Canadian Journal of Forest Research

Long-term taper and growth reductions following pruning intensity treatments in *Sequoiadendron giganteum* (giant sequoia)

Journal:	<i>Canadian Journal of Forest Research</i>
Manuscript ID	cjfr-2019-0118.R1
Manuscript Type:	Article
Date Submitted by the Author:	31-May-2019
Complete List of Authors:	York, Robert; UC Berkeley, Environmental Science, Policy, and Management
Keyword:	stem taper, pruning, giant sequoia, mixed conifer, plantations
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

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1 **Long-term taper and growth reductions following pruning intensity**
2 **treatments in *Sequoiadendron giganteum* (giant sequoia)**

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3 **Abstract**4 A high degree of stem taper limits the potential value of *Sequoia giganteum* (giant sequoia)

5 when grown for timber. I measured the effect of pruning to different height targets (0, 2, 3.5,

6 and 5.5m), resulting in the removal of 25 to 85% of crown length, on the growth of 360 *S.*7 *giganteum* trees for 17 years. Height and dbh growth were both negatively related to pruning

8 intensity to a similar degree. Within the 17 years following pruning, repeated measurements of

9 stem growth at different heights above the ground revealed that radial stem growth reductions

10 were localized on the stems where branches were removed. The higher up that trees were

11 pruned, the more that stem radial growth was reduced compared to controls, with the greatest

12 reductions occurring at stem bases. Over time, pruning effects declined, but there were still

13 significant differences after 17 years. Girard form class was only influenced by the most intense

14 pruning of up to 5.5 m stem height. Reduced taper was a benefit of pruning, but at a cost of

15 reduced stem growth. Pruning in *S. giganteum* must be done carefully with respect to its timing,

16 intensity, and interactions with other young stand management treatments.

17 **Keywords:** Stem taper, pruning, giant sequoia

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Introduction

Pruning individual trees can be done to meet a variety of stand-level objectives, but care must be taken to ensure that negative effects on growth do not outweigh benefits (Ashton and Kelty 2018). Pruning to increase wood value has demonstrated effectiveness across many species globally, including *Pinus radiata* in New Zealand (Cown 1973), *Eucalptus* species in Australia (Alcorn et al. 2008), *Larix* hybrids in Japan (Takiya et al. 2010), *Pinus* species in Spain (Hevia et al. 2016), and *Populus* hybrids in Canada (Maurin and DesRochers 2013). The majority of these pruning studies, however, typically measured growth response on time frames that are much shorter than the temporal scale over which pruning effects are meant to occur. Pruning is unlike other intermediate treatments which can have multiple economic and ecological benefits in shorter time frames. Pre-commercial thinning, for example, can improve tree vigor immediately while pruning is typically limited to “crop trees,” i.e. trees that are meant to be harvested at a rotation age several decades away. For landowners, pruning can therefore be a difficult cost to justify given inevitable uncertainty in economic returns that may occur in the distant future. While pruning was a common practice among Native American people in mixed conifer forests to meet specific management objectives (Anderson 1999), it is uncommon across current landowner groups and there is very little literature on the effects of pruning in mixed conifer forests that could guide pruning efforts in the future.

While clear wood production is likely the most common objective of pruning, another benefit that has long been recognized is the reduction of stem taper (Staebler 1963). Tree stems with less taper produce sawlogs that are more efficiently utilized when milling dimensional lumber.

1 Log transport efficiency is also improved since low-taper logs (i.e. more cylindrical as opposed to
2 conical) can be bundled more efficiently during transport from stumps to landings to sawmills.
3 Economically, low taper logs have potential to realize returns on a shorter time frame while
4 providing long term benefits from clear wood production. On productive mixed conifer forest
5 sites, first-entry commercial thins in plantations are possible at age 30. If trees are pruned at age
6 10, a potential return therefore occurs after 20 years. While early commercial thinning in
7 plantations can help enhance growth and yield objectives, it is often delayed even where trees
8 are of merchantable size. This is because small, knotty, high-taper trees that are typical of young
9 plantations are of low sawlog value (e.g. Guldin and Fitzpatrick 1991). If pruning can reduce
10 taper by the time of the first commercial thinning without significantly reducing wood
11 production, then pruning could improve economic incentive for early thinning (via low taper
12 logs from those trees that are harvested).

