

Stem and Branch Diameter Response in Pruned Douglas-fir Plantations  
(*Pseudotsuga menziesii* var. *menziesii*):

Implications for Volume and Clear Wood Production in the U.S. Pacific Northwest

John W. Kirby

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Committee:

Eric Turnblom

Robert Harrison

Derek Churchill

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John W. Kirby

University of Washington

## Abstract

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John W. Kirby

Committee Chair:

Associate Professor Eric Turnblom

School of Environmental and Forest Sciences

*Enhancement of timber quality from self-pruning in Douglas-fir stands typically begins to occur around 60-80 years of age. Due to 40-year rotations in production settings, this species has the potential to benefit from the silvicultural treatment of pruning. Previous literature indicates that pruning may increase overall height and diameter growth rates, reduce log taper and produce more valuable clear wood. This study measured 426 trees located in Stand Management Cooperative installations throughout Western Washington and Oregon to determine stem and branch diameter response to pruning and implications to volume and clear wood production. Pruned trees received a 20, 40, 50, or 60% crown reduction with either an “all pruned” or “pruned with followers” treatment. Stems were measured for diameter at breast height (4.5’) and top the 1st, 2nd and 3rd logs (17.5’, 34’, 42’) with the largest branch diameter recorded in each quadrant of the logs. Results indicate that, compared to the controls, removing any portion of the lower crown begins to decrease DBH and height growth rates as well as reducing log taper. The reduction in taper does not appear to be sufficient to account for the loss in overall tree volume. Branch sizes above the pruning treatment showed a slight increase in vigor but not enough to degrade the value of the upper log. Pruning produced clear logs with little epicormic branching in the 40-60% crown removal treatments. Recommendations for land managers desiring to prune is to (1) remove as little of the live crown as possible to minimize growth reductions while still meeting clear wood goals, (2) remove the “followers” in a subsequent entry to prevent the overtopping of the pruned trees, and (3) pruning should not be hindered by concerns of degrading upper logs.*

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## DEDICATION

*For my family:*

*To my wife:* Thank you for your continued patience and ability to endure my absence  
in this project as well as others.

*To my children:* May you find both solace and inspiration in the natural world and  
may it strengthen whatever dreams you might pursue.

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## Chapter 1

### *Introduction*

It takes an enormous amount of hard work, understanding, and time to be in the forestry profession. The silvicultural treatment of pruning is no exception, except that it is also very expensive. Pruning, or the removal of lower canopy branches, has been utilized around the world in attempts to modify tree growth rates and produce more valuable knot-free wood. However, in the U.S. Pacific Northwest, few studies have examined the effects of pruning Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) in a plantation setting on a broad scale. Douglas-fir is a commercially grown timber species valued for its strength and often used for veneers and construction. Due to its high demand and widespread use, Douglas-fir is one of the most commercially valuable and commonly grown timber species in the Pacific Northwest. In 2005, a survey of 22 timber management groups showed that 68% of forestland in the Pacific Northwest was being managed solely as Douglas-fir (Briggs 2007). In short, the desire for stands of Douglas-fir that are managed principally for timber objectives is to obtain the largest volume, at the highest possible quality, in the most economic fashion. These objectives require careful analysis of the intricacies of stand dynamics and the effects of altering stand variables on a desired final objective. One such example is the effect of branch removal on breast height and upper stem diameters and branch sizes. Previous research (Stein 1955) has suggested that removing portions of the lower crown in the shade intolerant Douglas-fir may actually increase height and diameter growth rates, yielding more volume.

Alternatively, shifting the base of the live crown higher up the bole can increase diameter growth rates higher up the stem thereby reducing taper and yielding more volume at the mill. Lastly, pruning has the potential to be lucrative to landowners if there is a price premium on clear wood. Pruning removes branches, and given enough time, clear knot-free wood can form over the branch stubs. These have the opportunity to be sold at higher prices than a comparable unpruned log. This paper examines the effects of various pruning treatments on the diameter and branches sizes up the bole, helping bridge a gap in the previous literature and providing valuable information to land managers about the implications for volume and clear wood production of pruned Douglas-fir.

## **Chapter 2** *Literature Review*

**M**any studies have explored the stand and growth dynamics of Douglas-fir in relation to different densities and/or species combinations in plantation settings; however, few studies have examined the effect of pruning Douglas-fir in order to improve timber quantity and quality in terms of volume and branch size up the tree bole. Of those studies that have examined pruning's effect on tree growth rates and branch sizes, sample sizes are small, the trees used in the study are open-grown/not in a plantation setting as in industrial forestry, the study was not conducted in the Pacific Northwest and/or the study does not take stand density into consideration (e.g. Stein 1955; Lehtpere 1957; Staebler 1964). The results from these studies limit the conclusions that can be drawn from a timber production standpoint. This chapter outlines the current state of knowledge of pruning Douglas-fir in order to provide a solid background and a tool for comparison when looking at this study's results, as well as provide support for its management recommendations.

### **Benefits of Pruning**

Douglas-fir is species that does in fact self-prune. However, it takes 60-80 years for the effects of this pruning to begin to enhance the wood quality and has been estimated that it requires 100 years to produce a 16' clear log (Kachin 1940). Since stands managed for timber production are edging closer to a 40-year rotation, perhaps the primary reason for pruning is the reduction of time required to yield

improved wood quality. Apart from this, perhaps obvious aside, the benefits of pruning are detailed below.

### **Potential Increases in Volume**

There are two potential ways pruning can increase the volume in Douglas-fir: (1) increasing the nutrients available to the stem and thereby increasing overall diameter and height growth rates and (2) altering where the diameter growth itself occurs thereby yielding more board foot volume at the mill (reduction of taper).

Douglas-fir is a shade intolerant species, so depending upon the density of the stand, the portion of the lower crown that receives little light and falls below its light compensation point is unproductive at best and has been hypothesized to be a drain on the resources of the tree at its worst (Stein 1955). These lower branches on a Douglas-fir have been referred to as “nonfunctional” because the branches cease to grow in diameter and export photosynthate for the benefit of the tree (Reukema 1959). Branches may remain for a time after productivity ceases and it is no longer exporting carbohydrates to the stem perhaps to take advantage of an opportunity to become productive once again as in the case of a disturbance that opens a gap in the canopy. Essentially there is a delay between when the branches in the lower crown should die and when they actually die (in terms of photosynthate production).

Pruning, as with thinning suppressed trees destined for mortality, simply accelerates this process.

Stein (1955) studied the effects on height and diameter growth rates on trees with 0, 25, 50, and 75% lower crown removal. For the treatment of 25% of the lower crown removal, he found increased height and diameter at breast height growth rates in Douglas-fir. He attributed this result to the removal of what he determined was the portion of the lower crown which was a drain on the resources of the rest of the tree. However, his study was later criticized by Møller (1960) who stated that the trees in the 25% crown removal only exhibited increased diameter growth rates due to a higher proportion of dominants in that treatment group. Other studies have found either similar growth rates (between control and pruned trees) or a reduction in growth rates from pruning. Naturally, these results depend on the pruning intensity and where the diameter growth was measured. O'Hara (1991) and Finis (1953) found that pruning treatments which removed 33% and 45% or less of the lower crown, respectively, did not significantly reduce diameter and height growth rates. Other studies (Lehtpere 1957; Staebler 1963) have found a reduction in diameter at breast height (DBH) and height growth with pruning treatments; ~33% crown removed and 33, 50, and 66% crown removed based on the total height, respectively. Lehtpere found that these decreases were accompanied by increased diameter growth rates up the bole (reduction of taper) whereas Staebler came to the conclusion that increased pruning intensity resulted in reduced diameter growth at all heights except the highest, the pruning treatment that reduced live crown ratio to 33%.

The second way to increase volume by pruning is by shifting where the major diameter growth occurs. The region of maximum growth is reached in the general

vicinity of the live crown base and this region shifts upward as a tree matures and crowns recede (Larson 1963). The removal of branches affects the allocation of carbohydrates along the bole resulting in differences in diameter growth along the stem. Specifically, removal of branches on pruned trees allocates more growth in the upper part of the bole and reduces the overall taper of the bole (Lehtpere 1957; Staebler 1963, 1964). In the Pacific Northwest, logs are scaled from the small end using Scribner log rule. Volume is then calculated with this diameter. Reduction of taper is important because it allows the bole to be more completely utilized yielding larger timber volumes and higher grades (Steele 1984). So even if pruning doesn't increase the overall growth of a tree, it can change the shape of the bole so that it can get maximum utility at the mill and the seller can get paid for more volume. Of the two possible options for increasing volume (increasing overall growth rates versus changing where the growth occurs/reducing taper), the literature favors a potential increase in volume due to a reduction in the taper. However, while the results are mostly unified, few studies that have actually examined taper due to the increased difficulty of obtaining upper stem measurements.

### **Clear-wood Formation**

Pruning reduces the number of knots caused by branches resulting in increased clear wood that is stronger, more aesthetically pleasing and thereby has the potential to fetch a higher price on the market. However, in order to correctly prune to increase valuable clear wood and reduce taper and knots, numerous factors need to be considered: age at which to prune, percent of crown to be pruned, effect of the stand's

density on pruning success, risk of epimoric branching, visibility of pruned scars, and susceptibility to fungi such as heart rot (Childs and Wright 1956) that could diminish final returns.

Mitchell and Petruncio have the following recommendations for pruning for clear wood:

- Prune early to allow the most time for clear wood to develop and to rid the tree of visual branch scars that remain years after the pruning (Petruncio et al. 1997)
- Prune in lifts to maximize the volume of clear wood grown (Mitchell and Polson 1993; Mitchell 1995)
- Prune on sites of highest productivity to achieve maximum clear wood growth rates (Mitchell 1995)
- Time your pruning treatments to follow thinning treatments in order to minimize costs and maximize clear wood growth rates (Mitchell 1995).

Currently, pruning is limited in an operational and practical sense due to the lack of a viable price premium on clear wood. In the past, it was thought that the markets for clear wood would develop and make pruning a much more lucrative option. For example, in 1989 it was projected that a Douglas-fir C select log would reach prices around \$1040 per thousand board feet (MBF) in 1989 dollars (Haynes et al. 1988). However, today the price for a C select log is around \$525 MBF. These price premiums are important because the difference in price between products from

pruned logs and those from lower quality unpruned logs justify the pruning investment (Fight and Bolon 1995). These markets have yet to develop and are one of the main inhibitions to the practice of pruning. However, if clear wood is desired, Fight (1995) conducted a financial evaluation analysis that showed pruning was a cost-effective way to improve wood quality when compared to high levels of stocking or extending rotations (to allow for self-pruning). In summary, pruning is a proven way to produce clear wood, it just needs to be justified with higher premiums on the timber given the expense of the treatment, some of which are addressed in the economic considerations below.

### **Other Reasons**

Some non-revenue reasons for pruning Douglas-fir include pruning for aesthetics, increased habitat value of the forests, reduction of crown fire potential, and additional social benefits. In many urban areas or around homes, trees are pruned to create viewsheds, keep utility lines clear, or simply because homeowners enjoy the look of pruned trees. Pruning trees can also greatly increase the habitat value of forests especially in terms of ungulates and avian species. Many production timberlands are in the stem exclusion phase of forest succession (Oliver and Larson 1996) and as such have lowest habitat value for many species due to lack of biodiversity (Oliver 1994). Pruned forests may be more hospitable to ungulates and other mammals by quickening the transition from the stem exclusion phase of forest succession and increasing the biodiversity in the understory (Oliver 1994). Avian species, particularly the northern spotted owl may find habitat in pruned forests

more suitable due to the presence of flying corridors in the open space within and below the canopy (FWS 2016). Many companies have habitat conservation plans managing for the spotted owl and have thus utilized forest pruning to improve the habitat for this species. Increased biodiversity in the understory shrub community may also attract more ungulates and small mammals with the increased availability of forage and soft mast.

Pruning may also lower a stands risk to high severity fires. Pruning removes lower limbs on a tree that can often act as a ladder to the upper canopy of the stand during a wildfire event. This helps to keep fires in the understory and more manageable while minimizing loss of revenue to the stand. However, the increase in the base of the live crown is also accompanied by a commensurate increase in the height of the shrubs in the understory. This can sometimes be quite substantial as observed in this study, which may then serve as ladder fuels to the crown as a lower canopy would.

Lastly, pruning may also be considered beneficial from a social standpoint as well as being used as a tool to employ rural communities. Pruning can be used as an opportunity for employment in forestry-dependent communities, especially those where harvesting or manufacturing jobs have been lost. These jobs also provide a more stable year-round source of income during the offseason for those in the forestry profession (Winter and Penty 1995). Lastly, pruning can be employed as a social rehabilitation program by hiring convict crews to perform the labor as a service to

society at a discounted price while simultaneously allowing the inmates time outdoors (Oregon Department of Forestry 2016).

## **Potential Pruning Drawbacks**

Aside from economic limitations, there is a potential risk of sunscald (Harrington and Reukema 1983), epicormic branching (Collier and Turnblom 2001) and heart rot (Childs and Wright 1956) in pruned trees. Depending upon stand age and density, the clear bole of newly pruned trees can receive too much sunlight and scald the cambium of the tree resulting in stunted growth. Additionally, the sudden exposure to light may activate adventitious buds and sprout epicormic branches which have the potential to devalue the log. Foresters should also consider the effects pruning may have on the overall quality of the second log (Turnblom and Collier 2003) as well as the risk of reduction in growth rates by removing too much of the crown (Turnblom 1999). Previous research has determined that there are reasonable ways to avoid the negative consequences of sunscald, epicormic branching, and heart rot. There is still uncertainty on the effect of crown removal on growth rates and quality of the second log; two things on which this study hopes to shed light.

Sunscald has been found to occur at higher rates with increasing percentage of crown removal. Stein (1955) found that in a 28-year-old moderate to well-stocked even-aged stand of pure Douglas-fir, 33% of trees pruned with 75% of their live crown removed were affected by sunscald. That number decreased to 12% when 50% of the live crown was removed and only 2% of the pruned trees were affected when 25% of the live

crown was removed. It seems reasonable to keep crown removal to 50% or less when pruning to avoid any major damaging effects of sunscald. Epicormic branching is observed at statistically higher rates in the 60% crown removal than when compared to the 20 and 40%, suggesting that epicormic branching will only be a problem when more than 40% of the crown is removed (Collier and Turnblom 2001). Additionally, O'hara (1991) stated that pruning should not be deterred by epicormic branching so long as it does not reduce the live crown by greater than 50%.

Childs and Wright (1956) discovered that heart rot infections occur fairly commonly through pruning wounds, when looking at the risk of heart rot in pruned trees.

However, the infections tend to remain small, incipient and die soon after the pruning wounds close. To minimize the risk of heart rot from pruning, they recommended several strategies for young Douglas-fir stands; prune branches in the fall as the risk of infection is higher in the spring, keep the pruned stubs as short as possible so that the wounds heal as quickly as possible and prune low-vigor live branches only as these have the lowest risk of infection. Overall, the findings and recommendations presented by previous work indicate that by correctly timing pruning treatments and by not removing too much of the live crown, the risk of sunscald, epicormic branching, and heart rot should be minimal.

Another potential drawback of pruning is the potential of devaluing the upper logs by pruning the lower log. This could potentially occur by removing the lower branches and thereby increasing the vigor of the branches above resulting in branches with much larger diameters and possibly degrading the quality of the upper log. This is a

question that has not yet fully been investigated and another question this study hopes to address. Lastly, and perhaps the most obvious drawback to pruning is removing too much of the crown of a tree and hampering the growth rate of the tree in terms of height and diameter. From the previous studies mentioned above in “benefits of pruning,” crown removal >30-45% appears to be the intensity at which you will start to see reductions in growth rates at breast height. However, it is important to note that some of these reductions are followed by an increase in the growth rates further up the stem. This is again an area that needs further research.

