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GROWTH RESPONSE OF COASTAL DOUGLAS-FIR (PSEUDOTSUGA MENZIESII [MIRBEL] FRANCO) IN WESTERN OREGON FOLLOWING MECHANICAL COMMERCIAL THINNING DAMAGE

Jim Kiser, Dixie A. Daniels, Hailemariam Temesgen

Department of Forest Engineering, Resources and Management College of Forestry, Oregon State University, OR, USA

Abstract. Growth responses of coastal Douglas-fir (*Pseudotsuga menziesii* [Mirbel] Franco) were quantified 14 years following mechanical damage from commercial thinning. Damaged, adjacent, and non-adjacent trees were measured for total height, crown length, and diameter at breast height (DBH) to assess neighbor competitiveness between damaged and undamaged trees. Results indicated that mechanical damage had no significant effect between damaged and undamaged trees relative to adjacent or non-adjacent trees on total tree height, height/diameter curves, basal area growth after thinning, height to crown base, or crown length. However, there was a significant difference in crown length between the damaged and adjacent trees. Trends in height to crown base over tree diameter curves were not significantly different between damaged and undamaged trees of either the adjacent or non-adjacent group.

Keywords: Keywords: Commercial Thinning, Damage, Douglas-fir, Growth response.

1 Introduction

Commercial thinning can be an attractive management strategy to provide early financial returns and improve cash flow (Tappeiner II et al. 1982), while maintaining stand and tree vigor, diversifying stand conditions, and ensuring stand structure that will support future economic returns to landowners (Franklin and Johnson 2012).

Commercial thinning in the Pacific Northwest accounted for 1 – 7% of the total harvested volume between 1991 and 1999. In that same time frame, total acreage harvested doubled from 1.2 hectares to about 3.2 hectares per 405 hectare. By 2001this had dropped to about 2.6 but this was not unexpected due to the large acres of younger (10-30 year old) stands (Briggs 2007). Private timberland owners in western Oregon and Washington are projected through 2044 to increasingly adopt management regimes that include commercial thinning combined with precommercial thinning and other partial cutting strategies (Adams and Latta 2007). Forest policies in British Columbia, Canada have mandated that a proportion of the Provincial annual cut come from commercial thinning.

Commercial thinning volume in the Pacific Northwest is dominated by Douglas-fir (*Pseudotsuga menziesii* [Mirbel] Franco), making up between 70-80% of total species mix (Briggs 2007). Levels of residual damage during thinning operations have been reviewed (Han 1997) with estimates ranging from 5% to greater than 40 – 50%. The ability to conduct thinning activities without residual damage is certainly desirable, however, residual stem damage probably cannot be avoided (Vasiliauskas 2001), therefore it is more realistic to consider minimizing damage as a necessary goal of harvest prescriptions.

There is general agreement that damage is primarily related to factors of equipment type during transport of felled timber (Benson and Gonsior 1981) and operator skill (Makkonen 1991). Studies of damage have focused primarily on characteristics of damage by mechanical harvesting (Benson and Gonsior 1981, Cline et al. 1991).

Studies examining growth impacts from damage are lacking and responses of tree and stand level growth to damage are poorly understood. Diameter growth has been examined in a few studies but results may not be comparable due to differences in damage types. In eastern hardwoods, no significant differences were found in 5-year diameter growth between mechanically damaged and undamaged trees (Lamson and Smith 1988). Another study examined a number of damage types for western Oregon conifers (Hann and Hanus 2002). Although the study found significant differences for some of these damage types, mechanical logging damage was not significant. Additionally, no effects to diameter growth from damage were reported for Corsican pine (*Pinus nigra*) (Picchioa et al. 2011).

Table 1: Characteristics of the sites selected for study.

Site	Age	QMD cm (se)	QMD range (cm)	Height m (se)	Live Crown Height M (se)	Trees/ha (se)	Basal Area/ha m^2 (se)	Stand Density Index
1	50-60	46.6 -1.8	21.8-66.3	35.7 -0.8	47.5 -2.2	289.5 -33.1	49.5 -3.1	310.5
2	50-60	43.6 -1.2	22.9-58.4	31.6 -0.5	42.2 -1.6	332.5 -24.3	49.8 -2.3	319.9

Table 2: Characteristics of the tree wounds.