13
14 Long-term studies (more than 5 years) that measure the influence of pruning on taper are
15 uncommon, but physiological work and projections from short-term studies explain the
16 mechanism for how reduced stem taper can develop following pruning. The majority of pruning
17 studies- many of which were done several decades ago- have consistently found that removing
18 branches above those lowest on the crown reduces overall stem growth (Sprugel 1991).
19 Diameter growth reductions following pruning have usually been greater in magnitude than
20 height growth reductions (e.g. Alcorn et al. 2018; Takiya et al. 2010; Forrester et al. 2011). As
21 long as these diameter growth reductions are restricted to the lowest portions of the stem and
22 height growth reductions are not too severe, then taper reductions can be beneficial.
23 Maximizing pruning height will maximize the benefits. Logically, however, there will inevitably
24 be a point along the stem where pruning higher up will result in growth reductions that are too

severe for the pruning to be worthwhile. Identifying this level of pruning intensity at which pruning is no longer beneficial is a key consideration for pruning studies (Nielson and Pinkard 2003).

Sequoiadendron giganteum (Lindl.) Buchholz (giant sequoia) was once widespread in the Sierra Nevada range prior to contracting to its current population of disjunct groves covering only 14,600 ha (York et al. 2013a). This species has exceptional value as a plantation species throughout the mixed conifer forest for several reasons: 1) It may be able to resist future droughts relatively well as indicated by its markedly high survival compared to other species during an intense drought in its native range from 2012 to 2016 (Stephenson et al. 2018); 2) In mixed plantations it has been observed to have high survival after planting (York et al. 2007) and considerably faster growth than other species (Kitzmilller and Lunak 2012); 3) Density manipulations of *S. giganteum* stands may result in increased growth of individual trees without large reductions in total stemwood production (York et al. 2013b); 4) Its potential as a carbon sequestration species is arguably exceptional, because it grows for a very long time to an extremely large size, has high resistance to fire, and is host to relatively few insects and pathogens (York et al. 2013a). While not as widespread as some other plantation species such as radiata pine (*Pinus radiata* D. Don), *S. giganteum* has been planted throughout western Europe (Alexandrov et al. 2002; Hartesveldt 1969; Melchior and Herrmann 1987), where it is noted for both its superior growth and potential use in intensive forest management (Knigge 1992).

Limiting *S. giganteum*'s value for wider adoption in plantations is its high density of small branches (York et al. 2013b) and pronounced stem taper when young. Its exceptional taper

compared to co-occurring species in plantations, however, is thus far based on anecdotal observations. Pruning has the potential to mitigate both of these factors, but a basic study of pruning intensity on stem taper in *S. giganteum* has yet to be performed. To that end, I measured pruning intensity effects on tree growth and stem taper development over 17 years and compared the results with those of other species. The study trees have reached a size at which commercial thinning operations may be considered given local standards of merchantability. Hence the study has reached an age at which results are relevant to management.

Materials and Methods

Study Area

A pruning intensity study was started in the year 2000 at Blodgett Forest Research Station (BFRS; 38°53'20"N, 120°38'31"W). Trees in this region reach heights of about 31 m years after 50 years. BFRS is centrally located in the mixed conifer forest and is representative of a long south-north band of productive forests between 1200 and 1700 meters elevation along the western slopes of the Sierra Nevada range. The climate is Mediterranean with dry, warm summers (14 to 17 degrees C) and mild winters (0 to 9 degrees C). Annual precipitation averages 1660 mm, most of it coming from rainfall during fall and spring months, while snowfall (~30% of total precipitation) typically occurs between December and March. Before fire suppression (ca. 1890), the median point fire interval at BFRS was 9-15 years (Stephens and Collins 2004). The soil is well-developed from andesitic lahar parent material.

Taper in *S. giganteum* compared to other species

The high degree of taper in *S. giganteum* plantation trees appears to be well-known, but poorly documented. Because this study was initiated in part to understand how pruning might be able

to mitigate high taper, it was deemed necessary to document that *S. giganteum* do in fact have more taper than other species. To confirm this, I measured the ratio of diameter at breast height (1.37m) to basal diameter of various species in nearby mixed plantations that were of similar age as the study trees. Three plantations were identified and measured in 2017 utilizing 0.04 ha circular, fixed-radius plots. The species were not evenly balanced, so the number of trees measured per species differed. In total, 91 *Pinus ponderosa*, 76 *S. giganteum*, 36 *Abies concolor* (Gord. & Glend.) Lindl. Ex Hildebr., 33 *Calocedrus decurrens* Torr., and 19 *Pseudotsuga menziesii* (Mirb.) Franco were measured. Because this comparison with other species provides important context to the pruning study, I present the results here rather than later in this paper. The ratio between dbh and basal diameter was lowest for *S. giganteum* (mean = 0.77; Std. Dev. = 0.05). All other species had higher ratios (less taper) and were similar. The next highest ratio was incense cedar (0.82; 0.07), followed by white fir (0.84; 0.08), ponderosa pine (0.84; 0.04), and Douglas-fir (0.85; 0.05). Hence it was confirmed that *S. giganteum* grown in plantations tend to have a relatively high degree of taper in the lower portion of the stem compared to co-occurring species.