### **Economic Considerations**

Currently, the largest drawback of pruning is its cost of implementation. It is one of the most expensive silvicultural treatments there are. Pruning costs averaged \$210 per 70 trees in 1995 whereas regeneration surveys, alder release and broadcast burning were \$55, \$60, and \$300/per acre, respectively (Fight et al. 1995). The average Trees Per Acre (TPA) of a stand to be pruned can range anywhere from 100-300 TPA following a thinning, so it is easy to see how costly pruning a stand can become. More updated costs from 2016 Natural Resources and Conservation Survey were \$126 if pruning lower than 10' and \$284 when higher than 10' (USDA 2016). On top of the high cost of the treatment, tree response has remained somewhat vague making it even harder for land managers to justify pruning. In the past it has been said that pruning trees which are to be retained in long rotations have been shown to be an economically feasible way to produce clear wood, especially when performed early in the rotation (Fight et al. 1995). However, the conclusions the Fight and

others came to were based on estimated 2040 logs prices which are unlikely to be realized. For example, he states that a C select log in 2040 should fetch around \$1300/MBF whereas it is currently fetching around \$550/MBF and not likely to reach such a premium anytime in the near future. Even so, markets change and the future is uncertain, so there may be a time in the near future where the premium on clear wood can justify implementing a pruning program and knowing exactly when to implement the treatment could be key.

## Chapter 3

### *Methods*

#### Overview of Study Sites

The Stand Management Cooperative (SMC) is a regional research cooperative with funding from members of the private forest industry, federal, state land management organizations as well as educational institutions. The mission of the SMC is to “provide a continuing source of high-quality data, analysis, and outputs on the long-term effects of silvicultural treatments and treatment regimes on stand and tree growth and development, and on wood and product quality” (Stand Management Cooperative 2016). There are five SMC installation types which comprise the more than 500 installations throughout the Pacific Northwest region. Each type is designed to address differing research goals. Type I installations are pure Douglas-fir and hemlock stands to study the effects of initial spacing, thinning, fertilization and pruning (pure Douglas-fir stands only) on stand development and yield. Type III installations are primarily focused on the effects of initial stand spacing and subsequent pruning and thinning treatments on tree and stand growth and wood quality in young Douglas-fir plantations. Stands were planted at a wide range of initial densities with subsequent treatments assigned including pruning and the effects of early versus late thinning. For this particular study, twelve SMC research installations across western Washington and Oregon were sampled, six of which were Type I installations and six of which were Type III installations, each with roughly an equivalent latitude range (Fig. 1). Ten of the installations were located within

Washington and two within Oregon. The installations measured were selected based on a variety of factors including geographic distribution (ensuring there was enough of a latitudinal gradient), pruning treatment within the plots and any potential landowner limitations. Each SMC installation included pruned and control plots at matching densities. All trees in SMC plots were individually tagged at breast height, plot boundary trees painted 6' up the stem to clearly mark plot edges and each plot was marked with a plot marker to indicate the installation and plot number. The control plots measured area inside the buffer were 0.5 acres (0.20 ha) in size with a 30.5-foot buffer. The size of the buffer was determined to be large enough such that any border effects from neighboring stands would be minimized, if not eliminated altogether. The pruned plot measurement area inside the buffer width was 0.2 acres (0.08 ha) in size with a 30.5-foot buffer surrounding the plots. The same treatment that occurred in the measurement area was also carried over into the buffer to minimize edge effects. Pruned plots and the controls were measured at the year of establishment and every four years for species, DBH (nearest 0.1 in.), total height (nearest 0.1 ft.), and height to live crown (nearest 0.1 ft.). Height to live crown was defined as having live branches in three of the four quadrants in the lowest whorl (Curtis 1983). The bulk of the current data that was the basis for this study included numerous other measurements that will be discussed in the sampling protocol. While the basic plot and installations design was identical between Type I and Type III installations, they varied in other factors including post establishment treatments

such as thinning, type of pruning treatments, years since pruning, and stand age (Table 1). These are discussed below.

## **Treatment Comparison: Type I vs Type III Installations**

### **Type I Installations: Varying Percent Crown Removal**

Type I installations were the first research installations acquired by the SMC in 1985. These sites were designed to assess the effect of spacing, thinning, pruning, and fertilization on Douglas-fir stands (Maguire et al. 1991). Plot locations within each Type I installation were carefully selected based on numerous traits including slope, aspect, ground vegetation, stand composition, and site uniformity. The installations were initially planted by their respective landowners and then set aside later as research plots for the SMC. Since they were planted by their respective landowners, their density has been termed initial stems per acre (IPSA) with the mean of the measured installations having an IPSA of 486. They are older than Type III installations, making them on average taller with larger breast height diameters (Table 1). In addition, these installations had the option of being pre-commercially thinned to create three densities: not thinned (IPSA), thinned down to 50% initial stems per acre (IPSA/2) or thinned to 75% of IPSA (IPSA/4). Since the IPSA varied, the thinning created a range of densities within the thinning treatments themselves as witnessed in Table 2. Type I installations were pruned on average 24.5 years ago compared to 16.2 years ago in the Type III studies (Table 1). They also varied from the Type III's in the pruning treatment they received. Like Type III installations, all control plots were 0.5 acres (0.20 ha) in size with a 30.5' buffer strip around the

periphery. Pruned plots were smaller in size due to the expense of the treatment and therefore were 0.2 acres (0.08 ha) in size with a 30.5' buffer. Pruning occurred after the three plot densities (ISPA, ISPA/2, ISPA/4) had been established via pre-commercial thinning. Each pruning plot was randomly assigned one of three configurations: live crown reduction by 20, 40, or 60% (Fig. 2B). Every tree in the measurement plot was pruned to the treatment regime. The timing of the pruning in the installation was triggered when the average total height of all trees reached 30 feet. Plots were periodically re-measured over time (every 4 years) using the metrics described previously.

### **Type III Installations: Pruning with Followers**

Followers is a term originating from New Zealand Radiata pine (*Pinus radiata*) plantations and refers to the trees that remain unpruned in plots that received pruning treatments. The concept behind leaving following trees in the stand stems from the idea that they protect and “train” the pruned trees from damage, such as sunscald and epicormic branching. They could also provide a competitive advantage compared to a stand that was completely pruned such that they grew at a faster rate. Typically, the followers are removed in subsequent thinning entries as they can overtop the prune trees and stunt their growth if they remain too long.

A subset of the Type III installations experimented with the pruning with followers treatment. Stands were planted by the SMC from 1990 to 1999, at either 100 TPA (21x21 ft.), 200 TPA (15x15 ft.), 300 TPA (12x12 ft.) as well as 440, 680, 1210 TPA.

The latter densities (440, 680, 1210 TPA) received no pruning treatment and were not utilized in this study. Under the Type III pruning regime, trees were pruned in two or three approximately equal 8- to 10-foot lifts to a height of 22 feet (yielding a 20-foot log with trim over a one-foot stump). The initial lift could be less than 8 feet if less than 50% of the initial live crown remained or if less than three whorls remained. In subsequent 8- to 10-foot lifts, pruning left a 30% or larger live crown ratio with the exception that the final lift, remaining live crown ratio was allowed to be less than 30% on some individual trees in order to equalize the final pruned height in the stand (Turnblom 2000). Several possible pruning configurations exist within the planting densities (Table 3). At 100 TPA (21 x 21 feet) all 100 trees per acre were pruned. In 200 TPA plots (15x15 feet), two pruning possibilities exist: prune only 100 trees per acre leaving 100 followers, or prune all 200 trees per acre leaving no followers. In the 300 TPA plot (12x12 feet), two pruning possibilities also exist: prune either 100 or 200 trees per acre leaving either 200 or 100 trees per acre as followers, respectively (Turnblom 2000). Trees in Type III study plots were pruned when the dominant height was between 16-22 feet in the 200 TPA plots. Pruning took place the same growing season that the trigger was reached. The second lift was triggered when trees in the 200 TPA plot reached 26-33 feet in dominant height. Originally it was planned that all followers were to be thinned out two measurement cycles after the final lift; however, this was not accomplished and the followers remained in the plots during the summer of 2015 when the measurements on which this study is based

were gathered. Note however that there were no followers to thin out in the widest spacing (21 x 21 feet).

## **Experimental Design**

The SMC pruning installations utilized an incomplete randomized block design with each installation analogous to a block. Incomplete block design refers to the fact that every treatment did not occur at each installation. The advantage to this experimental design is that it incorporates variation from amongst the blocks to aid in determining the effect of the treatment on the whole (in this case the effect of the treatments on a regional scale). Since this was a large scale study, it also justifies why replication within each site is not necessary. The variation observed between installations in northern Washington and central Oregon help to determine the effect of pruning Douglas-fir in a more region-wide setting, making the results more far-reaching and applicable to the SMC cooperators who have land holdings throughout the region.

## **Sampling Protocol**

Once a pruned plot and its matching control had been identified, a total of six trees were randomly selected from each plot (seven to sample an unpruned follower if it was a Type III plot with followers). Tree numbers were randomly selected from each quintile of the DBH range in the plot (determined by previous years' measurements) with the exception that two trees were randomly drawn from the third quintile in order to double sample the median tree. If the plot had followers, a single follower

was randomly selected from the third quintile of the unpruned followers DBH range in order to obtain data on the average unpruned follower. Once trees had been selected and tree numbers recorded, they were then located inside the research plots. Before measurement, each tree was checked to ensure that it had good form. A tree that was forked, had a ramicorn branch greater than four inches in diameter, an unusual swell or crook was not measured. Instead, a backup tree was utilized that had been selected using the same process as described above. Four inches was determined as a cutoff for a ramicorn branch as it was of sufficient size to be visible from the ground without having to climb the tree and also seemingly substantial enough to have an effect on the diameter of the tree. Only trees of good form were candidates for measure simply because forking, swells, and large ramicorn branches can greatly affect the diameter of the bole up the stem and skew the results in a study only interested in the effects of pruning Douglas-fir under “normal” conditions. Trees of good form then had ground and upper stem measurements taken. Ground measurements included: DBH, total height, and height to live crown (determined by live branches in three of four quadrants), crown widths (determined by cardinal direction: NE, SE, NW, SW), breast-height whorl branch count, largest branch in the breast height whorl, and internodal branch count. Upper stem measurements included: diameters at 17.5’ (16’ log with a 1’ stump and 6” of trim), 34’ (2<sup>nd</sup> 16’ log with 6” of trim) and 42’ (8’: ½ log). The top diameter at 42’ was the highest chosen due to the reach of the Swiss-style climbing ladders that were being used (Fig. 2A). In addition to diameter measurements, the diameter of the largest branch in each

quadrant of the log was also recorded (quadrant was determined by cardinal direction). If a 4" top was reached prior to 42', the height to the 4" top was recorded. Data recorded in the field was later transferred into the SMC Microsoft Access database for analysis.

## **Statistical Analysis**

Once the data had been entered into Microsoft Access, a linear model using R statistical software (R Core Team 2015) was created to predict the average DBH of a tree and top diameter of the 1<sup>st</sup> log given significant stand and tree level variables. Significant variables in the final DBH model included pruning and thinning intensity, DBH (at treatment), age (at treatment), SDI (stand density index at time of treatment), ISPA, pruning type (follower, all pruned, etc.), and years since treatment. To select significant variables and the final model, nine different models were created, three based on Type I data, three based on Type III data, and three based on the combined data. The three models for each Type were based on forward selection, backward elimination, as well as an automated AIC based backward elimination method. The final model selection process took into account the explanatory ability of the model, simplicity, ability to be useful in a practical sense, as well as a residual analysis. In the end, a combined model using both Type I and III data was chosen due to the broader applicability and roughly equivalent explanatory power when compared to separate models of Type I and Type III pruning data. The R package ggplot2 (Wickham 2009) and stargazer (Hlavac 2015) were used to create the graphs

and tables in this paper while the model predictions were generated in excel using the coefficients from R.

## Chapter 4

### *Results*

**T**his section outlines results generated from the data and model predictions. It is important to note that the figures generated from the data (Type I and Type III results) can only take three variables into consideration whereas the model results (Model Predictions) account for all significant variables in its prediction by focusing on a few and then averaging across the rest. With this in mind, the models provide a more robust display of the trends associated with pruning; however, care must be exercised when interpreting model predictions beyond the data domain.

### **Stem Diameters**

#### *Type I Data Exploration*

When examining the breast height diameters on Type I installations (Fig. 3, Top), several trends appear. In general, the raw data shows that the 20% crown removal treatment increased the mean DBH of the trees at all three thinning intensities, whereas the 40% crown removal resulted in an equivalent mean DBH (across the thinning intensities) and the 60% crown removal nudged the DBH to lower values than the controls. It is important to note, however, that the error bars associated with all these values overlap, so despite the fact that the mean values differ numerically, they do not statistically. The one exception to this is seen in the 60% crown removal at the 75% thinning intensity compared to the control. Here it is statistically significantly lower than the controls. To account for difference in the starting values

of the treatment group, a figure showing only post-pruning diameter growth was created (Fig. 3, Bottom). This figure tells a different story than the one above with an increasing reduction at every pruning intensity. The same overall trends are witnessed in the top diameter of the first log with an increase in diameter under the 20% pruning intensity (Fig. 4), with no statistical difference with the exception of, again, significantly smaller top diameter at the 60% pruning intensity. Figure 5 looks at the top diameter to the logs by pruning intensity when ISPA is held to its average value. This figure then shows an increase in the 20% pruning treatment, but matching top diameters for the 40 and 60% crown removal treatments. When the thinning intensity is isolated to 50% (ISPA/2; Fig. 6) and 0% (ISPA; Fig.7), the mean top diameters show no statistical difference between any of the three logs across the pruning intensities despite the 20% crown removal again showing an increase over the controls; 40% crown removal has roughly equivalent diameters and the 60% crown removal shows a reduced mean top diameter. Interestingly, the largest gain in diameter seen between control and treated logs is in the third logs of non-thinned stands whereas plots thinned in half (ISPA/2) show the largest gain in the first log. The increase in the diameter of the first log appears to be driven by differences in the starting values and site characteristics as was the case in the breast height diameter response as well.

In addition to looking at mean diameters, it is important to determine the effect of crown removal on the diameter periodic annual increment (PAI) of the trees. Figure 8 shows the PAI of DBH over the treatment years by percent crown removal. In

general, increasing thinning intensity results in larger DBH growth rates. This is expected given the additional resources available to the remaining trees in a stand left with less competition. Another trend displayed in figure 8 is the effect of increasing crown removal on the DBH growth rates. At the 20% crown removal treatment, there appear to be equal growth rates to the controls whereas the 60% crown removal shows reduction in growth rates. The 40% crown removal treatment appears as if it is beginning to show reductions, but nothing definite can be said given the error bars associated with the value. It can be safely assumed that pruning at the 60% intensity results in a decrease in the growth rates and 20% pruning intensity at best matches the controls and doesn't hamper diameter growth at all. Lastly, the PAI of height growth rates in the Type I installations (Fig. 9) appears to fluctuate with increasing percent of the crown removed depending upon the thinning regime. In the 50% thinned plots, height growth decreases with any treatment but appears to become somewhat stable as intensity increases, resulting in about a 3.6" reduction in height growth compared to the controls. The height growth associated with the 75% thinning intensity spiked significantly with the 20% crown removal and then dropped drastically lower than the controls at the 60% removal. The reason for the spike is hard to reconcile but the general trend is a reduction in height growth. Also, trees allocate carbohydrates to height growth over diameter growth so any reduction in height PAI should first be witnessed in the DBH PAI, which was not the case. Unthinned plots showed a reduction in height growth rates comparable to the 50% thinned plots. However, there was no 40 or 60% crown removal treatment in those

plots so we are unable to conclude whether it similarly leveled out as the 50% thinned plots did.

Lastly, Fig. 10 examines the effect of increasing crown removal on the taper of the tree. Taper in this figure is defined as the difference (inches) between DBH and the top diameter of each log. Taper becomes increasingly smaller in the logs as pruning intensity increases. The most significant differences, in terms of error bars, are seen in the 1<sup>st</sup> and 2<sup>nd</sup> logs of the 40% treatment. 60% pruning had lower mean taper but the error bars associated with the values are substantial due to small sample size. The reduction in taper with increasing pruning intensity is to be expected as it has been supported in previous literature and our results support the notion that the base of the live crown is the area of increased growth rates.

