of thinning (i.e., increase in dib) and a negative effect of pruning on Douglas-fir

Table 4. Model predicted total volume inside bark (m^3) of a typical Douglas-fir of DBH = 30 cm, HT = 22 m, HCB = 9 m, using Kozak, Kozak BC, Walters and Hann, and Bluhm et al. equation with all combinations of treatment indicators and foliage retention.

Douglas-fir	Kozak SMC/SNCC/HSC	Kozak 04	Kozak BC	Walters and Hann	Bluhm et al.
Silviculture					
Control	0.586	0%	8%	2%	–
Thinning	0.610	4%	11%	6%	–
Fertilization	0.586	0%	8%	2%	–
Thinning × fertilization	0.611	4%	11%	6%	–
Thinning × pruning	0.545	−7%	1%	−5%	–
Swiss needle cast					
FolRet 1.5 years	0.532	−10%	−2%	−8%	–
FolRet 2.5 years	0.571	−2%	5%	0%	–
FolRet 4.5 years	0.624	6%	13%	8%	–
Red alder					
Silviculture					
Planted	0.771	3%	5%	–	−2%
Natural	0.746	−1%	2%	–	−5%

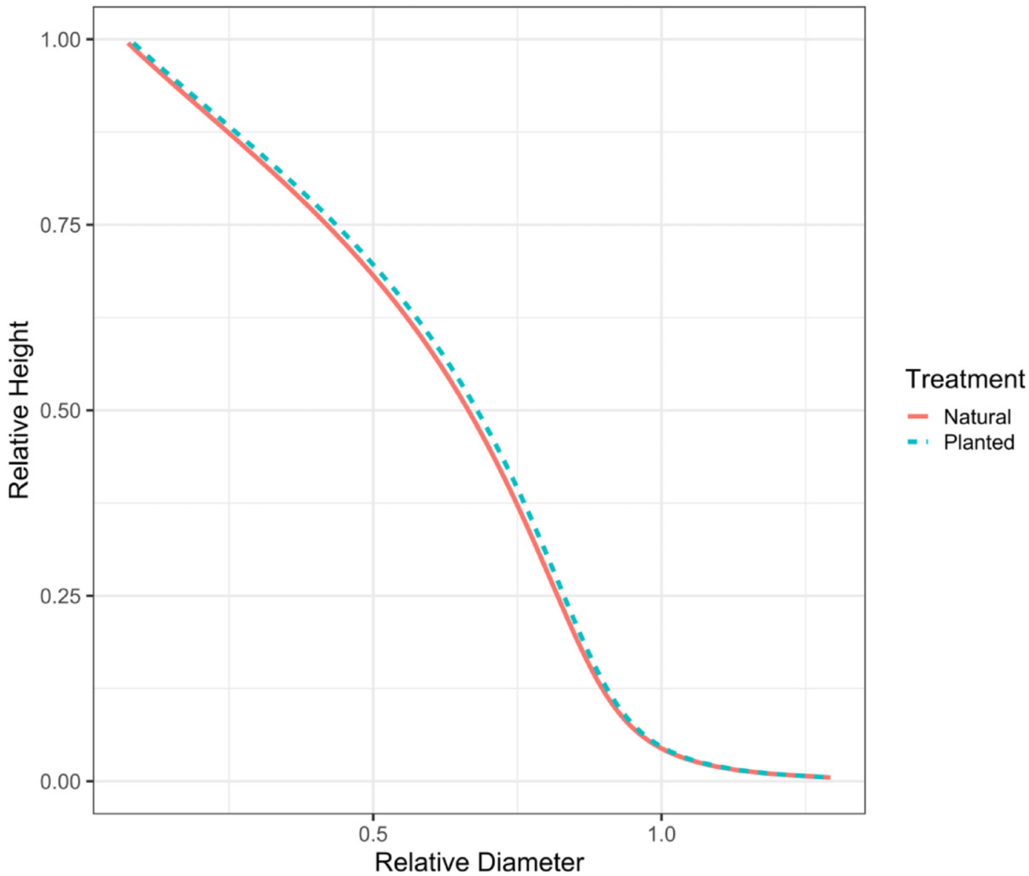
Note: Values in the Kozak SMC/SNCC/HSC column correspond to estimated tree volume (m^3), while the other four columns indicate the proportion of difference (%) when compared with other models included in the analysis. DBH, diameter at breast height; HT, total height; HBC, height to base crown; SMC, Stand Management Cooperative; SNCC, Swiss Needle Cast Cooperative; HSC, Hardwood Silviculture Cooperative.

Fig. 3. Swiss Needle Cast (SNC) in Douglas-fir predicted relative diameter outside bark versus relative height by Tree Health Category red line—1.5 years foliage retention (severe SNC); green line—2.5 years foliage retention (moderate SNC); and blue line—4.5 years foliage retention (healthy) for an example tree (DBH = 30 cm, HT = 25 m). DBH, diameter at breast height; HT, total height.