Experimental design and measurements

Study trees came from a stand that was 11 years old at the time the study was started. The stand was planted with 100% *S. giganteum* seedlings. The plantation had reforestation treatments typical of even-aged stands managed for timber in the mixed conifer forest region (site preparation, planting, and vegetation control with herbicide). The 11-year old trees were pruned to heights of 2.0, 3.5, and 5.5 meters above ground in 2001. These heights cover a wide yet feasible range of practice when pruning (i.e. they can be reached with standard pruning equipment). The heights also represent the target heights of different “lifts,” which are heights to which sequential pruning phases of the same tree can gradually increase pruned height while

avoiding removing too much leaf area at one time. Two meters is the height at which a person with loppers can typically reach from the ground. Following several years of additional growth, a second lift (with the aid of a ladder) can be applied to increase prune height to 3.5 m. Finally, a third lift with a tall ladder or a ladder stand prunes the tree to approximately 5.5 m, fulfilling the final objective of increasing clear wood production along the entire length of what will be the lowest and presumably most valuable sawlog in the stem. Operationally, the immediate pruning to 3.5 and 5.5m done in this study represents the option of skipping the 2nd and/or 3rd lifts and instead pruning to these heights with fewer separate lift treatments.

The study design focused on creating a sufficiently large sample size within each pruning intensity category to compensate for any long-term mortality and thinning removals that may occur in the future. Sample sizes also incorporated the possibility of splitting the original prune treatment groups into different sub-treatments over time. A greater number of trees were allocated to the 2.0 and 3.5 m categories, so that half of these trees could be pruned higher with subsequent pruning (a step that has not yet been done). Incorporating both random assignments and the desire for more trees in the 2.0 and 3.5m height categories was ensured by doubling the probability of assignment to these categories. When assigning trees to be lifted to 5.5m, some trees were still too short to be pruned to this height. These trees were skipped, which caused the number of trees pruned to 5.5m to be smaller and created a bias toward larger trees in this category. To correct for this, I clipped the shortest and tallest trees (as measured at time of pruning) from all categories of pruning intensity so that all study trees covered a similar height range at the beginning of the study while ensuring that power of detection was still sufficiently high. A group of 40 trees throughout the plantation were randomly selected to serve as unpruned controls for the duration of the study. Following

clipping to ensure similar sizes of trees, the final sample sizes per category was 31 control trees, 121 trees lifted to 2.0m, 123 lifted to 3.5, and 85 lifted to 5.5m. There was no significant difference in the height of trees among these categories, as determined with ANOVA ($p=0.7$; power = 85%).

At the time of initial pruning, trees were 11 years old and averaged 7.4 meters tall. This was a “green pruning,” where lower branches were removed while they still had live foliage. Pruning was done prior to crown closure in the stand, and trees had 100% live crowns as a proportion of stem length. Following standard practices, trees were pruned using bypass loppers to cut branches flush with the stem while not cutting into the branch collars. Epicormic sprouts were removed from stems at year 4. Pruning intensity as a variable was kept categorical, rather than continuous, as each pruning intensity level corresponded with a target height above the ground, rather than percentage of removal. Because of variability in tree heights, each category of pruning height had a tightly-concentrated (i.e. leptokurtic) distribution of crown removal intensity when expressed as a percentage of live crown removed. The resulting crown removal intensities were therefore clustered by pruning height treatment. This made it problematic to use crown removal intensity as a continuous variable for regressions. Pruning intensity (i.e. pruned to 0, 2m, 3.5m, or 5.5m) was therefore kept as a categorical variable, which was aligned with the original design’s intent. The percent of crown removed clearly increased with pruning height and therefore created a range of pruning intensity. The inter-quartiles of percent crown removed was 25-30% for those trees pruned to 2m height, 44-53% for the 3.5m height, and 68-80% for the 5.5m height.