### ***Type III Data Exploration***

Figures 11 and 12 show the effects of pruning a different number of trees in a plot (pruning density), on the mean DBH of the pruned and following trees in the Type III installations. In Figure 11 this equates to the mean DBH of the pruned trees in the plot by TPA. In the followers' graph (Fig. 12) this instead refers to the mean DBH of the remaining trees in that plot that were not pruned. For example, Figure 12 at the 300 TPA plot with a pruning density of 200 TPA, refers to the mean DBH of the remaining 100 TPA of unpruned followers whereas Figure 11 would refer to the 200 pruned trees. When holding stand density constant and comparing the mean DBH of the pruned trees by pruning density (Fig. 11), it reveals that the pruning regime at

the Type III level (50% crown removal up to a 22' lift) overall reduces the mean DBH of the trees regardless of how many followers remain in the plot. However, the biggest reduction and one that is statistically significant is seen in the 100 TPA plots with the trees that received an “all trees pruned” pruning density. These trees have a 3” reduction in mean DBH. The smallest reduction is seen at the 300 TPA planting density when 200 TPA are pruned. It also becomes evident that with more followers there tends to be a larger reduction in the mean DBH of the pruned trees. This is most evident in the 300 TPA plots with 200 versus 100 pruned trees. On the other hand, followers tended to have a very similar mean DBH (with overlapping error bars) when compared to the controls at the same density (Fig. 12); however, the DBH model results differ from the raw data in that it predicts larger followers DBH. Height and diameter growth rates for pruned versus followers varied as well (Fig. 13 and 14). In terms of height growth, the followers and controls exhibited similar height growth rates (with a small divergence of the followers to lower levels at the 300 TPA density). The pruned tree height growth was statistically lower than the controls and followers in the 100 and 200 TPA plots as well as the 300 TPA plots, but here the error bars ran slightly over into the followers. Diameter growth followed similar tendencies with controls and followers growing at significantly faster rates than any pruned tree. Diameter growth rates also tended to decrease with increasing plot density which is logical given the reduction in available resources for each individual tree. Lastly, taper in Type III plots varied significantly between the controls/followers and pruned trees with pruned trees having ~0.5” less in taper on average between the

logs than a control (Fig. 15). This figure also shows evidence of increased taper in the followers that becomes more drastic up the stem when compared to the controls.

## **Branch Sizes**

### ***Type I Data Exploration***

When looking at the first log of the Type I installations, unpruned tree branch sizes become larger with decreasing density (Fig. 16), as expected. The largest difference between any branch size across the pruning intensities and densities in the first log was 0.2 inches, seen in the 50% thinned plots between the controls and the 20% crown removal. Other differences in LLAD in the first logs remained insignificant.

When looking at the branch sizes of all 3 logs by pruning intensities (Fig. 17), in general, the first log always had a smaller branch size with the 2<sup>nd</sup> and 3<sup>rd</sup> logs having comparable LLAD's. The branch sizes in the first log of the 40% and 60% crown removal are extremely small simply because they are epicormic branches that sprouted post pruning. An interesting thing to note with crown removal is the apparent increase in the vigor of the branches in the 2<sup>nd</sup> and 3<sup>rd</sup> logs compared to the controls, most apparent in the 20% crown removal treatment. In this treatment, the 2<sup>nd</sup> and 3<sup>rd</sup> logs LLAD was ~0.2" larger than the same logs in the controls. This implies a potential of devaluing the upper logs with pruning the lower canopy, something addressed later in this thesis.

### ***Type III Data Exploration***

Figure 18 explores whole tree LLAD by breaking it down in terms of stand density. Whole tree LLAD was defined as the average LLAD in each of the three logs and while it is not used as an industry standard, it can help to reveal which trees tend to have the largest branches. Larger branches in the followers were clearly apparent in the 200 TPA plots with the pruned trees having much smaller (0.6”) LLAD’s (Fig. 18). In the 300 TPA plots, the followers match the controls and pruned trees tend to have smaller branch sizes. An interesting note in this figure is that the followers branch sizes in the 200 TPA plots (that would be a treatment of prune 100 leave 100 followers) nearly match the 100 TPA controls. This seems to indicate that followers are not at all impeded by the 100 pruned trees in the stand as they only show a 0.1” reduction in branch size (although DBH growth rates are less than the 100 TPA control, Fig. 12). Finally, in Fig. 19 we see that branch sizes up the stem are largest in the 2<sup>nd</sup> log, with evidence that pruning the first logs increased the vigor of the second log at the 50% crown removal pruning intensity but not enough to degrade the quality of the upper logs (Table 6). This would be expected given the lack of any significant increase in the 2<sup>nd</sup> log at a 40 and 60% crown removal in the Type I results. In addition, there is a difference in branch sizes between trees that were all pruned vs. pruned with followers. Trees that were pruned with followers had significantly smaller branch sizes than trees in an “all pruned plot” in all three logs (borderline significance in the 3<sup>rd</sup> log). This is likely due to the effect of followers by taking up crown space and slightly overtopping their neighbors thereby usurping

resources from the pruned trees resulting in less vigorous crowns. One benefit however to pruning with followers is the reduction in epicormic branches sizes seen in the first logs of plots “all pruned” versus “pruned with followers” (Fig. 20).

## Model Predictions

### *Diameter at Breast Height*

The final transformed linear DBH model:

$$(Dbh)^{.25} \sim prnInt + yrsTrt + ISPA + stDbh + thinInt + pruned + SDI + stage + Dq + ISPA:SDI + prnInt:stage + stDbh:pruned + yrsTrt:ISPA + yrsTrt:stage + yrsTrt:Dq$$

*where:*

prnInt= pruning intensity (20,40,50,60% of the lower crown removed),

yrsTrt= years since the pruning treatment occurred,

ISPA= initial stems per acre (TPA) at plot establishment/planting,

stDbh= initial DBH (in.) at the time of pruning,

thinInt= thinning intensity (factored; 0,50,75% of the stand pre-commercial thinned),

pruned = factored variable (0=control, 1=follower, 2=pruned tree with follower, 3=all pruned),

SDI= stand density index at time of treatment,

stAge= age (yrs.) at time of treatment,

Dq= stand quadratic mean diameter (in.) at treatment

Using R, a linear model was created predicting individual tree DBH given significant variables including pruning intensity and type of pruning (Table 5A). The untransformed model was then tested to see if it called for a transformation using the BoxCox transformation (Fig. 20). It was determined that model predictive powers could be improved by transforming the response variable to the  $\frac{1}{4}$  power. The

transformed values of DBH were then regressed against predictor variables to see if there was any impact on  $R^2$  and on the residuals and QQ plots. Transforming the response variable slightly decreased the  $R^2$  from .7513 to .7327, but stabilized the increasing variance seen at the smaller diameter values in the residual plot (Fig. 21: Top). It also helped normalize the distribution of the larger diameters (Fig. 21: Bottom) by bringing those values closer to the  $y = x$  line in the QQ plots. In addition, the transformed model was the most parsimonious of the two, having two fewer main effects and one less interaction term. Figure 22 (Top), examines the back transformed fitted values versus the actual values of the transformed model revealing no suspicious signs or patterns and fairly constant variance. Figure 23 shows the model predictions when the starting values are held constant (based on averages from the data; with years since treatment equal to the average Type I installation) and only the pruning intensity is changed. It shows that with increasing pruning intensity, DBH decreases. This is slightly different from the graphs the raw data provides; however, the model can account for multiple variables and differences between sites and starting values. Figures 24 and 25 predict an average tree DBH using the transformed model by “growing” the trees out 30 years after treatment, with pruning occurring at age 10. Figure 24 shows the model predicts linearly decreasing DBH with increasing pruning intensity when other variables in the model are held to the average starting values of the data. The diameter reduction becomes significant around 40% crown removal for both stands (50 and 75% thinned), similar to the raw data means. Figure 25 shows projections of DBH size based on the type of pruning

the tree received (follower, all pruned, etc.) and percent crown removal (20%). The graph shows predicted DBH of the followers having ~5” increase in DBH in the 200 ISPA and 300 ISPA stands compared to untreated controls. The trees “all pruned” and “pruned w/ followers” displayed slightly reduced diameters compared to the controls after 30 years of pruning treatment. The biggest reduction was in the “all pruned” stands, possibly due to the increased likelihood of sunscald in those stands which was observed in the field but not accounted for in the model. Lastly, the models projections for an individual tree’s DBH increased when adjusting the variables to maximize ISPA and years since treatment while minimizing pruning intensity and SDI.

### ***1<sup>st</sup> Log Top Diameter***

The untransformed 1<sup>st</sup> log top diameter model:

$$\begin{aligned} \text{TopDiam} \sim & \text{stDbh} + \text{prnInt} + \text{pruned} + \text{stCbh} + \text{stHt} + \text{yrsTrt} + \text{SDI} + \text{ISPA} + \text{stAge} + \\ & \text{thinInt} + \text{thinInt:SDI} + \text{thinInt:ISPA} + \text{yrsTrt:stDbh} + \text{stAge:yrsTrt} + \text{stAge:ISPA} \\ & + \text{thinInt:pruned} + \text{stHt:stCbh} + \text{stHt:pruned} + \text{pruned:prnInt} \end{aligned}$$

*where:*

stDbh= initial DBH (in.) at the time of pruning,

prnInt= pruning intensity (20,40,50,60% of the lower crown removed),

pruned = factored variable (0=control, 1=follower, 2=pruned tree with follower, 3=all pruned),

stCbh= initial crown base height (ft.) at the time of pruning,

stHt= initial tree height (ft.) at the time of pruning,

yrsTrt= years since the pruning treatment occurred,

SDI= stand density index at time of treatment,

ISPA= initial stems per acre (TPA) at plot establishment/planting,

stAge= age (yrs.) at time of treatment,

thinInt= thinning intensity (factored; 0,50,75% of the stand pre-commercial thinned).

A linear model was created predicting top diameter of the 1<sup>st</sup> log using the same process as described above for the DBH model. A model predicting form quotient was first attempted however pruning intensity was not significant in that model. The final top diameter model shown above was tested to determine if a transformation was appropriate and then refitted the transformed response variable to the predictor variables. Significant variables in the model included pruning intensity and type of pruning but not top diameter at time of treatment as this data was not available (Table 5B). However, while the refitted transformed model had equivalent predictive powers and was equally as parsimonious, it did not appear to improve the residuals or QQ plots. Based on this, the untransformed model was selected. Figure 22 (Bottom) shows the actual versus fitted values of the model with an  $R^2$  of .7256, only slightly less than the DBH model. Figure 26 shows the predicted top diameter of the 1<sup>st</sup> log by pruning intensity and pruning with followers. Looking at this figure we see that with increasing pruning intensity the top diameter begins to decrease with significant reductions in the  $\geq 40\%$  crown removal treatment. As expected, with increasing thinning intensity the top diameter of the log also increases due to the increase in resources available to the tree with less competition in the stand. Pruning with followers appeared to increase the top diameter of the first log more than a comparable “all pruned” plot. This result could be due to the shading of the followers on the crowns of the pruned trees, pushing the base of the live crown and zone of maximum diameter growth higher up the bole. Another interesting point is that the 20% pruning treatment actually is predicted to have a larger top diameter than a

control tree. This is potentially a model error since that specific treatment was never actually implemented in the plots. Lastly, the top diameter of the follower was predicted to be over 3" larger than the control. This increase in diameter growth could possibly be due to an overall increase in the tree vigor with less demanding neighbors (pruned trees) and a more productive lower canopy.

## Chapter 5

### *Discussion*

#### **Implications for Volume**

**T**aking the results and trends observed in the data into consideration, as well as the model predictions, there is no support that pruning at any intensity could significantly increase any diameter up the stem. This is drawn from the significant reductions in the mean diameters and/or overlap of the error bars from the raw data and the model. This conclusion is further supported by the decrease in height and DBH PAI growth rates over the treatment years. This hints that any crown removal is, in fact, detrimental to the growth of Douglas-fir. The models only further solidify the argument that pruning hampers growth rates as it predicts lower growth, even in the 20% treatment which appeared to be the most hopeful in the raw data. The possible increase there was most likely due to differences in the starting values, which the model has the ability to account for. These findings do not support Stein's (1955) results that suggest a 20% crown removal could actually increase resources available to the tree by removing branches that were not producing or were a sink for photosynthate. However, it seems logical that any branch that cannot support itself in terms of photosynthate production would quickly die and that removal of branches that are just barely self-supporting would not yield any more resources to the bole. This conclusion is supported by Sprugel et al. (2009), who reviewed numerous pruning studies and concluded that lower branches seem to be almost completely neutral as they do not put on annual growth rings, and do not contribute

carbohydrates to the rest of the tree but apparently just fix enough carbon to meet their own needs. This study supports Sprugel's (2009) hypothesis in that if lower crown branches did withdraw nutrients from the bole, a slight increase in growth rates should have been observed.

The other method of producing more volume would be reducing the taper of the pruned tree. Looking at the Type I diameter data, specifically Fig. 10, there does appear to be a trend toward shifting growth rates toward the upper logs of the tree with increasing pruning intensity; however, the error bars yet again overlap and there is no significant difference between the top diameters with any percent crown removal with the exception of the 40% pruning treatment which decreased log taper by ~0.4" in the first log. Given the trend in the data and the fact that the error bars on the 60% crown removal are large simply due to a small sample size (Table 3), it seems secure to conclude that shifting the crown up the bole encourages growth rates higher up the stem as well. This was confirmed in the Type III installations from the results in Fig. 15 showing that pruned trees (with or without followers) had on average 0.7" less taper than their matching controls in the third log. One thing to note is that for any volume gain to be realized at the mill it would need to be significant enough that it raises the diameter on average 1" using Scribner log rule and also account for the loss of volume due to the smaller top diameter caused by the pruning treatment itself. When looking at the model predictions for the top diameter of a log compared to the controls, we see this isn't the case. So while pruning may reduce taper, it is not enough to account for the overall loss in volume due to a

smaller top diameter. An exception to this appears to be in the pruning with followers treatment at the 20% crown removal. Here the model predicts slightly larger top diameters. However, the increase is not significant and possibly a model error, since that treatment was never actually implemented in the stands. The DBH and top diameter model also conflict in that the prediction for the top diameter is larger than the DBH for a tree of the same density and pruning treatment. This seemingly obvious error is likely due to the effect of different/more variables in the top diameter model compared to the DBH model. Regardless, the trends seen in both model predictions remain meaningful.

With the results provided, if a land manager is looking to increase the volume of his stand, pruning to increase overall growth rates is cautioned given the results from this study. However, pruning to reduce taper (and increase volume at the mill) has more support. Since logs are scaled from the small end, the top diameter of the log is technically the more important diameter when it comes to volume, it is just rather more difficult to obtain on a stand level. When justifying the expense, the increase in volume gained from a reduction in taper will need to exceed the cost of the pruning treatment itself. If pruning had the potential to increase top diameter, a land manager would need to determine what the real gains from the increase would be across the stand given the density and the cost to treat it. The answer to that question must be decided on a case by case, stand by stand basis (however, the conclusion provides a brief outline of what a break-even price would likely need to be to produce a clear 16' log). It is important to note that while the top diameter of the

1<sup>st</sup> log in the 20% crown removal showed a slight increase in the data, the model prediction for the top of the 1<sup>st</sup> log showed that increasing pruning treatments resulted in diameter reductions. As a result, pruning does not appear to reduce taper enough to account for the reduction in overall growth required to gain a clear 16' log. As a result, to generate any revenue it needs to be tied to a significant price premium on the clear wood.

### **Clear wood Production**

Even though pruning to increase volume did not necessarily produce overly convincing results, pruning for an increase in clear wood certainly showed more promise. It was evident that pruning at the 40 and 60% crown removal produced a 1<sup>st</sup> log with little to no branches; those present were solely due to epicormic sprouting. The largest epicormic branches appeared in the 60% crown removal at the 75% thinning intensity supporting the notion that risk of epicormic increases when pruning more than 40% of the live crown (O'Hara 1991). Epicormic branches were also seen in the 50% crown removal treatments (Type III installations), where pruned trees had branch sizes on average >0.2" in the first log. When grading logs, maximum branch diameter of No. 2 sort need to be >2.5" and No. 1 Peeler logs need to be 90% clear (Bell and Dilworth 1988; Table 6). Since the 40, 50 and 60% pruning treatments produce 1<sup>st</sup> logs that are clear with the occasional instance of an epicormic branch (but still maintain the 90% clear guideline) they can fetch higher prices at the mill. The difference in price premiums can be substantial but managers need to weigh the increase in the value of the first log with respect to the loss in volume associated with

that stand and the original cost to prune it. This may be difficult to do, especially since there are no guarantees that premiums for clear logs will hold into the future with changing markets and public demand. After speaking with several log yards in the area, current prices on high-quality domestic peeler logs are only running around \$615/MBF. This is only \$65-90/MBF greater than an unpruned Douglas-fir. Since the premiums on clear wood have yet to materialize, the primary objective of pruning Douglas-fir appears to be confined to aesthetics or habitat creation and enhancement.