Statistic	DBH (cm)	Wound Characteristics					
		Length (cm)	Width (cm)	Depth (cm)	Area (cm^2)	Ht above ground (m)	Area / Circum Ratio
Mean	41.1	71.5	15.0	3.3	2716.9	2.0	20.5
SD	8.7	28.5	5.4	3.6	1628.3	0.8	9.0
SE %	5.0%	9.4%	8.4%	25.3%	14.1%	9.3%	10.3%

The objective of this study was to test the null hypotheses that tree-level and stand level growth and yield of coastal Douglas-fir are not impacted by mechanical damage during commercial thinning. The statistical design and analyses for this study were planned to compare the following attributes between damaged and undamaged trees: 1) total tree height, 2) basal area growth and, 3) crown attributes (height to crown base, crown length, and height to crown base over diameter). Trees chosen for this study were small to medium-sized sawtimber in stands that had been thinned 14 years previous, and were similar to stands ready for regeneration harvest on privately-owned timberlands in the Pacific Northwest. Results therefore should pertain to many commercial-size Douglas-fir stands in western Oregon.

2 Data and Methods

2.1 Location and Data Collection The study sites were located in the McDonald-Dunn Forest managed by Oregon State University's College of Forestry. The sites were 3 km west of Corvallis, Oregon (44°33'N, 123°15'W) and were on 5 to 35% northeast-facing slopes (Figure 1). Annual precipitation over the last 20 years was 1100-1500 mm and mean annual air temperature was 12°C. The soil is a clayey, mixed mesic, Dystric Xerochrept (USDA 2009). The site is classified as a *Tsuga heterophylla/Acer circinatum/Gaultheria shallon* community type (Hubbard 1991). These planted second-growth stands are dominated by 50- to 60-year-old Douglas-fir that were commercially thinned by ground–based equipment in 1993. The thinned stands were similar in quadratic mean diameter (QMD), age, height (ht), trees per hectare (TPH), live crown height, basal area per hectare, and stand density levels (Table 1).

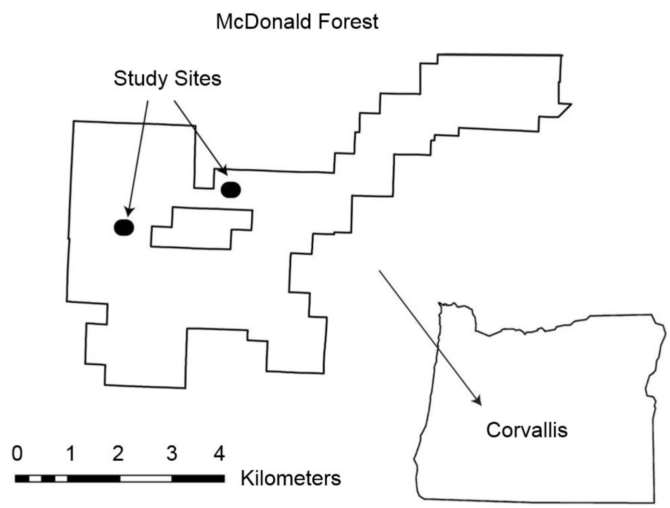

Figure 1: Study site locations.

A walking traverse of each stand was done to identify and select all damaged Douglas-fir trees in each stand. Eighteen trees were identified that had mechanical cambium damage in the lower bole with at least 930 square cm (1 sq. ft.) of damaged surface area (table 2). Damage was generally caused by ground-based harvesting equipment, for example, machine impact damage and rub trees. All cambial damage was visually assumed (location, edge characteristics, depth, and cambial damage) to have been caused by logging during thinning activities. An adjacent undamaged tree and a non-adjacent control tree of similar size (same crown position and DBH < 3.8 cm) were selected for each of the damaged trees and marked.

A 0.02 hectare (0.05 acre) fixed-radius plot was established around each damaged tree. All Douglas-fir trees within the plots were measured for diameter at breast height (DBH), height to the live crown base, defined as that point on the bole with live branches on 3 sides, total height, and azimuth and horizontal distance to damaged tree center. Total tree height and crown base height were measured with a Laser Technology Impulse 200 hand-held laser mounted on a fixed-height pole. Repeated measures from different positions were taken for each tree on the plot and verified to be within plus or minus 0.3 m (1 ft.).