At the time of pruning, all trees were measured for total height and diameter at breast height. To assess the impact of pruning intensity on stem growth at different heights along the stem, permanent sampling points were marked with paint on each stem at 0.3, 2, 3.5, and 5.5 meters above the ground. Trees were measured for dbh, height, and stem diameter at the four heights above ground at the same time as the pruning (year 0) and then again 2, 4, 10, and 17 years after pruning. The intent of multiple stem height measurements and a frequent measurement schedule was to closely track growth trajectories that may occur differently among the pruning treatments. I chose the stand age of 28 years as a logical time to report study results, primarily because average tree size in the stand had developed enough to consider a commercial thin (the degree of taper therefore being relevant to the decision on whether or not to thin). Closely tracking stem growth at the same location as the prune heights reflected the desire to explore the three possible responses of stem growth to pruning: 1) Early measurements and suggestions from managers who tried pruning *S. giganteum* indicated that taper could be reduced by increasing radial growth at crown bases following pruning. Presumably this would occur by removing lower branches that were parasitic rather than productive in contributing to stem growth, in theory possible but its occurrence in practice lacks evidence (Sprugel 1991). 2) Another alternative was that pruning decreased taper- not by shifting stem growth upwards as described above, but rather by reducing lower stem growth below the pruning height. This has been by far the most common way that pruning has been observed to reduce taper (Nielson and Pinkard 2003). 3) A third alternative was that pruning had no detectable effect on taper at all. This has also been a result of pruning studies, some of which are lacking in power of detection because of small sample sizes (Gartner et al. 2002).

Most of the repeated stem diameter measurements at different heights were collected by climbing to the marked stem height location and using diameter tapes. For safety reasons, some trees were not measured at 5.5 m height at years 2 and 4. The analysis of stem growth occurring at 5.5m height therefore includes 0, 10, and 17 years and not years 2 and 4. All other stem height locations include all measurement times (0, 2, 4, 10, and 17 years after pruning). Again for safety reasons, the 17-year measurement used a Jim-Gem pentaprism dendrometer for diameters at 3.5 and 5.5m heights. I measured a subsample of 17 trees with both the climbing/taping and the dendrometer method. Assuming the taping method represented the actual value, the root-mean-squared measurement error of the dendrometer was 12%. The dendrometer method, while not as precise as direct measurements with tapes, had no clear bias in accuracy and was judged to be sufficient considering the large sample sizes in this study. This conclusion regarding the acceptability of the pentaprism method agrees with that of Rennie and Leake (1997), who similarly compared a pentaprism to direct measurement in hardwoods.

Many studies have made interpretations about growth allocation adjustments and taper changes based on assessing the relative degree to which height versus dbh was influenced by pruning. To assess taper more directly within the applied context of how log form tends to be measured during conventional stand assessments, I used Girard Form Class (Mesevage and Girard 1946) - a general form quotient that has been used widely for decades (Dilworth 1976; Avery and Burkhart 2002). Girard Form Class is the inside-bark diameter at 5.3 m stem height divided by the outside-bark diameter at 1.37m height. Because the 5.3 m height used for estimating Girard Form Class was different than the 5.5m used for tracking growth trends, I re-measured all trees at 5.3 m height using a pentaprism dendrometer 17 years after pruning. In addition, given the lower precision of this measurement as mentioned above, I increased the

control sample size to 99 trees so that the sample sizes were similar among treatments. This was done as a cautionary step to reduce the potential for reduced power during analysis related to a higher variance around the mean because of measurement error. It should not influence the average difference in form class between pruned and control trees. The additional control trees were randomly chosen from locations throughout the stand and were of the same size range as pruned trees. Diameter inside bark was estimated by multiplying outside bark diameter by 0.9472. This is a correction factor based on direct measurements of bark thickness at 5.3 m stem height from 23 *S. giganteum* trees that were cut down and analyzed in a nearby 18-year old plantation at BFRS (unpublished data).