### **Dynamics of Pruning with Followers**

The results from the Type III installations also provide some insight into the dynamics of stands containing a mixture of pruned and unpruned trees. In general, pruning at the 50% crown removal intensity hampered growth which resulted in reductions in DBH and diameter and height growth rates. The number of unpruned followers remaining in the stand also affected the diameter of the pruned trees. The followers that remained in the stand appear to be morphing into “wolf” trees, commanding the sites resources (Fig. 25) with poorer form (Fig. 15). This resource dominance was seen prominently in 300 TPA plots with 200 trees pruned versus a 300 TPA plot with 100 trees pruned (Fig. 11). The 100 pruned trees likely had smaller diameters because they were forced to compete with 200 unpruned followers growing at a faster rate than themselves, whereas the plots with 200 pruned trees only had to compete with 100 unpruned followers that were outcompeting them. This is also corroborated by the height and DBH growth rates (Fig. 13 and 14) showing a reduction in growth of pruned trees compared to the followers and controls. These

results also add further support to the belief that if you opt to prune with followers, it is necessary to thin them out during a later entry to prevent them from overtopping the pruned trees and stunting their growth. The original plan of the Type III study design was to remove the followers, however, interest was lost and they remained in the stand. Regardless, it still provides a useful examination of the potential consequences of missing that treatment window. Based on research in the New Zealand plantations, this window is said to be just 1-2 years after the original pruning treatment if growth reductions are to be avoided (Knowles 1995). The trees in our study were sentenced to approximately 16 years with the followers.

Another important result of note was the equivalent diameters of the followers and controls compared to the pruned trees in the raw data. This result is slightly surprising because the followers had more growth space/resources to utilize after pruning due to increased light and dominance in the canopy. The DBH model, accounting for all the variables, projected larger DBH for the followers both for the current years since treatment and with 30 yrs. of treatment (Fig. 25). This seems more likely as followers would expand their crowns to fill the growing space and therefore have more resources compared to a control tree at the same overall density. Trees that received any Type III pruning treatments showed reductions in the DBH, especially in stands that received “all pruned” treatments. The all pruned treatments may have only exhibited smaller DBH than the pruned with followers treatment due to the presence of sunscald in the stand that was observed in the field. Damages were not accounted for in the model and may help to explain the reduction. This helps to

serve as a reminder of the benefits of pruning with followers and the associated risk of sunscald by removing 50% of the crown on every tree in the stand.

### **Economic Analysis**

To aid in determining what the price of clear wood needs to be, a short analysis (Table 7) was conducted. Volume revenue and treatment costs associated with a 40% pruning intensity were discounted to the present and compared to an unpruned stand of the same density. A 40% pruning intensity was chosen because it was the minimum pruning intensity required to produce a clear first log in this study. The economic analysis also makes some assumptions including: 1) all costs outside of the pruning are equal, and 2) the inches of taper doesn't change when the calculations are projected to a stand age of 40. It fails to take into consideration volume differences outside 42' up the stem. Unpruned trees are also likely to have greater volume above 42', so the premium estimate should be viewed as a minimum required to break even. Based on these assumptions and with these limitations in mind, it is estimated that at the end of a 40-year rotation, the minimum price premium would need to be \$900/MBF for a clear 16' log; a substantial difference from the \$615/MBF domestically offered now and even above the \$800-850/MBF offered by the export log market. An important thing to note in both the domestic and export markets is the minimums on clear log lengths. For the domestic market, it appears that no one is willing to pay the premium if the log is less than 16'. The export market has much higher standards with minimum log length at 26' and preferred to be 36-41'. The

clear log lengths in this study were a far cry from even 26' (22' in the Type III's) so export prices would be unavailable for the stands in this study.

### **Other Implications**

Currently, pruning is often used to create dispersal habitat for northern spotted owl via the creation of flying corridors in the lower canopy. This study found that with increased pruning intensity, the overall growth rate of the tree declined. However, it would seem that pruning may only be a short-term fix in the creation of spotted owl habitat. The reasoning for this notion stems from their apparent preference for old-growth forest. A characteristic of old-growth forests in the Pacific Northwest is large trees with complex crowns. While pruning may increase crown-complexity by creating epicormic branches at a younger age, the size of the trees will be delayed (if not reduced) due to the pruning treatment itself. Managers will need to evaluate the benefits and drawbacks given the goals (immediate or long-term) of the stand.

Pruning to improve habitat for ungulates appears to have less uncertainty as pruning allows more light to the understory and a subsequent increase in biodiversity. This increase in biodiversity allows not only more browse for ungulates, but also for small mammals. This increase in light may also affect forest succession by lengthening the stand initiation phase (Oliver et al. 1995). As a result, it is possible that pruned stands may never really reach an intense stem exclusion phase and instead slowly transition toward a more mature forest. For most animals, the avoidance of the stem exclusion phase would enhance the habitat value of the forest (Oliver and Larson 1996).

Reduction of crown fire potential as a result of pruning appears to be supported in this study. With increasing pruning intensity, the base of the live crown shifted upwards and created a larger gap between the forest floor and tree canopy. In the Type III installations, the mean crown base height was 20.7' for the controls and for pruned trees was 23.62' (50% crown removal). This created an extra 3' on average between the forest floor and crown base in the pruned stands. However, in some stands, this gap was partially filled with intense shrub competition that was over 6' tall which would likely mean an actual increase in crown fire risk. In addition, pruning with followers created trees with more vigorous lower canopies and may serve as ladder fuels to the crown if not removed in later entries. It is likely that pruning to reduce the risk of crown fire is highly effective initially when the stands are young, and with time, the benefits fade away as the stand matures. On the other hand, as the stand ages, the likelihood of a crown fire in these plantations becomes less probable as the crowns move up the tree. Based on these findings, pruning to reduce crown fire risk is supported but most applicable in younger stands.

## Chapter 6

### *Management Recommendations*

Given the results of the observed trends in the data (displayed in the figures) and the linear models, pruning at any intensity is likely to decrease the diameter and height growth rates of a tree. As a result, pruning intensity should be minimized and only done to the point to gain a clear first log. The percent of crown removed to gain a clear 1<sup>st</sup> log will depend on how old the trees are when pruned and needs to be weighed against the number of years left before harvest so that clear wood can form over the stubs of the branches. Removal should remain less than 50% to avoid dramatic decreases in stand volume and reduce the risk of epicormic branching, sunscald, and heart rot. Pruning should also follow thinning in order to minimize costs and maximize clear wood production on the remaining trees. In addition, if pruning later in the rotation, there needs to be a realization that the logs may be downgraded at the log yard due to knot indicators which may be present many years after the pruned branches are grown over. However, if managers do choose to prune, they should not be worried about any significant increase in the branches sizes of the upper logs as they remain well below branch size requirements for a decent sawlog. In addition, if they opt to prune with followers, they should be removed in a subsequent entry in order to prevent overtopping of the pruned trees and reduction in their growth. If for some reason followers are chosen to be retained in the stand, they should be minimized and not entail more than 40-50% of the stand, based on the increased growth reductions seen with followers comprising 66% of the stand. While pruning with followers did tend to reduce the risk/size of epicormic

branches, the branches on the “all pruned trees” still were not large enough to degrade the clear log and a reduction in the pruning intensity (recommended) would aid with this unwanted side-effect. Based on this logic, pruning with followers in Douglas-fir stands appears to be unnecessary as they require more entries into the stand that are not outweighed by a benefit to the pruned trees themselves (and can actually hurt pruned trees if they are not removed). An exception to pruning with followers would be in stands that are at high risk of sunscald, such as on southern aspects, but perhaps these should not be pruned at all.

The question then centers on the price premium for clear wood, specifically, what does the premium need to be given the reduction in volume and the costs associated with the pruning treatment? Export prices for clear logs range from \$800-850/MBF; however, with the minimum log lengths mentioned, pruning becomes even less economically feasible. Longer log lengths mean increased costs associated with pruning due to the numerous entries into the stand and height to which a manager would be required to prune. An alternative would be finding a buyer willing to purchase 8' clear logs domestically. This may be the best option as a land manager could use a 20% pruning treatment that minimizes growth reduction (nearly the same as a control tree) while also minimizing pruning costs. Pruning costs about \$284/acre above 10' but only \$126/acre when below 10', a substantial difference of \$158/acre. Although this situation would be ideal, after calling several log buyers, it didn't sound as if anyone wanted logs less than 16' domestically. Given the estimated price required to break even, this serves as an explanation of why pruning currently

remains feasible for the less economically-driven objectives such as habitat creation and crown fire reduction.

In conclusion, removal of any amount of crown in a Douglas-fir shows signs of harming the diameter growth rates of the tree; however, if there is a sufficient premium on clear wood that exceeds the costs of treatment and loss of volume, pruning can then become a lucrative option. However, given the current premium for clear logs, it is understood why pruning is rarely implemented and until markets respond otherwise, will remain on the fringes of production silvicultural management.

### **Limitations/Future Research**

This study had several limitations including small sample sizes for some of the more specific pruning / stand density combinations and a lack of upper stem diameters at the time of treatment. Larger sample sizes would have helped minimize the error estimates and produced a more accurate model. Having upper stem diameters at the time of treatment would help to build a model that could more accurately predict the top diameter of pruned and unpruned logs and help track where the growth rates have shifted.

Further research in the area is needed to gain a complete understanding of the effects of pruning, especially pruning with followers. A study focusing on pruning with followers in which the followers are removed shortly after the pruning treatment and

at a different pruning intensity, specifically one that doesn't hamper tree growth as much as the 50% crown removal would be valuable. This would not only assess the effect to diameter of the pruned trees, but also to determine if sunscald and other damaging agents would become an issue when the followers are removed.

Lastly, tracking upper stem diameters over time would be of great use due to the implications in volume. Many studies examine DBH growth over time due to the ease of measurement but few studies measure upper stem diameters, and no studies seem to follow upper stem diameters over time.

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## TABLES

**Table 1:** Comparison of mean stand metrics of Type I and Type III installations. Note that Type I installations were thinned whereas Type III were not but rather planted to the desired final density.

	Type I	Type III
Mean Stand Age (yrs.)	35.7	26
Mean Stand Height (ft.)	84.1	59.5
Mean DBH (in.)	13.5"	10.4"
Pruning Treatment (% LC Removed)	20, 40 60%	50% max 22 ft.
Age at Pruning	11.2	9.75
Yrs. Treatment	24.5	16.2
Densities (TPA*)	ISPA, ISPA/2, ISPA/4	100, 200, 300
Sample Size	204	222

\*Trees Per Acre (TPA)

**Table 2:** Comparison of the variability of the post thinning densities in the Type I installations in terms of TPA and Site Index (Plot SI).

	ISPA	ISPA/2	ISPA/4
Range (TPA)	(362, 630)	(215, 315)	(91,158)
Mean (TPA)	498.6	248	117
PlotSI*	73.3	73.5	71.1

\*Plot SI source: (Flewelling et al. 2001)

**Table 3:** Table showing the unique Type I (thinned) and Type III (planted ISPA) pruning treatment combinations with the number of trees sampled. Note that some treatments contained very few trees or were not sampled at all. Note however that the 50% pruning has no thinning repetitions as its treatment regime was based on planting to a final density.

Type I:	Control	20%	40%	50%	60%
ISPA	36	6	0	NA	0
ISPA/2	36	12	30	NA	6
ISPA/4	36	12	0	NA	30

Type III: Control- Follower -Pruned W/Followers- All Pruned					
100	30	NA	NA	30	
200	36	5	30	6	<b>Total Trees Sampled</b>
300	36	7	42	NA	<b>426</b>

**Table 4:** Datasheet used to gather measurements this paper was based upon. Note: LrgBHBr = Large Breast Height Branch Size; WhlBrCt= Whorl Branch Count; IntBrCt = Internodal Branch Count; CW = Crown Widths; LBD = Large Branch Diameter.

<u>Ground</u>			
Inst: _____	Plot: _____	Tree: _____	Quint: _____
DBH: _____	Ht: _____	Ht -> LCB: _____	
LrgBHBr: _____	WhlBrCt: _____	IntBrCt: _____	
CW NE: _____	CW SE: _____	CW SW: _____	CW NW: _____
<u>Top of first log (17.5')</u>			
Dia: _____			
LBD NE: _____	LBD SE: _____	LBD SW: _____	LBD NW: _____
<u>Top of second log (34')</u>			
Dia: _____			
LBD NE: _____	LBD SE: _____	LBD SW: _____	LBD NW: _____
<u>Bottom half of third log (-&gt; 42')</u>			
Dia: _____	Ht -> 4" _____		
LBD NE: _____	LBD SE: _____	LBD SW: _____	LBD NW: _____

**Table 5A:** ANOVA (top) and Summary table (bottom) results from the transformed combined DBH model which utilized the forward selection method.

	Df	Sum Sq	Mean Sq	F value	Pr(> F)
prnInt	1	0.387	0.387	78.972	< 2.2e-16
yrsTrt	1	1.299	1.299	265.241	< 2.2e-16
ISPA	1	0.362	0.362	74.023	< 2.2e-16
stDbh	1	2.340	2.340	477.852	< 2.2e-16
thinInt	2	0.521	0.260	53.192	< 2.2e-16
pruned	3	0.106	0.035	7.213	9.995e-05
SDI	1	0.141	0.141	28.893	1.292e-07
stAge	1	0.110	0.110	22.535	2.865e-06
ISPA:SDI	1	0.203	0.203	41.398	3.501e-10
prnInt:stAge	1	0.068	0.068	13.787	0.0002333
stDbh:pruned	3	0.046	0.015	3.144	0.0251402
yrsTrt:ISPA	1	0.045	0.045	9.290	0.0024541
yrsTrt:stAge	1	0.022	0.022	4.571	0.0331227
yrsTrt:Dq	1	0.034	0.034	6.959	0.0086603
Residuals	406	1.988	0.005		

	Term	Estimate	Std.Error	Statistic	P.Value
1	(Intercept)	1.00949	0.29440	3.42902	0.00067
2	prnInt	-0.00421	0.00146	-2.88710	0.00410
3	yrsTrt	0.04724	0.01419	3.32910	0.00095
4	ISPA	0.00057	0.00029	1.99675	0.04652
5	stDbh	0.06631	0.00486	13.64192	0
6	thinInt50	0.11456	0.01506	7.60676	0
7	thinInt75	0.18078	0.01560	11.59131	0
8	prunedUnpruned Follower	0.26057	0.08050	3.23705	0.00131
9	prunedPruned Tree (with Followers)	0.05933	0.04640	1.27856	0.20178
10	prunedAll Pruned	-0.04328	0.03938	-1.09917	0.27234
11	SDI	-0.00540	0.00097	-5.57295	0.0000000
12	stAge	0.02542	0.02449	1.03775	0.30000
13	ISPA:SDI	0.00001	0.000001	6.61407	0
14	prnInt:stAge	0.00016	0.00011	1.48244	0.13900
15	stDbh:prunedUnpruned Follower	-0.04394	0.02634	-1.66832	0.09602
16	stDbh:prunedPruned Tree (with Followers)	-0.00244	0.01085	-0.22504	0.82206
17	stDbh:prunedAll Pruned	0.01590	0.00610	2.60736	0.00946
18	yrsTrt:ISPA	-0.00006	0.00001	-4.55653	0.00001
19	yrsTrt:stAge	-0.00199	0.00112	-1.78056	0.07573
20	yrsTrt:Dq	0.00291	0.00110	2.63800	0.00866

**Table 5B:** ANOVA (top) and Summary table (bottom) results from the combined top diameter model which utilized the forward selection method.