The 18 damaged trees, 18 adjacent (nearest) undamaged trees, and 18 nonadjacent (within the plot) undamaged trees were felled and disks approximately 15 cm. (6 in.) in thickness were removed at DBH and the base of the live crown. Year of thinning was marked by back-counting annual rings and annual radial growth was measured and averaged for four quadrants of each disk under magnification using a Mitutoyo digital caliper (0.01 mm) for the 14 years after thinning and for 14 years before thinning. Basal-area growth was calculated from the averaged radial growth.

Increment cores were taken at DBH for all other trees in the plot, placed in labeled straws, and transported back to the College of Forestry, Forest Research Laboratory (FRL). Annual radial growth inside bark for the two 14-year growth periods was measured under magnification using the digital caliper. Annual diameter and basal area growth were calculated from radial growth measurements.

2.2 Statistical Analysis Analyses for tree height compared total height and the height to diameter relationship between three groups: damaged trees, adjacent undamaged trees, and non-adjacent undamaged trees. Differences in total height were tested with a linear regression model that included indicators for damage and adjacency. The height to diameter relationship was tested with a general Weibull-based height/diameter model that also included indicators for damage and adjacency. The Weibull-based model has been shown to have a best-fit, unbiased single function model for Douglas-fir (Temesgen et al. 2007). Response of basal area growth to damage was tested by the ratio of growth after thinning to growth before thinning using a linear regression model with indicators for damage and adjacency. The response of live-crown to damage was tested on three attributes: crown length, height to the base of live crown, and height to crown base over tree diameter. Differences in the former two attributes were tested by linear regression models that included indicators for damage and adjacency. The height to crown base over diameter was tested with a general height/diameter model by replacing total height with height to crown base and including indicators for damage and adjacency.

2.2.1 Total Tree Height Differences in total height between the groups were tested by comparing the regression parameters for the single-factor analysis of variance model:

$$Height = \beta_{10} + \beta_{11} I_N + \beta_{12} I_A + \varepsilon_1 \quad (1)$$

Where:

- I_N = Indicator term for adjacent (1 = non-adjacent undamaged, otherwise 0);
- I_A = Interaction term for adjacent (1 = adjacent undamaged, otherwise 0); and
- β_{10}, β_{11}, and β_{12} are parameters to be estimated from the data and $\varepsilon_1 \overset{iid}{\sim} N(0, \sigma_1^2)$.

The adjacent undamaged and non-adjacent undamaged indicator variables were tested for significance with the extra sums of squares F-test. Differences in the height/diameter curves between the groups were tested by comparing the nonlinear regression parameters for the general height/diameter model:

$$Height = 1.3 + e^{[\beta_{21} + \beta_{22} DBH^{\beta_{23}}]} + \varepsilon_2 \quad (2)$$

Where β_{21}, β_{22}, and β_{23} are parameters to be estimated from the data and $\varepsilon_2 \overset{iid}{\sim} N(0, \sigma_2^2)$.

Modification of the model was made to include indicator terms for the adjacent and non-adjacent trees. There were no significant differences in the coefficients for either the non-adjacent trees ($P > 0.99$) or the adjacent trees ($P > 0.99$).

2.2.2 Basal Area Differences in basal area growth were examined by testing for differences in the ratio of basal area growth before and after thinning (eq. 3). Differences in the ratios of basal area growth between the groups were tested using the regression approach to single-factor analysis of variance:

$$\frac{BAG_{post}}{BAG_{pre}} = \beta_{30} + \beta_{31} I_N + \beta_{32} I_A + \varepsilon_3 \quad (3)$$

Where:

- BAG_{post} = Basal area growth for 14-year period after thinning;
- $BAG_{pre=}$ Basal area growth for 14 year period before thinning and β_{30}, β_{31}; and
- β_{32} are parameters to be estimated from the data and $\varepsilon_3 \overset{iid}{\sim} N(0, \sigma_3^2)$.

2.2.3 Live Crown Length Differences in crown length between the three groups of trees were examined using the regression approach to single-factor analysis of variance:

$$CL = \beta_{40} + \beta_{41} I_N + \beta_{42} I_A + \varepsilon_4 \quad (4)$$

Where:

- CL = Live crown length; and
- β_{40}, β_{41}, and β_{42} are parameters to be estimated from the data and $\varepsilon_4 \overset{iid}{\sim} N(0, \sigma_4^2)$.