Analysis

The analysis was designed around two objectives. The first was to examine the detailed time series of measurements to explore how pruning intensity may have influenced stem radial growth trajectory at different heights. The second was to detect differences in final tree size and stem form at the end of the study period. To meet the first objective, stem diameters were converted to stem cross sectional areas. Although most pruning studies have relied on diameter as a measure of stem growth, Gartner et al. (2002) assert that in terms of wood production, the cross sectional area growth (i.e. basal area) is more useful than diameter growth. In agreement with this, the repeated measures of cross sectional area were analyzed with a multivariate repeated measures approach (MANOVA-R). This was done separately for each height above ground (0.3, 2, 3.5, and 5.5 m). The MANOVA-R tests for overall differences in growth across time among pruning treatments (i.e. the between-subject test), as well as for differences in the trends of growth over time (i.e. the within-subject test), which detects non-parallel trends in growth over time). Final differences in stem cross sectional area at the end of the 17 year period among pruning intensity treatments were evaluated with ANOVA, and prune height treatments

1 were grouped as similar or different using Tukey’s Honestly Significant Difference (HSD) tests.
2 The second objective of detecting differences in final tree size and stem form was addressed
3 with ANOVA tests. Final tree dbh, height, and Girard form class were compared among
4 categories of prune height (control, 2, 3.5, and 5.5 m), followed by pairwise Tukey HSD tests if
5 significant. All tests were evaluated with an alpha level of 0.05 using JMP statistical software
6 (SAS).

7 **Results**

8 At each stem height location of 0.3, 2, 3.5, and 5.5m above ground, the amount of stem growth
9 occurring across the 17 year period was different among the prune intensities ($p<0.001$ for 0.3
10 and 2m height, $p=0.02$ for 3.5m, and $p=0.004$ for 5.5m). This indicates that the overall amounts
11 of stem cross sectional area growth (i.e. the heights of the lines in Figures 1A-D) were different
12 than each other according to the level of pruning intensity. Likewise, the interaction of time and
13 pruning treatment was different ($p<0.001$) for all stem heights, indicating that the trends in
14 growth following pruning were different among treatments (i.e. the lines in Figures 1A-D are
15 non-parallel). This was the case at all stem heights. Overall, the MANOVA-R tests confirmed that
16 pruning intensity influenced both the magnitude and temporal pattern of radial growth along
17 the length of the lowest 5.5m of stems, depending on the intensity of the prune treatments.

18
19 Specifically at stem bases (Fig 1D), trees that were pruned to any height grew at slower rates
20 immediately following pruning compared to unpruned control trees. The extent of the reduction
21 in stem growth generally increased with prune intensity, with trees pruned to 5.5m growing the
22 least near the ground. The slope of the relationship between growth at stem base and time
23 across the 17 year period when expressed linearly (used here as a simple expression of growth

1 rate) was highest for controls (64 cm²/yr), followed by 50 cm²/yr for trees pruned to 2m, 38
2 cm²/yr for trees pruned to 3.5m, and 33 cm²/yr for trees pruned to the highest height of 5.5m.
3 Toward the end of the study period (between 10 and 17 years), basal growth of control stems
4 slowed down, resulting in a size difference between controls and trees pruned to 2m that was
5 not large enough to detect significance. The average stem cross sectional area of these two
6 groups compiled together was 0.166m² (vertical lines in Fig 1D show the groupings). Other
7 pairwise comparisons of total cross sectional areas at the end of the study period at stem bases
8 indicated groupings of trees pruned to 2m and 3.5m (average = 0.142 m²), and trees pruned to
9 3.5m and 5.5m (average = 0.127 m²).

10

11 At 2m above ground (Fig 1C) the growth profiles were similar to those observed at stem bases,
12 with controls again outpacing the pruned trees across the 17 years. Likewise, stem growth at
13 this height was generally slower as pruning intensity increased. Controls grew at a rate of 29
14 cm²/year, followed by 23 cm²/yr for trees pruned to 2m, 18 cm²/yr for trees pruned to 3.5m,
15 and 16cm²/hr for trees pruned to 5m. At year 17, the total cross sectional area for controls
16 were grouped with trees pruned to 2m (average = 0.065m²), while trees pruned to 3.5 and 5.5
17 m were grouped together (average = 0.050 m²).

18

19 At 3.5m above ground, growth was roughly similar among pruning treatments until after year 4,
20 when the controls began to outpace the pruned trees (Fig. 1B). Growth rates again declined with
21 pruning intensity. Unlike at lower portions of the stem, however, the slopes were not as distinct
22 among pruning treatments. Unpruned controls grew at a rate of 22 cm²/year, trees pruned to
23 2m grew 19 cm²/yr, trees pruned to 3.5m grew 17 cm²/yr, and trees pruned to 5.5m grew 16

cm²/yr. At the end of the study, controls and trees pruned to 2.0m and 3.5m were grouped together (average = 0.04 m²). And trees pruned to 2.0m, 3.5m, and 5.5m were grouped together (average = 0.06 m²).