	Df	Sum Sq	Mean Sq	F value	Pr(> F)
stDbh	1	1,319.737	1,319.737	510.782	< 2.2e-16
prnInt	1	195.929	195.929	75.831	< 2.2e-16
pruned	3	129.450	43.150	16.701	3.067e-10
stCbh	1	26.903	26.903	10.413	0.001355
stHt	1	108.518	108.518	42.000	2.695e-10
yrsTrt	1	334.915	334.915	129.623	< 2.2e-16
SDI	1	141.738	141.738	54.857	7.784e-13
ISPA	1	225.255	225.255	87.181	< 2.2e-16
stAge	1	58.217	58.217	22.532	2.885e-06
thinInt	2	266.004	133.002	51.476	< 2.2e-16
SDI:thinInt	2	21.837	10.918	4.226	0.015273
ISPA:thinInt	2	21.683	10.841	4.196	0.015762
stDbh:yrsTrt	1	15.839	15.839	6.130	0.013703
yrsTrt:stAge	1	15.103	15.103	5.845	0.016067
ISPA:stAge	1	15.194	15.194	5.880	0.015753
pruned:thinInt	2	18.309	9.155	3.543	0.029837
stCbh:stHt	1	19.092	19.092	7.389	0.006848
pruned:stHt	3	37.441	12.480	4.830	0.002582
Residuals	399	1,030.918	2.584		

	Term	Estimate	Std.Error	Statistic	P.Value
1	(Intercept)	-19.41350	7.99903	-2.42698	0.01567
2	stDbh	-0.28688	0.40741	-0.70414	0.48176
3	prnInt	-0.05623	0.01100	-5.11073	0.0000005
4	prunedUnpruned Follower	4.14728	2.45235	1.69114	0.09159
5	prunedPruned Tree (with Followers)	1.08565	1.15729	0.93810	0.34876
6	prunedAll Pruned	-1.93434	0.97216	-1.98973	0.04730
7	stCbh	-0.27161	0.22153	-1.22604	0.22091
8	stHt	-0.00907	0.01285	-0.70575	0.48076
9	yrsTrt	2.25370	0.54362	4.14573	0.00004
10	SDI	-0.01419	0.00544	-2.60634	0.00949
11	ISPA	-0.04514	0.01110	-4.06762	0.00006
12	stAge	2.41292	0.77457	3.11517	0.00197
13	thinInt50	-2.18723	1.47047	-1.48743	0.13769
14	thinInt75	0.92826	1.17881	0.78745	0.43148
15	SDI:thinInt50	-0.00222	0.00629	-0.35303	0.72426
16	SDI:thinInt75	-0.00075	0.00635	-0.11873	0.90555
17	ISPA:thinInt50	0.00990	0.00355	2.78923	0.00554
18	ISPA:thinInt75	0.00695	0.00323	2.15086	0.03209
19	stDbh:yrsTrt	0.07789	0.01981	3.93241	0.00010
20	yrsTrt:stAge	-0.19143	0.05262	-3.63762	0.00031
21	ISPA:stAge	0.00309	0.00101	3.07256	0.00227
22	prunedAll Pruned:thinInt50	-0.29408	0.59603	-0.49339	0.62201
23	prunedAll Pruned:thinInt75	-0.44905	0.58540	-0.76709	0.44348
24	stCbh:stHt	0.00790	0.00749	1.05470	0.29220
25	prunedUnpruned Follower:stHt	-0.06219	0.13804	-0.45054	0.65257
26	prunedPruned Tree (with Followers):stHt	0.04053	0.05070	0.79947	0.42449
27	prunedAll Pruned:stHt	0.13732	0.03669	3.74326	0.00021

**Table 6:** Criteria used to estimate log grades following the Northwest Log Rules Advisory Group (1998) except for branch frequency requirements for Special Mill and net scale requirements for all grades. Taken from (Barbour and Parry 2001).

Grading criteria	Log grade			
	Special Mill	No. 2 Sawmill	No. 3 Sawmill	No. 4 Sawmill
Minimum rings per inch outer portion	6 rings per inch	None	None	None
Minimum scaling diameter	16 inches	12 inches	6 inches	5 inches
Maximum branch diameter	1.5 inches	2.5 inches	3 inches	None
Minimum length	17 feet	12 feet	12 feet	12 feet

**Table 7:** Break-even price premium estimates of pruned Douglas-fir logs. The estimate assumes cost are equal outside the pruning and doesn't account for volume differences above 42' (which the unpruned will have more of). Because of these limitations it should be viewed as a rough estimate of the minimum premium required.

	Log 1		Log 2		Log 3		TPA	
	Control	40%	0%	40%	0%	40%	220	
<b>DBH</b>	18.78	16.46	18.78	16.46	18.78	16.46	<b>Prices</b>	
<b>Taper</b>	1.8	1.4	3.3	3	4.4	3.9	<b>No.2</b>	<b>Peeler</b>
	16.98	15.06	15.48	13.46	14.38	12.56	\$525.00	\$900.00
<b>Scribner Top Diameter</b>	17	15	15	13	14	13	<b>Interest</b>	
<b>Volume</b>	180	140	140	100	60	50	<b>Years</b>	<b>Rate</b>
							40	0.05
<b>Total Volume (MBF)</b>	39.6	30.8	30.8	22	13.2	11		
<b>Gross Rev.</b>	\$20,790.00	\$27,720.00	\$16,170.00	\$11,550.00	\$6,930.00	\$5,775.00		
<b>NPV Gross</b>	\$2,953.13	\$3,937.51	\$2,296.88	\$1,640.63	\$984.38	\$820.31		
<b>Pruning Costs/Acre</b>		\$284.00						
<b>NPV Pruning Costs</b>		\$164.44						
<b>Total NPV/Acre</b>	\$2,953.13	\$3,773.07	\$2,296.88	\$1,640.63	\$984.38	\$820.31		
			<b>NPV Revenue/Acre:</b>				Log 3 = 8ft	
			<b>Control</b>	\$6,234.38				
			<b>40%</b>	\$6,234.01				

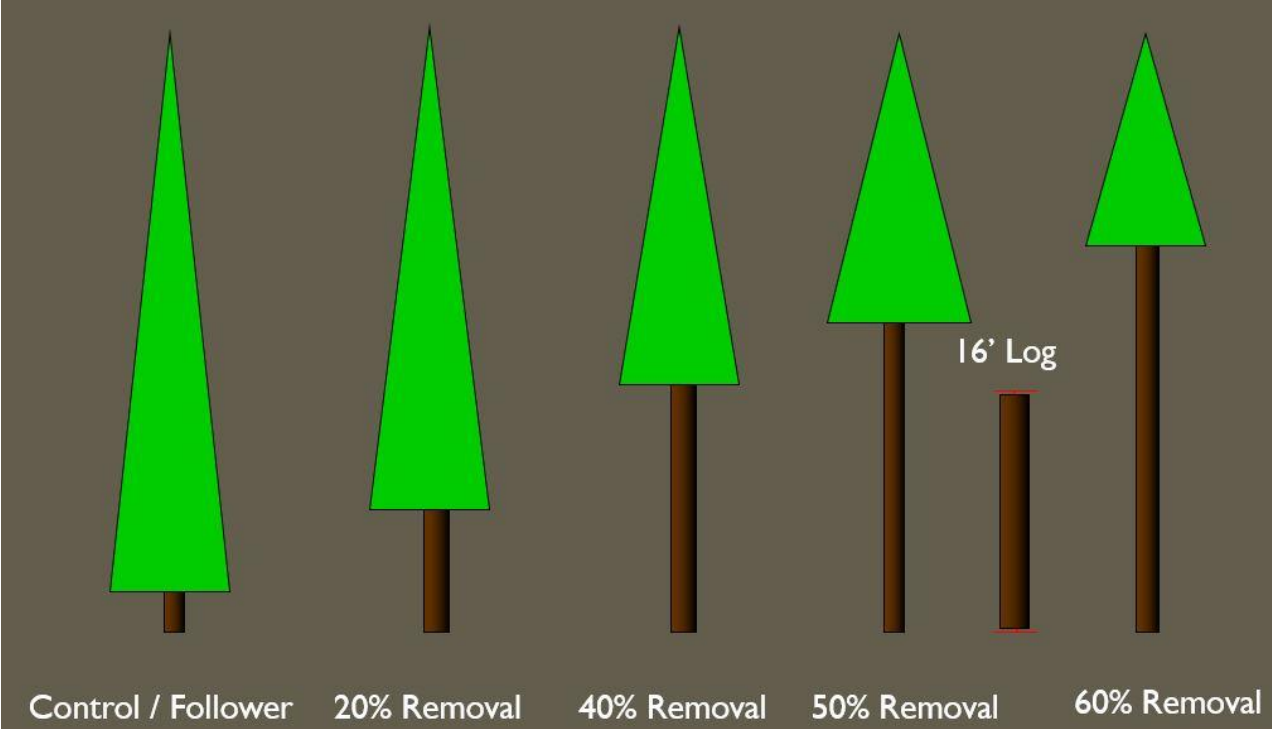
## FIGURES



**Figure 1:** Locations of the 12 measured Stand Management Cooperative (SMC) installations throughout Washington and Oregon which contained pruned study plots and their matching controls at the same density.

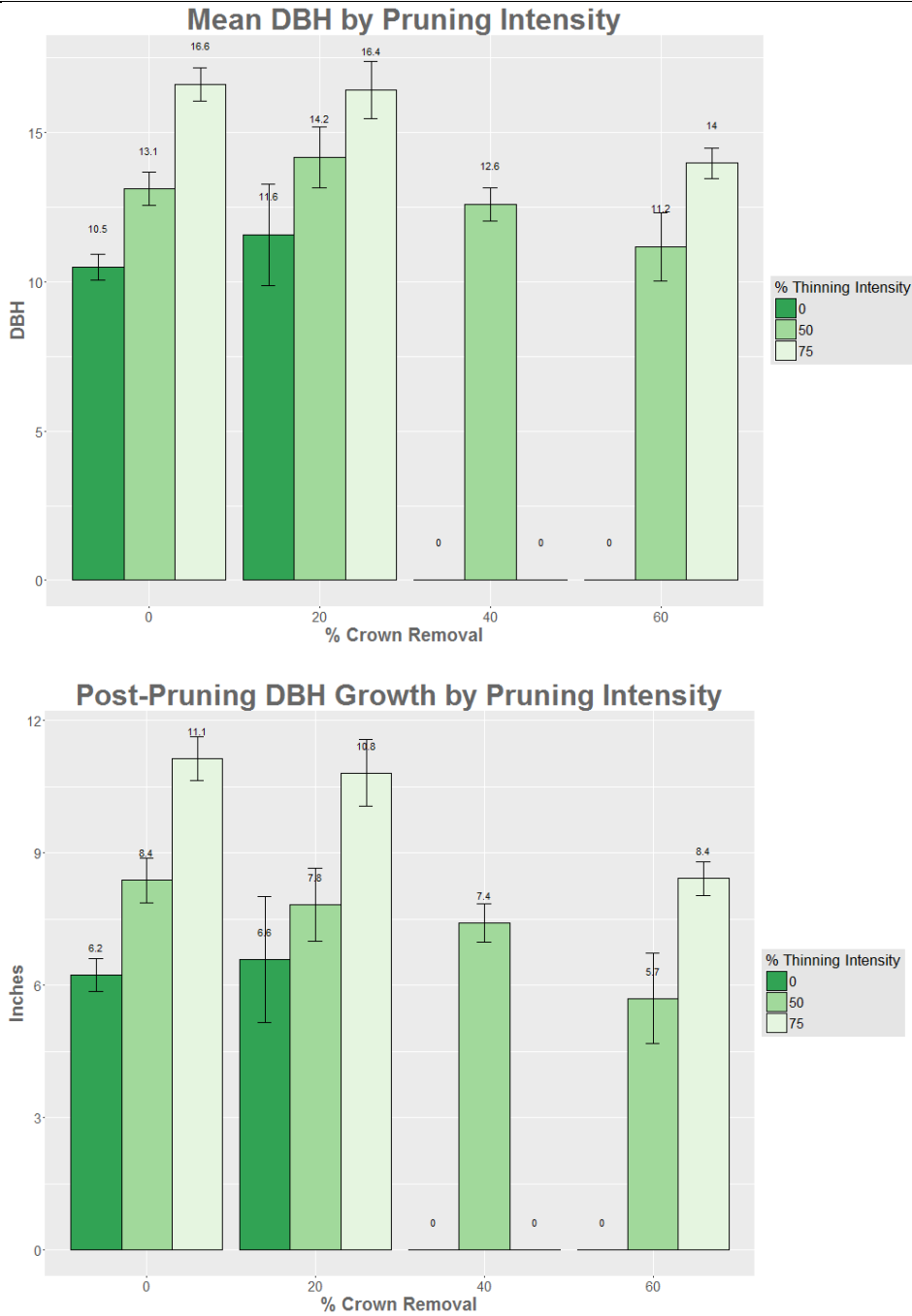


**Figure 2A:** Swiss-style climbing ladders were used to reach 42' in the canopy of measurement trees, in this case an unpruned control. The ladder combined with a harness was used to safely climb the tree.



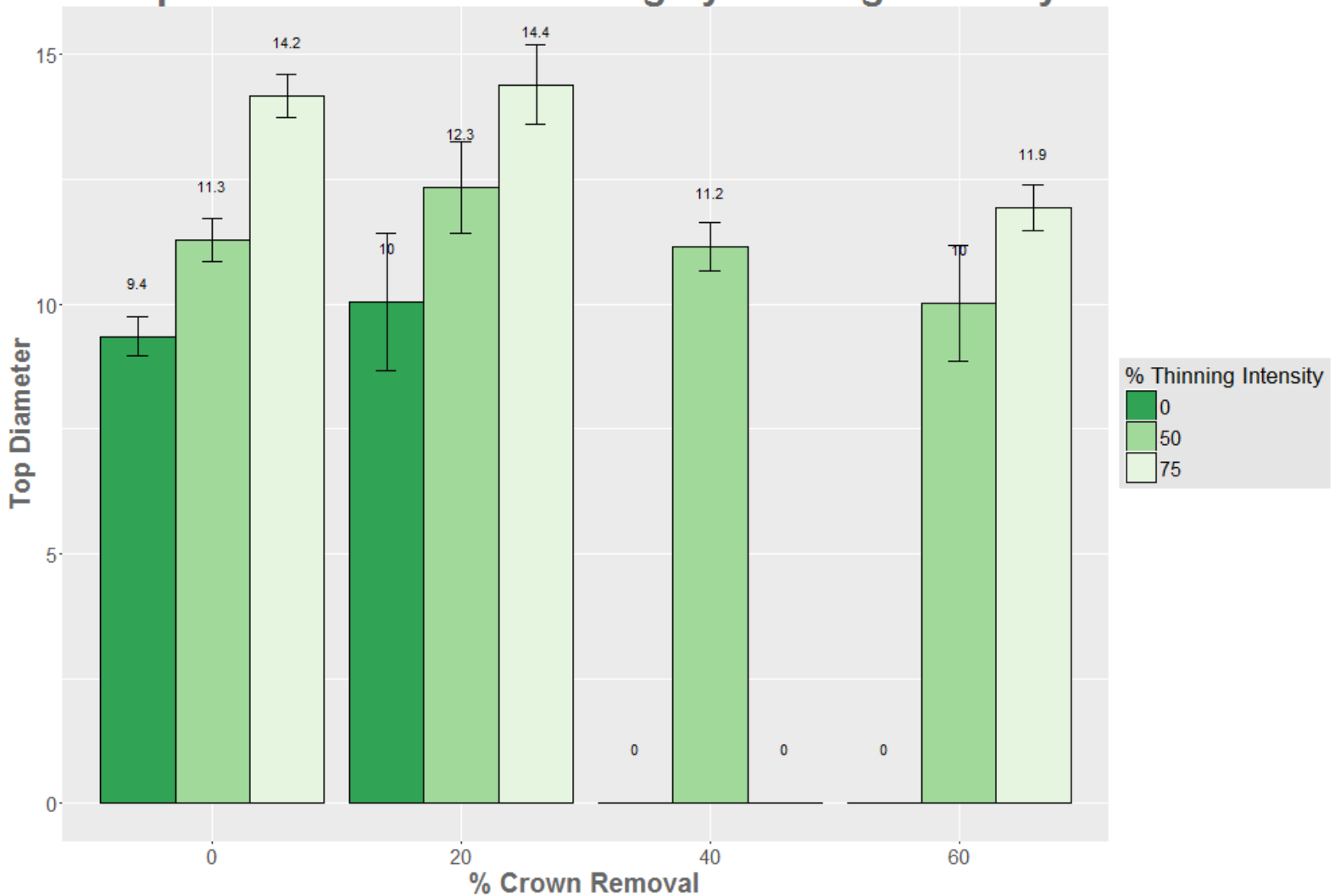
**Figure 2B:** Simple visual representation of the effects of pruning to the lower live crown. Note that in this study, the  $\geq 40\%$  treatment produces a clear 16' log. The 50% crown removal was the pruning intensity used in the Type III installations.