The adjacent undamaged and non-adjacent undamaged indicator variables were tested for significance with the extra sums of squares F-test.

Differences in height to crown base and live crown ratio between the three groups of trees were next examined by the same regression model:

$$HCB = \beta_{50} + \beta_{51} I_N + \beta_{52} I_A + \varepsilon_5 \quad (5)$$

Where:

- HCB = Height to live crown base; and
- β_{110}, β_{111}, and β_{112}, are parameters to be estimated from the data, and $\varepsilon_5 \overset{iid}{\sim} N(0, \sigma_5^2)$.

The adjacent undamaged and non-adjacent undamaged indicator variables were tested for significance with the extra sums of squares F-test. Modeled height/diameter relationship is shown in Figure 2.

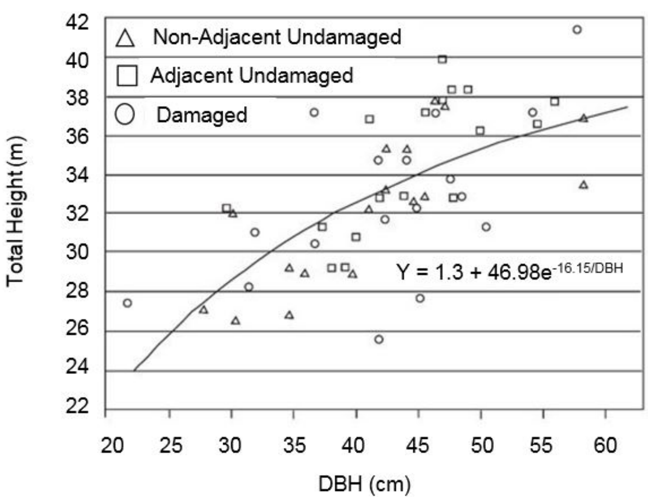

Figure 2: Height diameter relationship for the study trees.

A final test was conducted to examine differences in the relationship of height to crown base to tree diameter as described by the following nonlinear regression model:

$$HCB = 1.3 + e^{[\beta_{61} + \beta_{62} DBH^{\beta_{63}}]} + \varepsilon_6 \quad (6)$$

Where: β_{61}, β_{62}, and $\beta_{63}$are parameters to be estimated from the data and $\varepsilon_6 \overset{iid}{\sim} N(0, \sigma_6^2)$

Modification of the model was made to include indicator terms for the adjacent and non-adjacent trees. The full model tested is:

$$HCB = 1.3 + e^{[(\beta_{71} + \beta_{72} I_N + \beta_{73} I_A) + (\beta_{74} + \beta_{75} I_N + \beta_{76} I_A) DBH^{(\beta_{77})}]} + \varepsilon_7 \quad (7)$$

Where: β_{71}, β_{72}, β_{73}, β_{74}, β_{75}, β_{76}, and β_{77} are parameters to be estimated from the data and $\varepsilon_7 \overset{iid}{\sim} N(0, \sigma_7^2)$.

The adjacent undamaged and non-adjacent undamaged indicator variables were tested for significance with the extra sums of squares F-test.

3 Results

3.1 Total Tree Height Mean total tree heights are summarized in Table 3. Although mean total heights were slightly larger for both the adjacent (+2.4 m) and the non-adjacent (+0.6 m), there were no significant differences in the coefficients for either the non-adjacent trees (P = 0.14) or the adjacent trees (P = 0.13). Modification of the model was made to include indicator terms for the adjacent and non-adjacent trees. There were no significant differences in the coefficients for either the non-adjacent trees (P > 0.99) or the adjacent trees (P > 0.99). Modeled height/diameter relationship is shown in Figure 2.

3.2 Basal Area Average ratios for growth are shown in Table 4. Basal area growth ratios were slightly lower for the adjacent (-0.03) and non-adjacent (-0.19), however there were no significant differences in the coefficients for either the non-adjacent trees (P = 0.24) or the adjacent trees (P = 0.87).

3.3 Live Crown Length Mean crown lengths, height to crown base, and live crown ratios for the three groups are shown in Table 5. There were no significant differences in the coefficients for the non-adjacent trees (P = 0.14). However, there was a significant difference in live crown height for the adjacent trees (P = 0.01). Live crown lengths for the adjacent trees were 3.2 m greater than damaged trees (Table 5), however this may be attributed to the larger diameters of the adjacent trees (Table 3).