At 5.5m above ground (Fig. 1A), while there was a difference in the growth trends among treatments as indicated by the time x treatment interaction in the MANOVA-R, differences were much less pronounced compared to lower portions of the stems. Controls grew at a higher rate until year 10, but converged with the rest of the prune treatments by year 17. Trees pruned to 2m had grown the most at this height, but overall there were no differences in stem size after 17 years among prune treatments ($p=0.18$). Growth rates declined only slightly (albeit significantly) as pruning intensity increased, with controls growing at 17 cm²/yr, trees pruned to 2.0 m growing 18 cm²/yr, trees pruned to 3.5m growing 15 cm²/yr, and trees pruned to 5.5m growing 14 cm²/yr.

Seventeen years after pruning, diameters at breast height were different among pruning intensities ($p<0.001$), with a steady decrease in dbh growth with pruning intensity (Fig 2A). Relative to trees pruned to 5.5 m high, the average dbh for controls was 23% greater. Pairwise comparisons did not detect differences between controls and trees pruned to 2 m height (average = 31.8 cm). Nor was there a difference between trees pruned to 3.5 and 5.5 m heights (average = 26.6 cm). As was the case with dbh, total heights were different among pruning intensities ($p<0.001$), with a similar downward trend with pruning intensity and a similar grouping of pairs (Fig. 2B). Relative to trees pruned to 5.5 m high, controls were 18% taller after 17 years.

1

2 Girard form class was different among pruning intensities ($p < 0.001$), with the driver of the
3 difference clearly coming from the elevated form class of trees pruned to 5.5 m (Fig 3). Overall,
4 form class ranged widely from 31 to 84 for all study trees. There was no difference in average
5 form class between controls, 2.0, and 3.5 m pruning heights.

6 Discussion

7 Relative to other species of the mixed conifer forest, *S. giganteum* has relatively high stem
8 taper. The intensity of crown removal when pruning *S. giganteum* is clearly an important factor
9 affecting stem growth. Pruning reduces taper in *S. giganteum* plantation trees, not by increasing
10 growth higher up on the stem, but rather by simply reducing radial growth that would have
11 otherwise occurred lower on the stem. While a few pruning studies have suggested that pruning
12 can reduce taper by increasing growth higher up on the stem (e.g. Kirby 2016), the majority of
13 studies have found that, similar to this study, taper is reduced via reductions in growth lower on
14 the stem. A unique leaf-reduction study involving loblolly pine (Kidombo and Dean 2018)
15 demonstrated experimentally how removing branches has localized negative effects on stem
16 growth. This localization of pruning-related growth reduction also appears to generally be the
17 case in *S. giganteum*. There appears to be some degree of cumulative impact of pruning
18 incrementally higher up from a given location on the stem, however. The farther away from the
19 stem base that branches were removed, the more that basal radial growth was reduced relative
20 to controls (Fig. 1C).

21

1 Physiologically, the decreased stem growth below the pruning height is in line with the branch
2 autonomy theory (Sprugel et al. 1991), suggesting that even branches located at the crown base
3 where sunlight exposure is lowest contribute to wood production in the main stem. The lower
4 branches in the *S. giganteum* trees from this study were contributing substantially to stem wood
5 production. It is possible that the very lowest branches could be either “holding their own” or
6 even parasitizing resources from branches farther up on the stem. If either does occur in *S.*
7 *giganteum*, it is restricted to the very lowest branches in the crown and targeting removal of
8 low-productivity branches would involve pruning at lower intensities than were tested here.
9 Such a low pruning intensity would likely be impractical at operational scales. It is worth noting
10 that the trees in this study still had full live crowns. Hence, inter-tree competition was not yet
11 causing lower crown recession. With the objective of pruning being to maximize clear wood
12 production, it is likely that this green pruning is the most practical approach if pruning of *S.*
13 *giganteum* is to be undertaken at larger scales. In fact, pruning at a stand age of 11 years, as was
14 this case in this study, is at the older range of typical pruning studies. Similar timings occurred in
15 *P. menziesii* (Kirby 2016), and *Larix gmelinii* var. *japonica* X *L. kaempfer* (Takiya 2010). Most
16 other studies occurred at even younger stand ages, although the height at which *S. giganteum*
17 were pruned in this study matches with common target heights for initial pruning (e.g.
18 Fernández et al. 2017). Given that pruning tends to occur early in stand development, it is not
19 surprising that lower crowns would still be contributing significantly to stem growth.