## Type I: Diameter/Height Graphs



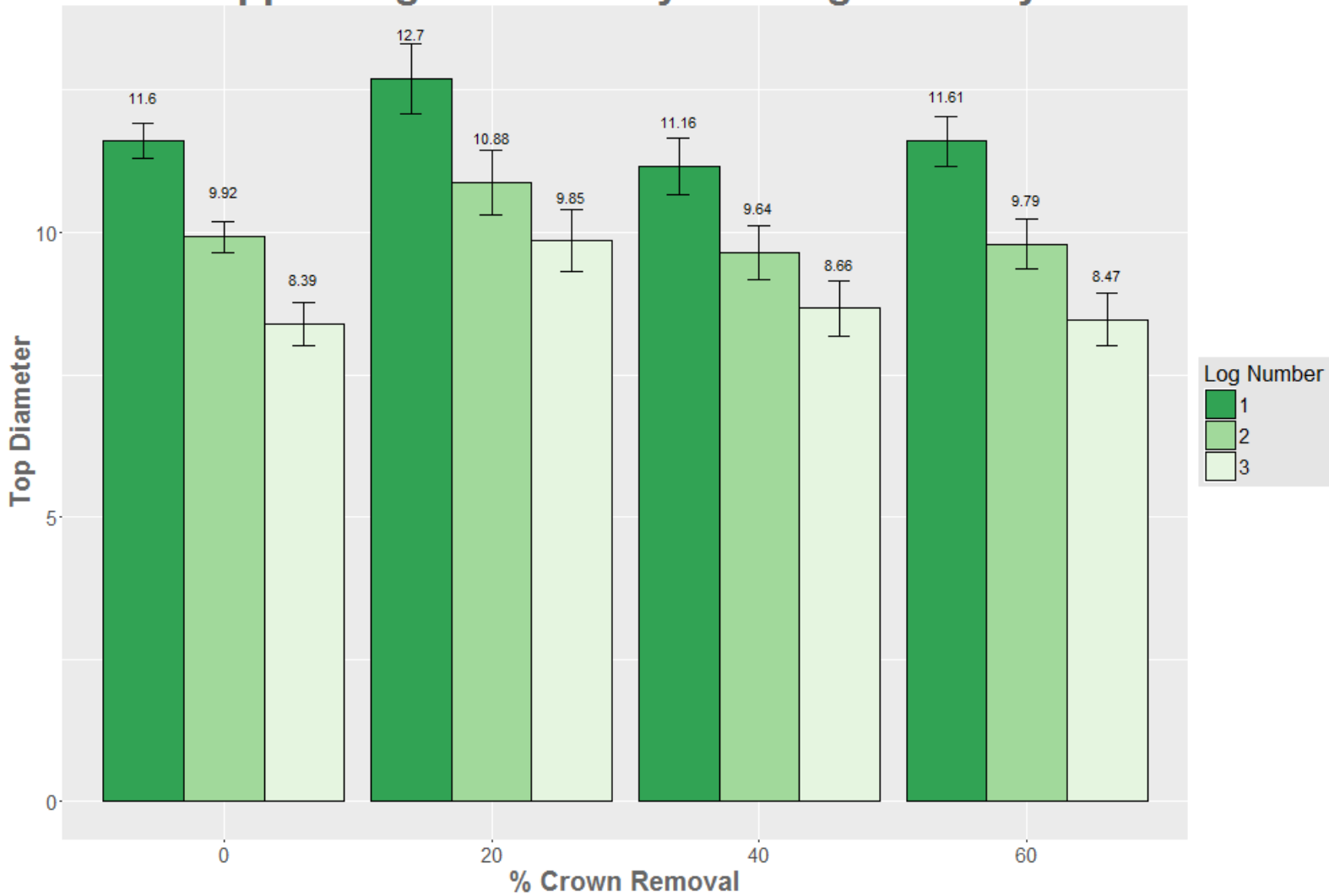
**Figure 3: (Top)** Mean DBH by percent crown removal and thinning intensity, based on the raw data. Note this figure is misleading because it fails to account for the diameter differences at the time of pruning at which time the controls started ~1.0" smaller than the average of the treatments. **(Bottom)** A more reliable estimate of the effects of pruning on DBH growth is seen here with inches of growth, post-pruning. This figures accounts for the starting differences by only examining growth trends after crown removal. Here the 20% crown removal treatment shows a slight reduction but is not significant with increasing pruning intensities resulting in increasing DBH growth reductions. Note: error bars are  $\pm 1$  SE.

## Top Diameter of the First Log by Pruning Intensity



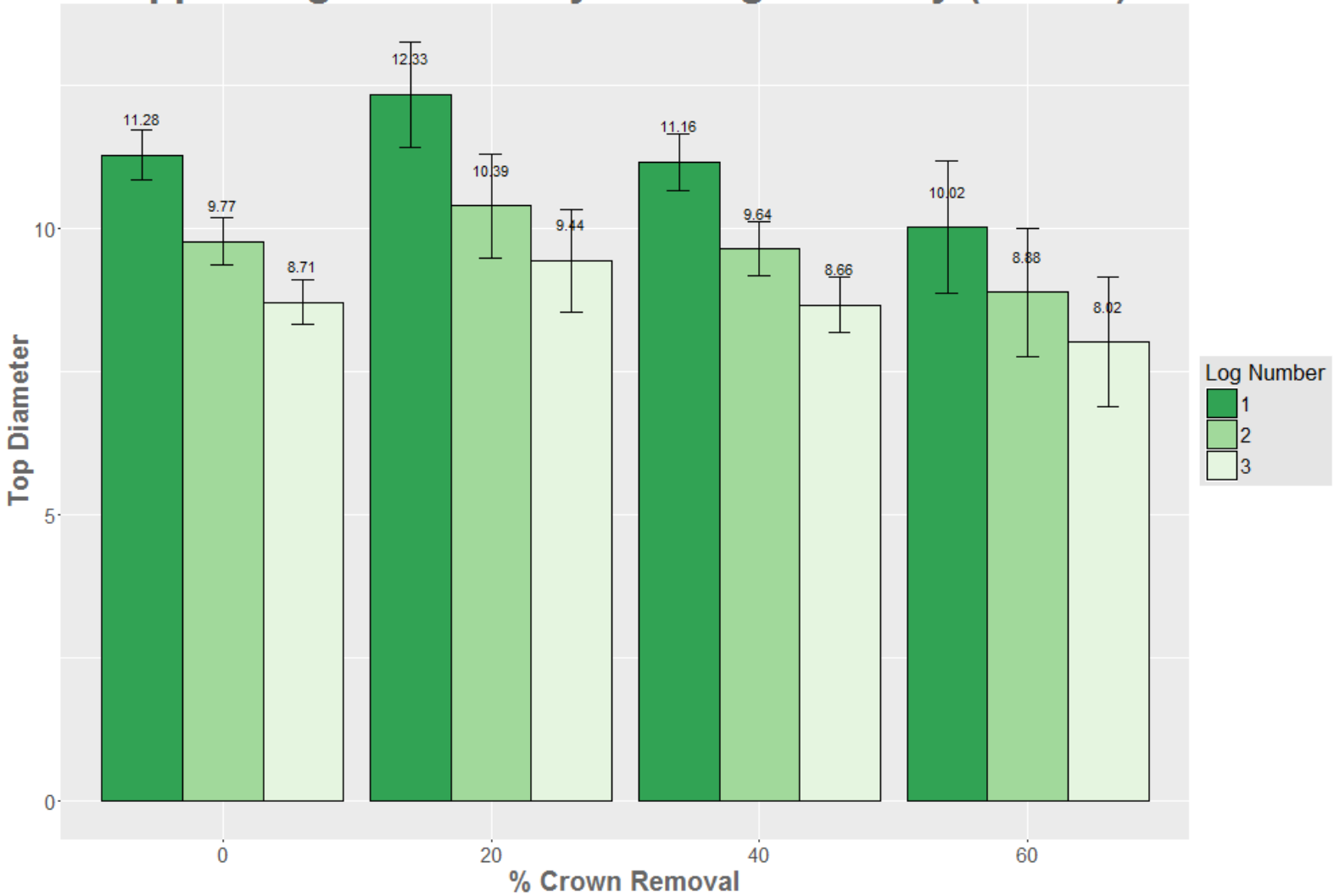
**Figure 4:** Mean top diameter of the first log (17.5' from the ground) by pruning intensity and percent of stand thinned, based on the raw data averages. Overall, the top diameter of the first log appears to show gains with the 20% crown removal across the thinning variations with the largest increase is seen at the 50% thinning intensity (ISPA/2). Note: this figure may be misleading as it fails to account for differences in the starting values (one that does cannot be made since upper stem diameters were not recorded at time of treatment). The model, which accounts for other measured values, contradicts the raw data and predicts a reduction in 1<sup>st</sup> log top diameter with increasing crown removal. Error bars are  $\pm 1$  SE.

## Upper Log Diameter by Pruning Intensity



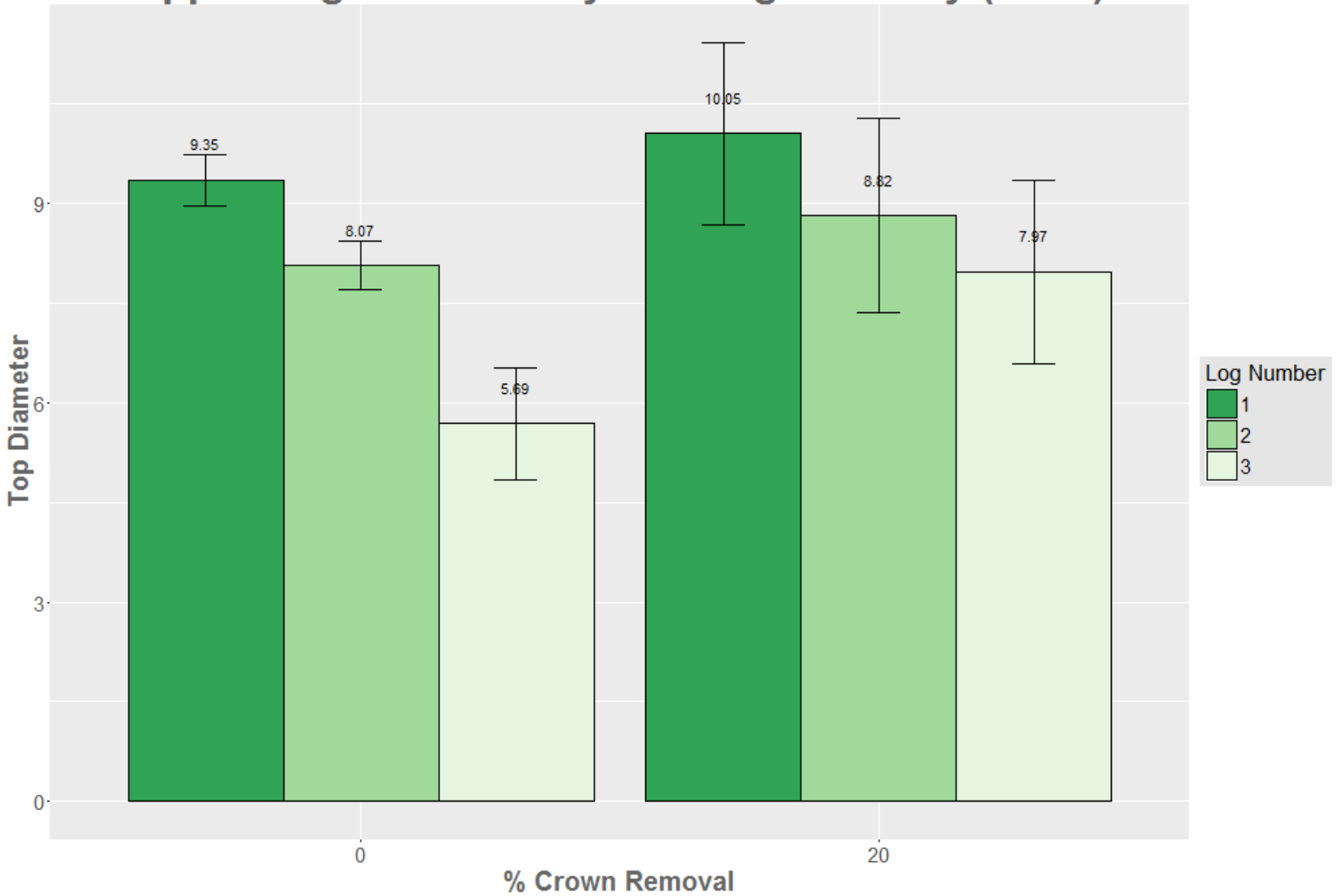
**Figure 5:** Top diameter of the three logs measured by pruning intensity. 20% crown removal shows increases in top diameter up the stem whereas 40% and 60% show equivalent diameters. Consider again the predicted reduction of DBH in the 20% treatment the model suggest will occur. The mean top diameter is across all stand densities and thinning intensities and based on the raw data. Note: this figure may be misleading as it fails to account for differences in the starting values (one that does cannot be made since upper stem diameters were not recorded at time of treatment). The model, which accounts for other measured values, contradicts the raw data and predicts a reduction in 1<sup>st</sup> log top diameter with increasing crown removal. Error bars are  $\pm 1$  SE.

## Upper Log Diameter by Pruning Intensity (ISPA/2)



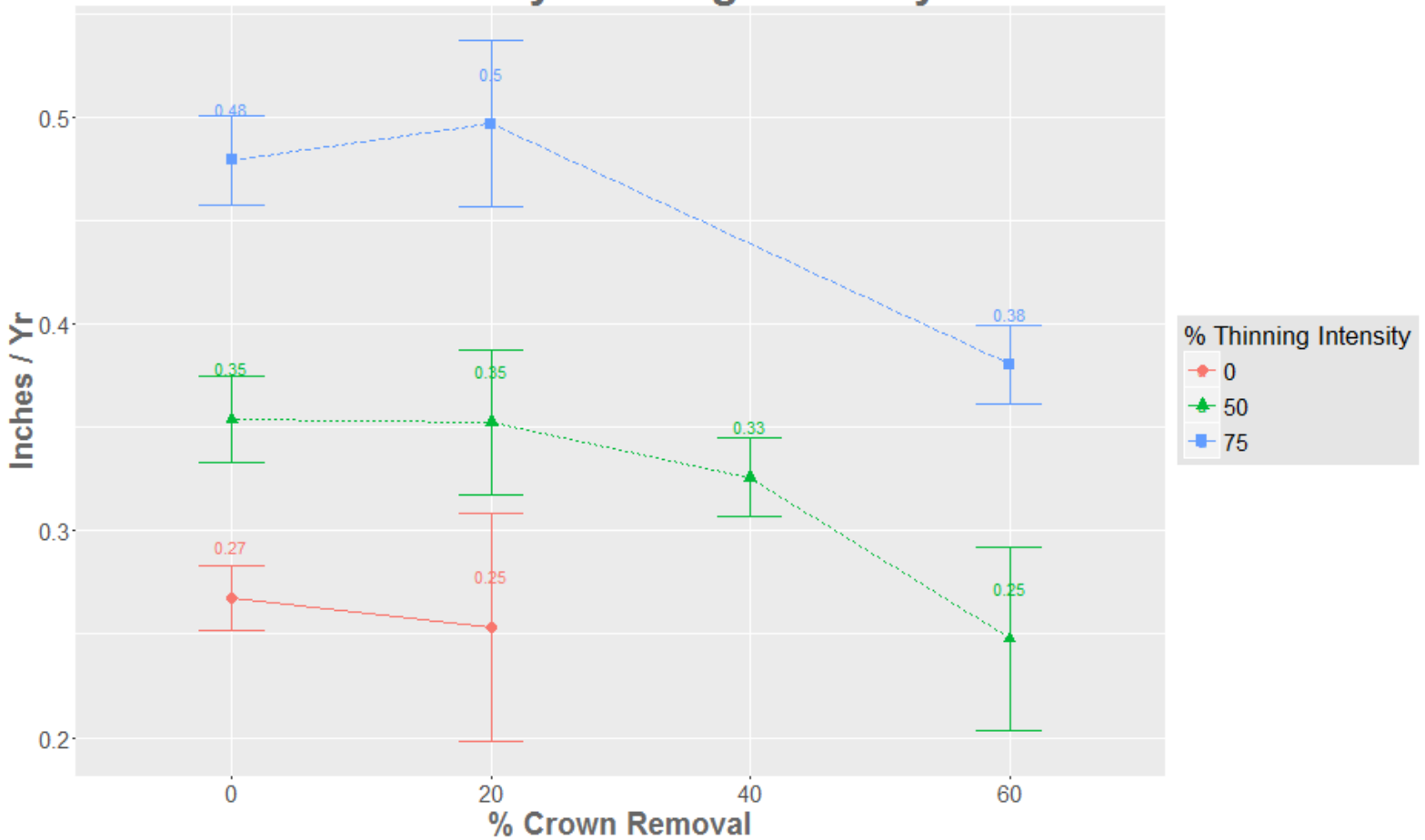
**Figure 6:** Upper log top diameters by pruning intensities of the trees thinned by 50% (ISPA/2). At this spacing the 20% crown removal shows an increase in diameter up the bole (with the largest increase in the first log), the 40% crown removal has roughly equivalent top diameters and the 60% crown removal shows a decrease in upper stem diameters. Note: this figure may be misleading as it fails to account for differences in the starting values (one that does cannot be made since upper stem diameters were not recorded at time of treatment). The model, which accounts for other measured values, contradicts the raw data and predicts a reduction in 1<sup>st</sup> log top diameter with increasing crown removal. Error bars are  $\pm 1$  SE.