(decrease in dib). Since all pruned trees were from thinned stands, it can be assumed that pruned trees in unthinned stands would show an even more substantial reduction in total bole volume. The fertilization indicator variable in the DF-SMC model contributed meaningfully to model performance but was found to be statistically nonsignificant. This

Fig. 4. Predicted relative diameter inside bark (dib) versus relative height of natural (solid red line) versus planted (dashed blue line) red alder for an example tree (DBH = 20 cm, HT = 20 m, and HCB = 10 m) in the HSC dataset. DBH, diameter at breast height; HT, total height; HCB, height to crown base; HSC, Hardwood Silviculture Cooperative.



result may indicate an effect of interaction between the indicator variables and should be investigated further. A study by Huiquan and Turner (1994) of *Pinus radiata* found significant increase in lower bole diameter in fertilized trees, but no other significant form factor changes in response to usage or amount of fertilizer. Prior research in Douglas-fir has indicated that fertilization can alter crown shape and branch dynamics (Weiskittel et al. 2007), which are presumably influenced by shifts in tree leaf area, yet the influence depends highly on the time since treatment and cumulative amount of fertilizer applied. While fertilized trees in the SMC dataset generally had much greater DBH at similar age as unfertilized trees, lower bole relative diameter was not significantly greater, and so this result was not confirmed by the study and may be an effect of species or stand density. Regardless, further study is required to fully understand effects of fertilization, especially in terms of potential gains in merchantable volume.

Since SNC is a foliar disease that affects leaf retention and the vertical distribution of leaf area in Douglas-fir (Weiskittel et al. 2006*a*), it is not surprising that fitted model predictions from the SNCC dataset revealed a strong correlation between disease severity as quantified by foliage retention and reduction in upper stem diameter of studied trees. The 13.8% reduction in mean upper stem diameter increased to 35.6% in the top 10% of the bole, where defoliation is often the most severe (Weiskittel et al. 2006*a*), when comparing healthy stands to unhealthy ones. This result, along with associated impacts on total volume, can now be used by managers to assess economic impacts of the disease and quantify costs and benefits of potential interventions and treatments. This is important as a recent financial assessment found significant declines in total stand value (50% on average) when SNC-defoliated stands were compared to healthy stands (Susaeta et al. 2024), even when changes in stem form were not accounted for. Based on this analysis, these financial impacts might be expected to be even higher given the likely reduction in merchantable volume caused by SNC.

Thinning and pruning of red alder were found to have nonsignificant effects on stem taper. Since less than 5% of red alder in the HSC database were pruned, additional data would be needed to confirm this result. However, previous research such as a study of growth response following pruning of *Eucalyptus pilularis* have shown no significant effect of pruning on stem taper in hardwoods (Alcorn et al. 2008). The lack of a thinning effect is the more surprising result, yet it is possible that the variability in stem form caused by thinning is sufficiently captured by the model terms related to crown

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ratio. Further study of thinning effects on red alder stem taper is required, though this study suggests any potential effects are smaller than those seen in Douglas-fir. Planted red alder trees were found to taper more uniformly with relative height, with a more cylindrical stem form and reduced mean above-breast height diameter of 14.6% compared to naturally regenerated trees. These results parallel findings in conifer species of Li et al. (2012), as planted red alder exhibited narrower stem taper above breast height than naturally regenerated trees, which tapered off more quickly in the upper bole section. This is likely due to differences in early competition dynamics between planted and naturally regenerated stands as the latter tends to be clustered with a greater number of stems.

The work presented here suggests that the inclusion of crown variables, foliage retention (in the case of SNC) and silvicultural treatment terms can increase the predictive power of stem taper in Douglas-fir and red alder in the PNW. While these terms only marginally improved model performance, they had a significant impact on predicted total volume, which can compound substantially when considering large stands or extensive managed land bases. The study is also testament to the quality of the Kozak (2004) equation, which was again shown to be a flexible, unbiased, and easy to use model form which can be modified to include additional information without significant changes in behavior. It should be noted that this work does not explicitly address the effect of site variables and geographic variation in stem taper across the wide range of the PNW which could lead to a confounding effect when interpreting the results. Moving forward, the inclusion of topographic features and digital soil attributes may further improve estimates of recoverable volume in the PNW, as seen in recent findings in longleaf pine (*Pinus palustris* (Mill.)) in the southeast US (Sheeks 2021). Overall, our findings suggest the sensitivity of individual tree stem form to variation imposed by changes in crown attributes due to contrasting stand conditions across both a conifer and hardwood species. This suggests the need to continually refine regional stem taper equations to account for crown variables and specific stand conditions as assessed in this present analysis.

Article information

History dates

Received: 17 January 2025
Accepted: 5 May 2025
Accepted manuscript online: 9 May 2025
Version of record online: 15 July 2025

Copyright

Data availability

Data are not publicly available but may be acquired at the discretion of the research cooperatives.

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Competing interests

The authors declare no competing interests.

Funding information

This work was made possible by funding support provided by the Center for Advanced Forestry Systems, Center for Intensive Planted-Forest Silviculture, Hardwood Silviculture Cooperative, Stand Management Cooperative, and the Swiss Needle Cast Cooperative.

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