20
21 Pruning intensity studies have resulted in a variety of conclusions regarding the practical
22 significance of pruning effects on growth and management objectives. It is difficult to categorize
23 studies by their conclusions on the effects of pruning because many studies either had poor
24 replication or did not track growth responses over time frames that could be meaningful for

management (Gartner et al. 2002). But in general, the three main factors in determining whether or not pruning is worthwhile are: 1) the extent and persistence of overall height and diameter growth reductions; 2) the extent of taper reduction; 3) the extent of clear wood production. Since this study has not yet involved a log harvest and milling study, this third factor cannot yet be evaluated.

Regarding the first factor, a common conclusion among studies that tracked growth effects for long enough is that pruning effects are short lived (Fenton 1977; Hevia et al. 2016; Endo and Mesa 1992; Banks and Prev 1976; Luckhoff 2010; Takiya et al. 2010). The finding here that pruning effects on dbh and height are still observable 17 years after pruning, therefore, is notable. If production of wood volume, regardless of its quality or form, is the objective then pruning in *S. giganteum* with high intensities (>44% of crown length removed) defeated that objective based on this study. Pruning to the lowest intensity of 2 m high (25-30% of crown length removed), however, resulted in dbh and height reductions that were not significant compared to controls after 17 years.

Regarding the second factor, the reduction in taper clearly comes at the cost of overall stem wood production. The loss of wood production near the base of a tree, from a utilization standpoint, is of little consequence since the wood that was lost would have been discarded during milling anyway. The reduced taper should, in fact, be beneficial for log transport efficiency. If pruning comes at the cost of substantial height growth, however, then the taper benefit of pruning could be negated by the loss in merchantable volume (Nelson and Pinkard 2003). Several studies have assessed the relative effect of pruning on height versus diameter

growth. The vast majority of them have concluded that diameter growth is more sensitive than height growth, leading to the general inference that there is a benefit of pruning for timber production (i.e. taper reduction without log length reduction). Of the studies I reviewed, only two of them found height growth to be as sensitive as or more sensitive than diameter growth (Dakin 1982; Pinkard et al. 2004). The negative effect of pruning intensity in *S. giganteum* in this study was generally the same for both diameter and height growth (Fig. 2), in agreement with these two studies which involved *Cryptomeria japonica* and *Eucalyptus* spp. While the negative effect of pruning on diameter growth can be viewed as a positive outcome, the effect on height growth will be negative if the pruned trees do not eventually recover by the time trees are harvested at rotation age. As Nielson and Pinkard (2003) point out, if pruning puts trees at a competitive disadvantage, then a negative effect of pruning on height growth could compound over time if they are put at a competitive disadvantage compared to neighboring unpruned trees. In Sierra Nevada mixed conifer forests, where plantations with numerous species are the norm, the risk of pruning *S. giganteum* is that they lose their dominant competitive advantage over other species. This risk is probably low, given that without pruning, *S. giganteum* often outgrow all other species in mixed plantations (e.g. York and DevRies 2013). In fact, pruning may help maintain an equal canopy position between *S. giganteum* and other species. This is obviously speculative, as pruning effects on the individual species making up mixed conifer forests- let alone pruning interactions with different species mixtures, has not been studied.

Each unit of increase in form class can represent an additional 3% of merchantable volume (Avery and Burkhart 2002). This suggests that trees pruned to 5.5m may have an additional 15% of merchantable volume due to reduced taper. While this is a considerable gain in merchantable volume within the lowest log, recall that the trees pruned to 5.5m also had considerably less

overall height growth. At time of harvest, therefore, the benefit of reduced taper may be traded off with less overall timber yield from entire stems. This will need more time to assess. This study was an analysis of pruning intensity on stem taper and tree growth, and not a trial of different pruning techniques and schedules. Aspects of the results, however, suggest how traditional lift pruning in giant sequoia may be able to avoid the above-mentioned tradeoff between increased taper and reduced growth. Given the localized effects of pruning on stem growth found in this study, it can be expected that removing branches anywhere on the stem will reduce radial growth at that location. It would be necessary to prune to at least the height of the first log (5.5m) if both taper reduction and clearwood production are objectives. If this can be accomplished in a series of lifts, it may avoid the large growth reductions observed in this study and should improve taper. There were no differences in final stem size at any stem height between controls and those trees pruned to 2m height (Fig. 1). This suggests 2m as a reasonable target for first lift pruning. Further studies evaluating alternative lift schedules would be necessary to further optimize lift pruning.