## Upper Log Diameter by Pruning Intensity (ISPA)



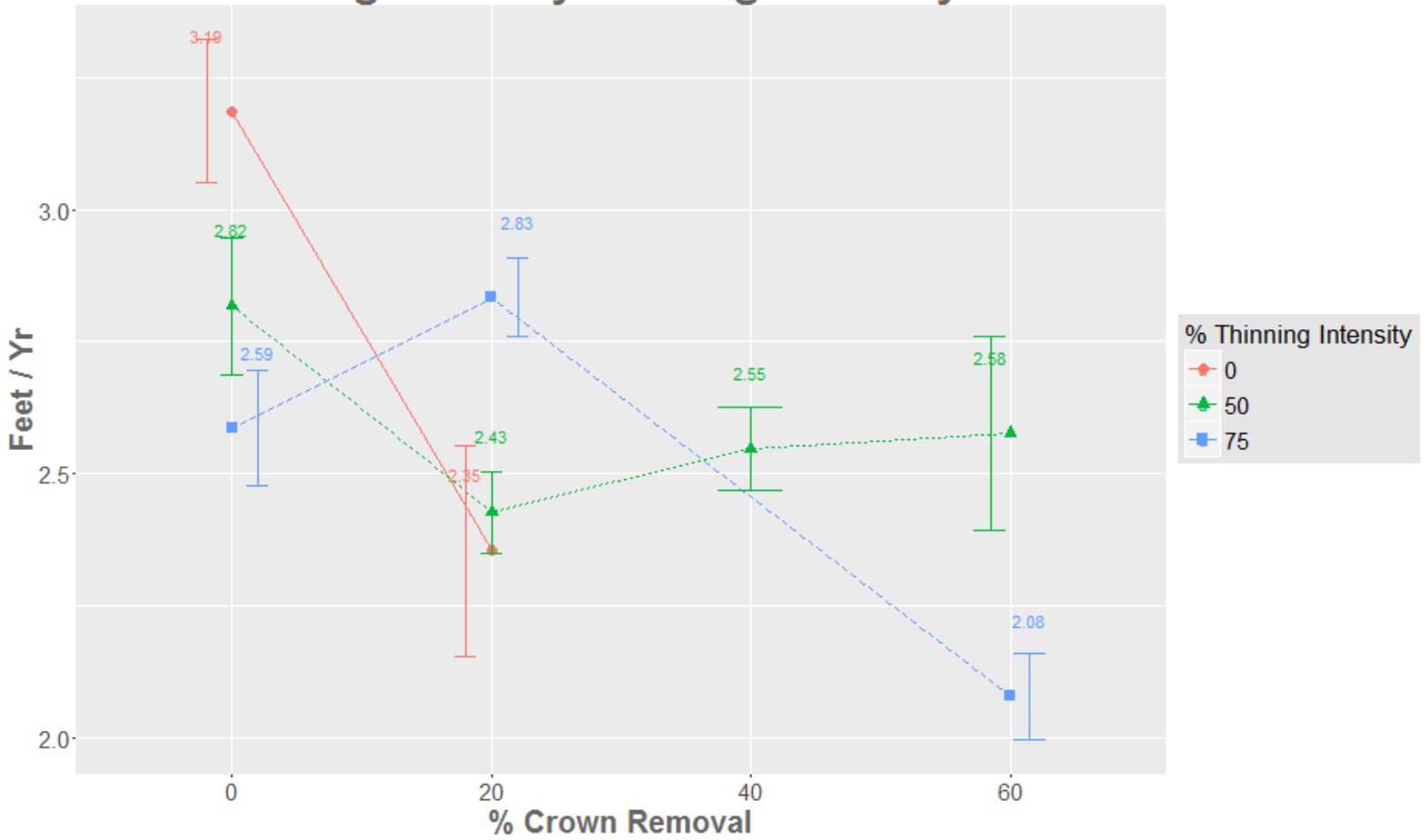
**Figure 7:** Upper log top diameters by pruning intensities of the unthinned trees (ISPA). Figure is based on the raw data of the sole ISPA pruned plot at one installation. At this spacing, the 20% crown removal shows an increase in diameter up the bole with the largest increase in the third log; however, all three logs error bar ( $\pm 1$  SE) overlap are not significant. This differs with the trees thinned in half (ISPA/2) which showed the biggest gains in the first log. Likely due to differences in the amount of light reaching the lower branches at higher stand densities. Note: again this figure may be misleading as it fails to account for differences in the starting values (one that does cannot be made since upper stem diameters were not recorded at time of treatment). The model, which accounts for other measured values, contradicts the raw data and predicts a reduction in 1<sup>st</sup> log top diameter with increasing crown removal.

## DBH PAI by Pruning Intensity



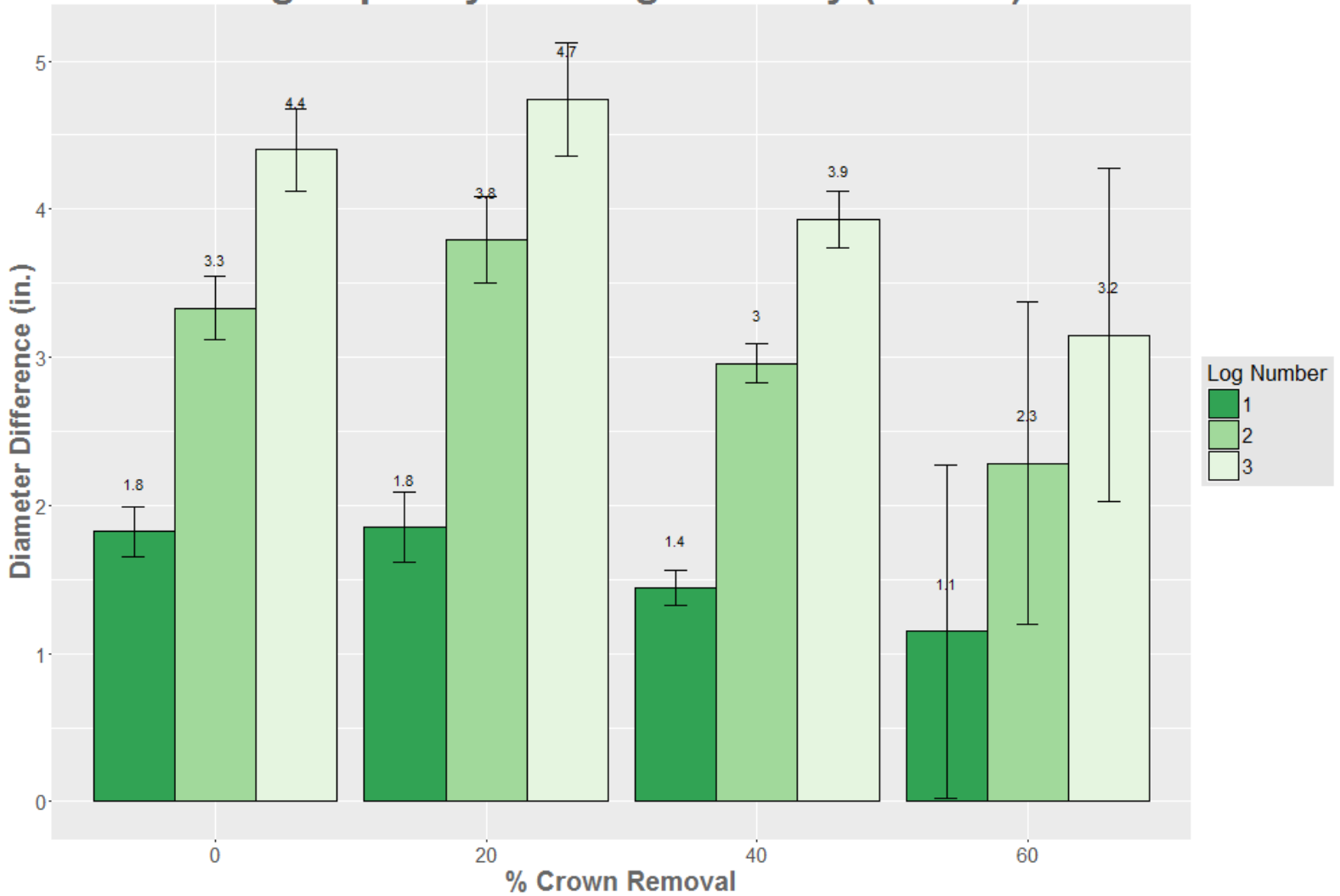
**Figure 8:** Periodic annual increment of breast height diameter by pruning intensity and thinning intensity in Type I installations. Periodic annual increment was defined as the mean inches per year diameter growth over the treatment years. 20% crown removal showed equivalent growth rates to the controls whereas the most intense 60% crown removal had reduced DBH growth rates. 40% crown removal showed a slightly reduction but nothing to be significant given the error bars ( $\pm 1$  SE) associated with it.

## Height PAI by Pruning Intensity



**Figure 9:** Height periodic annual increment over the treatments years by pruning intensity and thinning intensity in the Type I installations. Note the increased growth rates with less intense thinning in the controls (0% crown removal). Pruning tended to reduce height growth rates for the unthinned and thinned in half plots but interestingly enough increased height growth in the 20 and 60% crown removal at a 75% thinning intensity. Note: error bars are  $\pm 1$  SE.

## Log Taper by Pruning Intensity (ISPA/2)



**Figure 10:** Log taper by pruning intensity in 50% thinned plots (ISPA/2). Taper of the three logs was defined as the difference between DBH and the top diameter of each log. The general trend in the data indicate a reduction in the taper of all three logs with increasing percentage of the crown removed. Most error bars ( $\pm 1$  SE) tend to overlap across pruning intensities with the exception of the taper seen in the 1<sup>st</sup> and 2<sup>nd</sup> logs of the 40% crown removal.

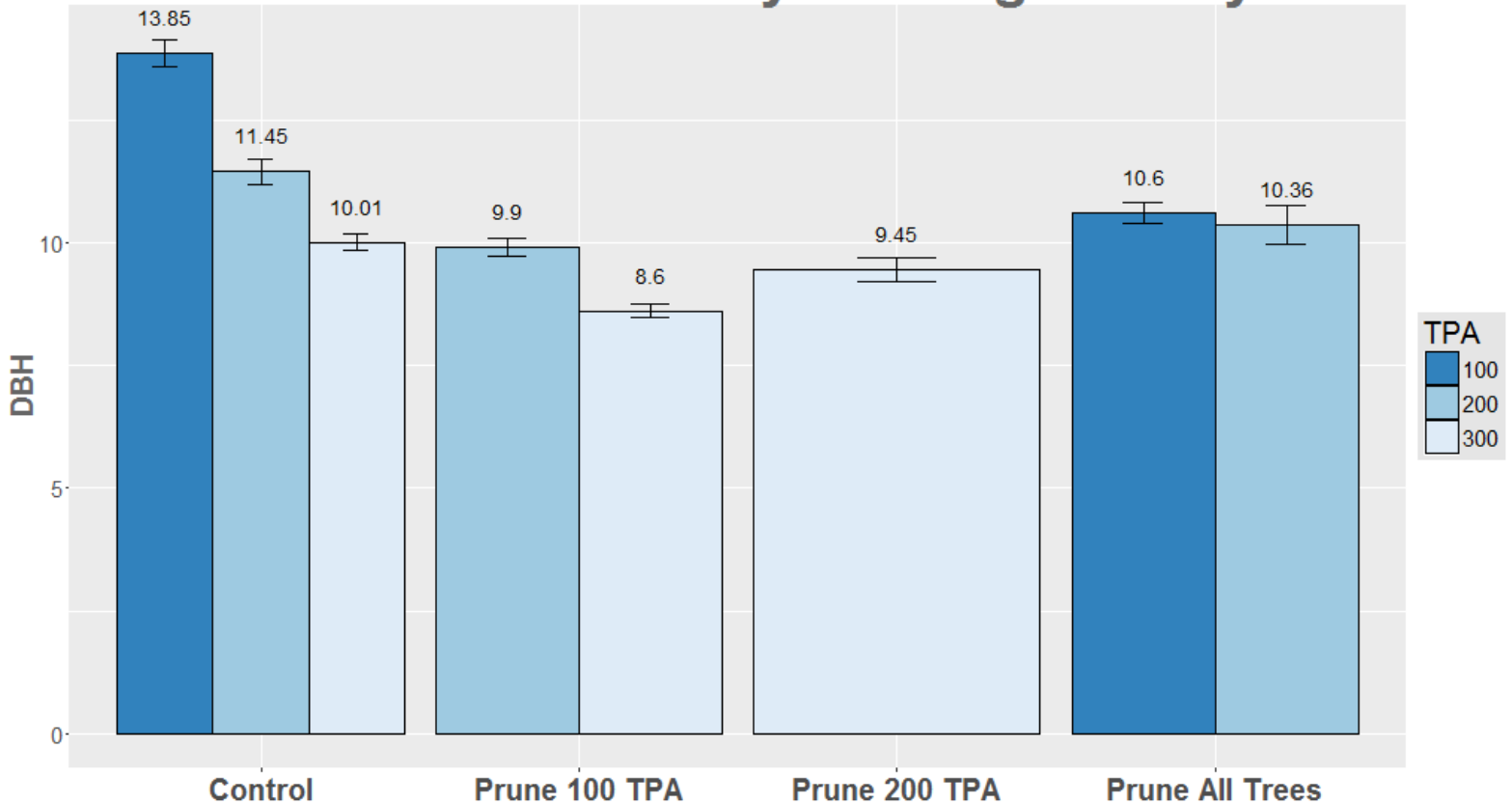
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## Type III: Diameter/Height Graphs