Mean height to crown base was slightly lower (-1.2 m) for the adjacent trees and (-1.1 m) the non-adjacent trees. However, there were no significant differences in the coefficients for either the non-adjacent trees (P = 0.32) or the adjacent trees (P = 0.27).

Mean values for tree crown ratios were also slightly lower for the adjacent (-0.08) and non-adjacent (-0.03) trees, but again there were no significant differences in the coefficients for the non-adjacent trees (P = 0.76) or the adjacent trees (P = 0.90).

4 Discussion

Studies examining the impacts of harvesting damage on growth are particularly sparse in the literature. Hann and Hanus (2002) examined a number of damage codes in the de-

Table 3: Mean total tree height and DBH for the three damage groups.

Class	Mean Total Tree Height (m)	Std. Dev. (m)	Avr. DBH (cm)	Std. Dev. (cm)
Damaged	32.1	3.5	41.1	6.5
Undamaged Adjacent	34.5	3.5	44.3	8.7
Undamaged Non-adjacent	32.7	4.1	42.7	8.6

Table 4: Mean BA (basal area) growth and pre-to-post-thinning BA growth ratios.

Class	BA growth before thinning (cm^2)	Std. Dev. (cm^2)	BA growth after thinning (cm^2)	Std. Dev. (cm^2)	Average Ratio
Damaged	454.2	225.3	905.9	399.2	2.14
Undamaged adjacent	541.9	259.6	1024.1	273.0	2.11
Undamaged non-adjacent	676.3	404.1	1186.4	555.0	1.95

velopment of their 5-year height-growth equations in Douglas-fir. In their case, mechanical damage was not significantly related to height growth, but natural bole wounding (abrasion from trees, rolling rocks or logs, etc.), was significant. Similar findings were reported earlier for total height prediction (Hanus et al. 1999) and height to crown base (Hanus et al. 2000) using the same set of damage variables. Mechanical damage in these three studies was not well-defined, however, and comparisons of results may not be appropriate.

Because the trees used in this study are effectively of the same cohort, any differences in total height between the two groups should have resulted in significant differences to the height diameter relationships. However, no differences were detected in either the damage or adjacency variables. This suggests that damage to the residual stems not only did not affect total height of the damaged trees, but also did not afford a competitive advantage to the trees immediately adjacent. Because total height was not significantly impacted by damage, the inference is made that no significant reduction in resource use by damaged trees occurred over the duration since thinning. Therefore, no additional resources are necessarily available to adjacent trees and therefore it was not surprising that adjacency was not significant.

4.1 Diameter and Basal Area Pre-thinning differences in basal area growth were not expected, largely because residual trees were all effectively of the same cohort and condition, so were expected to grow similarly. The lack of a negative response in basal area increment growth following wounding may at first seem unexpected. However there may be a two-fold explanation supported by the general energy reserves found in larger conifers.

Typically, large long-lived trees, such as Douglas-fir invest large amounts of non-structural carbon in reserve to maintain hydraulic transport (Sala et al. 2012) At the time of wounding, these reserves are tapped and cells become undifferentiated to form callus tissue. Xylem cell production becomes enhanced and can result in wide annual increments of a denser and stronger wood tissue (Kiser 2011, Smith 2015), not only in the initial wounding response to seal off impacted tracheids, but also in the formation and maintenance of compartmentalized walls (Tippett and Shigo 1981).

Additionally, the positive basal area growth response may lie in the required mechanical support function of the stem. Long, et al. (1981) demonstrated that sapwood cross-sectional area in Douglas-fir remained fairly constant below the live crown supporting the "pipe model" theory (Shinozaki et al. 1964). Bending stress in free-growing trees has been shown to be evenly distributed throughout the main portion of the bole (Jacobs 1954). However, in larger trees, the cross sectional area of xylem required for foliage transpiration support was not sufficient to provide necessary uniform support to bending resistance from the crown (Long et al. 1981). Necessary cross-sectional area for bending stress appears to be a combination of heartwood and sapwood. Thus, the loss of sapwood area to surface wounding could create a more rapid response from carbon reserves to restoring the mechanical stability of the sapwood/heartwood area to support the existing tree column.