Pruning as a complement to young stand management practices

In mixed conifer forests of the Sierra Nevada, reducing wildfire severity meets objectives of both improving public safety and conserving forest ecosystem services. There is a basic understanding of how the vertical configuration of fuel in forests can modify fire behavior, and modeling of pruning effects on crown profiles suggests a likely reduction of fire hazard (Hevia et al. 2018). However, very little experimental research exists to demonstrate the actual effectiveness or lack thereof of pruning. Despite the lack of research, pruning for reducing fire hazard around homes is generally recommended (California Forest Practice Regulations 2019- Technical Rule

1 Addendum No. 4) for wildfire safety. In wildland areas, the impact of pruning on fire behavior in
2 plantations may be more relevant for low-intensity prescribed burns than wildfires. On one
3 hand, removing lower branches before prescribed fires presumably reduces torching of
4 individual trees during burning operations. On the other hand, it increases the amount of
5 surface fuel directly beneath the most desirable trees, possibly increasing scorching of crowns.
6 Crown damage from a prescribed fire is somewhat similar to pruning in that heat from the fire
7 preferentially removes the lower portions of crowns. *S. giganteum* is relatively resistant to
8 prescribed fire-related mortality in young stands (Bellows et al. 2016), suggesting the possibility
9 that prescribed fire could be used instead of pruning to reduce taper. However, besides being
10 extremely imprecise in terms of how much crown is removed, burning also leaves behind dead
11 branches connected to the stem. This would create loose knots, which may cause reduced wood
12 quality compared to knots forming from green branches and certainly compared to knot-free
13 wood. Prescribed fire is being proposed for use in young plantations to pre-emptively reduce
14 fuels and subsequent fire intensity (North et al. 2019). New research that targets the interactive
15 effects of pruning and prescribed fire on wood quality, tree vigor, and stand growth should be
16 helpful for assessing pruning effectiveness from both a fire and timber management
17 perspective. For *S. giganteum*- a species with a relatively high density of branches and a high
18 degree of taper, one can expect to gain the typical benefits expected of pruning: clear wood
19 production and, as was the focus of this study, a reduction of stem taper. Its rapid growth
20 suggests significant potential for clear wood production beyond the defect core following
21 pruning. Rapid growth appears to be maximized with density management practices (i.e.
22 thinning) that occur early during stand development and are relatively aggressive in terms of
23 lowering density (York et al. 2013b). While early thinning can maximize individual tree growth, it
24 should also be expected to either maintain or increase stem taper in giant sequoia because of

the likelihood that lower live branches will be retained for longer. Pruning as a treatment that follows pre-commercial thinning can be viewed as a positive step toward cumulating value in *S. giganteum* trees at the time of harvest.

However, care must be taken since aggressive pruning when trees are young should also be expected to reduce height and wood volume growth. Additionally, it should be noted that epicormic sprouts are common in *S. giganteum* following damage to crowns (Stephens and Finney 2002). This sprouting can be counter-productive to the objective of clearwood production and, if sprouts survive, may also negate pruning benefits on stem taper. The one study that was related to pruning of any mixed conifer species in the Sierra Nevada involved *S. giganteum* (O'Hara et al. 2008), which found that epicormic sprouting increased when the percent of crown removed was greater than 40%. Whether or not these sprouts persisted over a time frame relevant for management is unclear. Whether pruning is cost-effective will ultimately depend upon objectives and the timber products that are eventually produced. Even aggressive early pruning followed by a height growth reduction may be cost effective if there is a premium on reduced taper or if pruning increases survival during prescribed burns.

Acknowledgements

The Sierra-Cascade Intensive Management Cooperative provided funding to support final measurements. Blodgett Forest Research Station provided labor for treatments and early measurements. R. Heald designed the original study. R. Satomi and R. Tompkins provided helpful reviews of the manuscript.

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Draft

Figure captions

Fig. 1. Stem cross-sectional area growth profiles over 17 years at different heights above the ground following different pruning intensities of *Sequoiadendron giganteum*. Vertical lines represent groupings of pruning intensity categories following pair-wise comparisons of final stem size with Tukey HSD.

Fig. 2. Means and 95% confidence intervals for diameter at breast height (top) and total height (bottom) 17 years after pruning *Sequoiadendron giganteum* to different intensities. Horizontal lines indicate similar means, as indicated with Tukey HSD.

Fig. 3. Means and 95% confidence intervals for Girard form class of *Sequoiadendron giganteum* pruned to different heights. The horizontal line indicates similar means, as indicated with Tukey HSD.

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