One of the difficulties with this explanation is that uniform bending stress (σ) assumes a circular cross-section where bending stress is inversely related to the cube of the stem *diameter*, and thus, small differences in measured diameters would give large differences in calculated stress. Trees in fact are generally asymmetrical and any damage to one side of the tree will most likely add to an even greater asymmetry. Cambial damage to the trees in this study averaged 38.1 cm in width (30% of the circumference) but only about 3.3 cm deep (8.4%). This is probably not enough of an impact to warrant concern over the impact to mechanical integrity.

Mechanical damage in the study trees was shown to increase sapwood area by as much as 1.5 cm on the opposite side the damaged bole (Kiser 2011).It was also shown that the

Table 5: Mean crown measurements and post-thinning live crown ratios

Group Group	Mean Live Crown Length (m)	Std. Dev. (m)	Mean Height to Crown base (m)	Std. Dev. (m)	Mean Live Crown (m)	Std. Dev. (m)
Damaged	12.1	3.6	20.4	2.9	0.44	0.09
Undamaged adjacent	15.3	3.9	19.2	3.4	0.36	0.08
Undamaged non-adjacent	14.3	3.9	19.3	3.8	0.41	0.09

wound direction to the prevailing winds was not a factor in the response and that the response was instead more likely a delay in transition to heartwood. If there was a mechanical stress-related response to the damage, we would expect to see the response directionally related to the stress and the delay of a transition to heartwood would not be likely. It has been suggested that the response is more likely one of maintaining physiological support to the crown, assuming that the damage has not affected crown mass.

4.2 Live crown No significant differences were found in crown length, height to crown base, or crown ratio to tree diameter relationship between damaged and undamaged trees with the exception of a significant difference in the live crown length between damaged trees and adjacent undamaged trees. This may be explained by differences in diameter between the two groups. Although the live-crown-ratio variable is typical for assessing growth, live-crown length provides a more refined measure for understanding growth response and related measures of foliage mass and retention following disturbance (Maguire and Kanaskie 2002).

Studies of damage effects on live crowns typically focus either on direct injuries of the crown like fire (Peterson and Arbaugh 1986, Stephens and Finney 2002), insect defoliation (Kulman 1971), or fungal crown disease (Mainwaring et al. 2005). Only one study was found that specifically examined effects to the crown based on mechanical damage (Hanus et al. 2000).

Hanus et al. (2000) reported significant regression coefficients for modeling Douglas-fir crowns for a number of natural damaging agents (insect, disease, suppression for example), but found no significant effect on model coefficients related to mechanical-logging damage. Populations of that study are quite different from the current however as they extended to trees as old as 250 years and did not include any trees in stands thinned less than 20 years previous.

While coefficients of the regression equations are not significant, there is agreement with other studies that any effects on crowns in stands thinned less than 50 years may be difficult to separate from effects of the thinning itself (Zumwari and Hann 1989).

5 Conclusions

The effects of residual mechanical wounding on the growth response of basal area, total height, and crown length of coastal Douglas-fir do not appear to be a serious concern over short time spans up to 14 years. Comparisons were tested for damaged trees and both adjacent and non-adjacent Douglas-fir of similar size and age, trees damaged from ground-based logging. Height to diameter relationships from a general Weibull-based height/diameter model that also included indicators for damage and adjacency showed not only that total height of damaged trees was not affected but that the adjacent trees appear to not have gained a total height advantage over them. Similar results were obtained for both basal area growth following damage and crown variables for crown length, height to crown base and crown ratio to diameter measurements.

Results from this study suggest that there may be no short-term effects from mechanical damage on growth and yield of young managed Douglas-fir trees. However, inference beyond the time frame of this study is not known at this time. Likewise, no suggestion is made that damage of trees during harvest may be an acceptable practice because no short-term growth effects are apparent. While not within the scope of this work, residual tree damage may have longer term effects and additionally should be avoided from the perspective of worker safety, work production and quality. Within the scope of this work, a number of areas need further investigation including: effects on other conifer species, in particular western hemlock, and longer term effects at both the tree and stand levels.

Residual stand damage should be an important consideration of any silvicultural or other forest health management program. Guidelines for mitigating the effects of residual damage depend on an understanding of some fundamental ideas about the response of trees and stands to damage that are currently lacking or in some cases are not universally accepted (Manion 2003).

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