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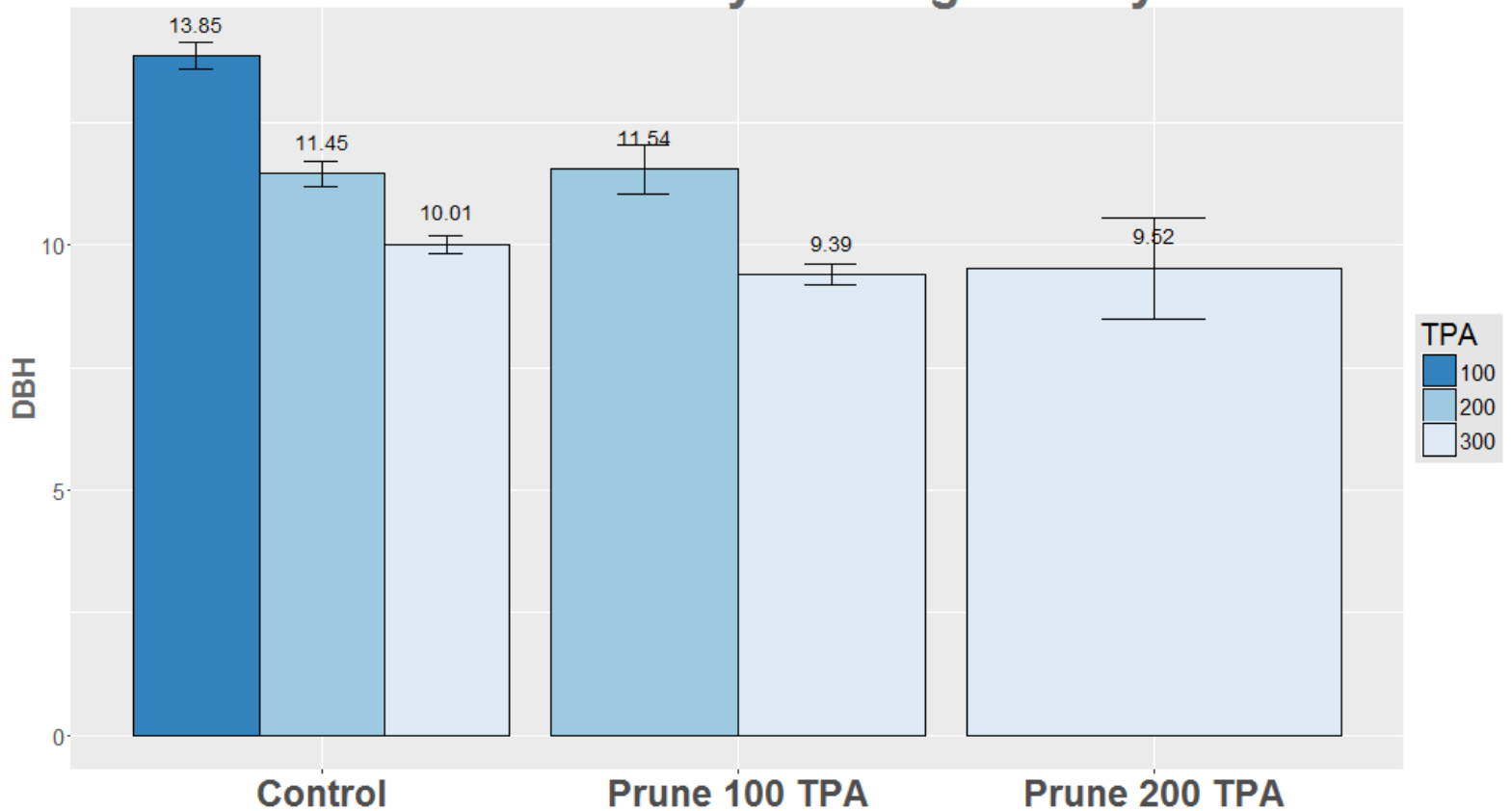
\*\*\* **Note:** Bar widths in the following graphs are just an artifact of the software and implicate nothing. \*\*\*

### Pruned Tree DBH by Pruning Density



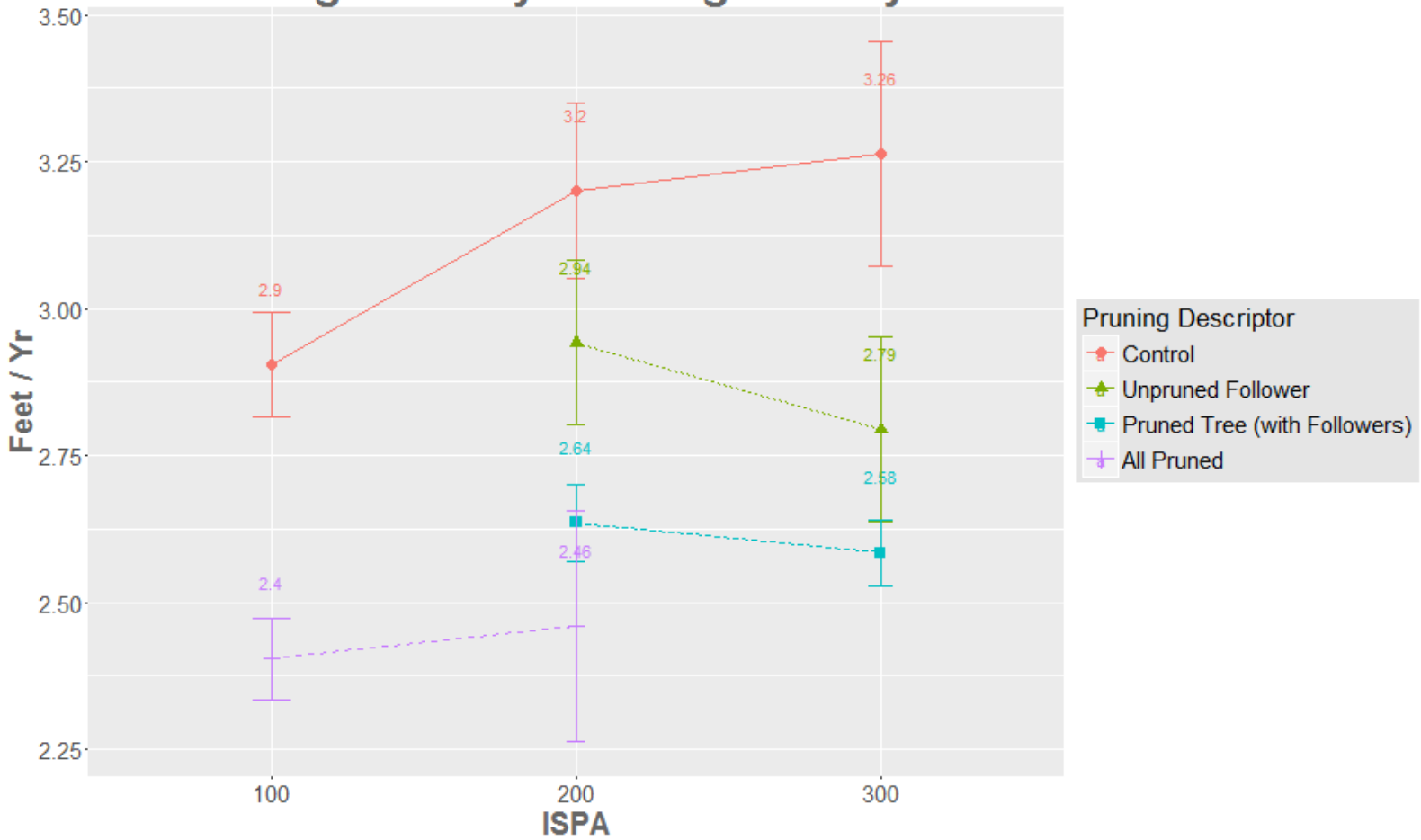
**Figure 11:** Type III pruned tree mean DBH by pruning density based on the raw Type III data. Overall pruning at this the Type III regime (50% crown removal up to a 22' foot lift) reduced diameter of all pruned trees, most drastically in the 100 TPA spacing. Note the difference in pruning intensity from the Type I, and pruning density. Here it refers to the number of trees pruned in the plot, not the percent live crown removed. Note as well the difference in pruned tree DBH of trees at the same planting density (TPA) but with different numbers of followers remaining. The best example of this is seen in the 300 TPA trees with a pruning density of 200 TPA vs. 100 TPA. Error bars are  $\pm 1$  SE.

## Followers DBH by Pruning Density

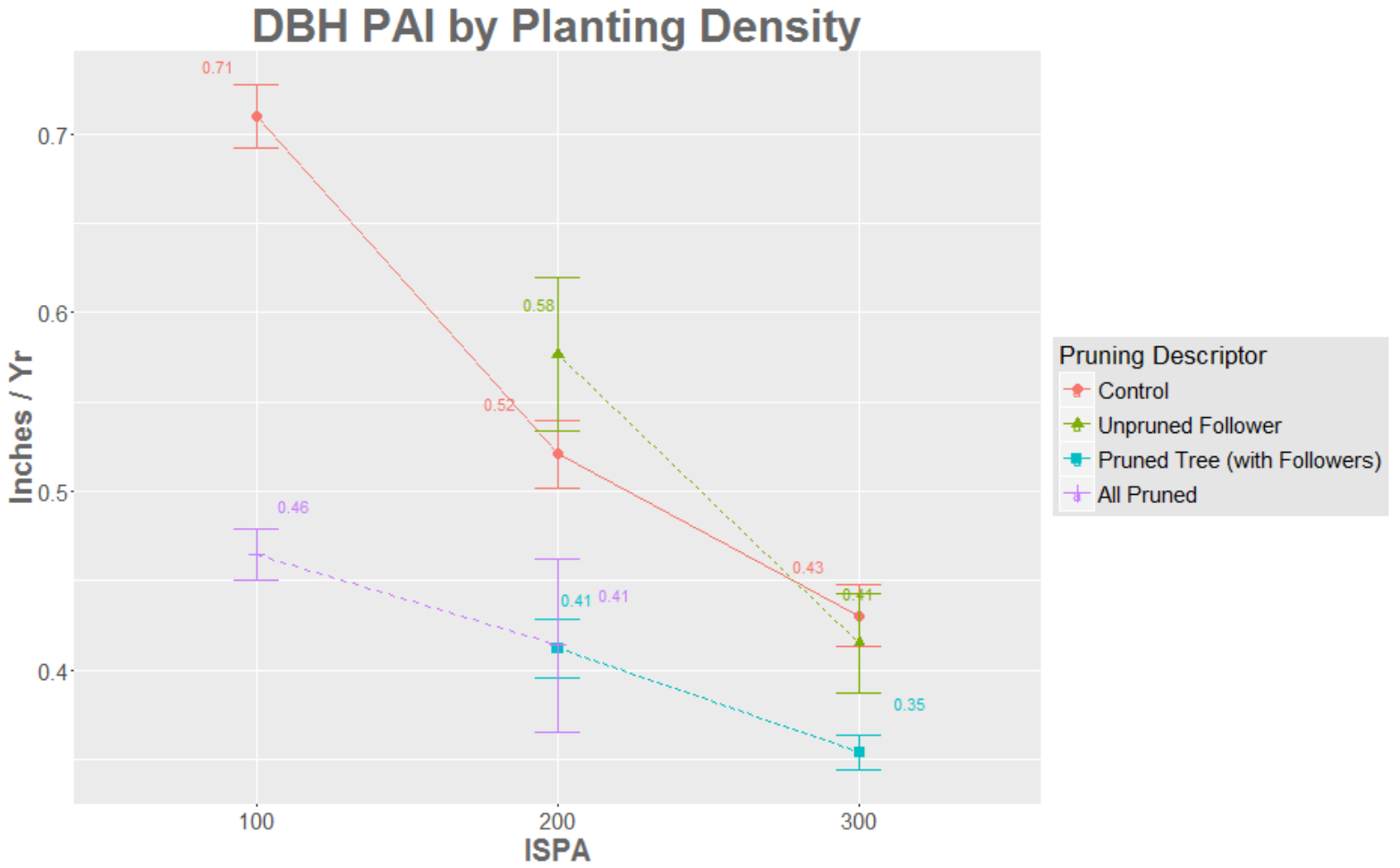


**Figure 12:** Mean DBH of the unpruned followers that remained in the pruned plots. Based on raw Type III data. For example, if 200 TPA were pruned on a 300 TPA plot then the figure presented is the mean of the 100 followers that remained unpruned (on a one-acre plot). Overall, the followers tended to have roughly equivalent diameters at breast height. The decrease seen in the 300 TPA plot with 200 followers compared to the 300 TPA plot with 100 followers is likely due to increased competition amongst the followers themselves. Error bars are  $\pm 1$  SE.

## Height PAI by Planting Density

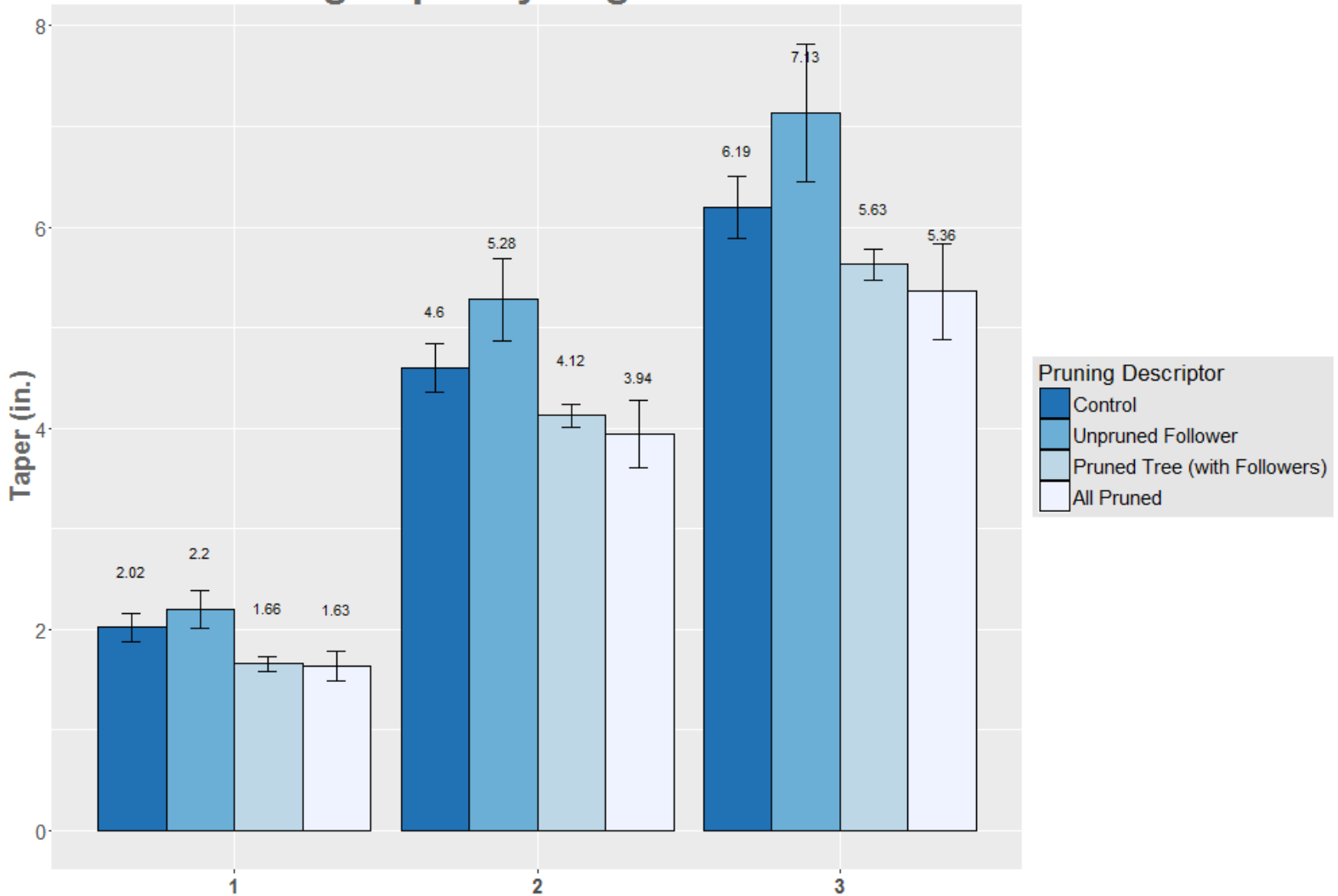


**Figure 13:** Mean feet per year of height growth over the treatment years in the Type III installations by planting density (ISPA) and factored by the pruning descriptor of the tree. Control and all pruned trees tended to increase in height growth rates as stand density increased whereas pruned and pruned w/ followers showed a reduction. Figure based on raw data. Error bars are  $\pm 1$  SE.



**Figure 14:** Mean inches per year of DBH growth over the treatment years in the Type III installations by planting density (ISPA) and factored by the pruning type. The overall trend is that with increasing density the DBH growth rate decreases. Control and follower trees have statistically identical growth rate whereas as a tree that received a pruning treatment (with followers present or not) has a lower DBH growth rate than any unpruned tree. Figure based on raw data. Error bars are  $\pm 1$  SE.

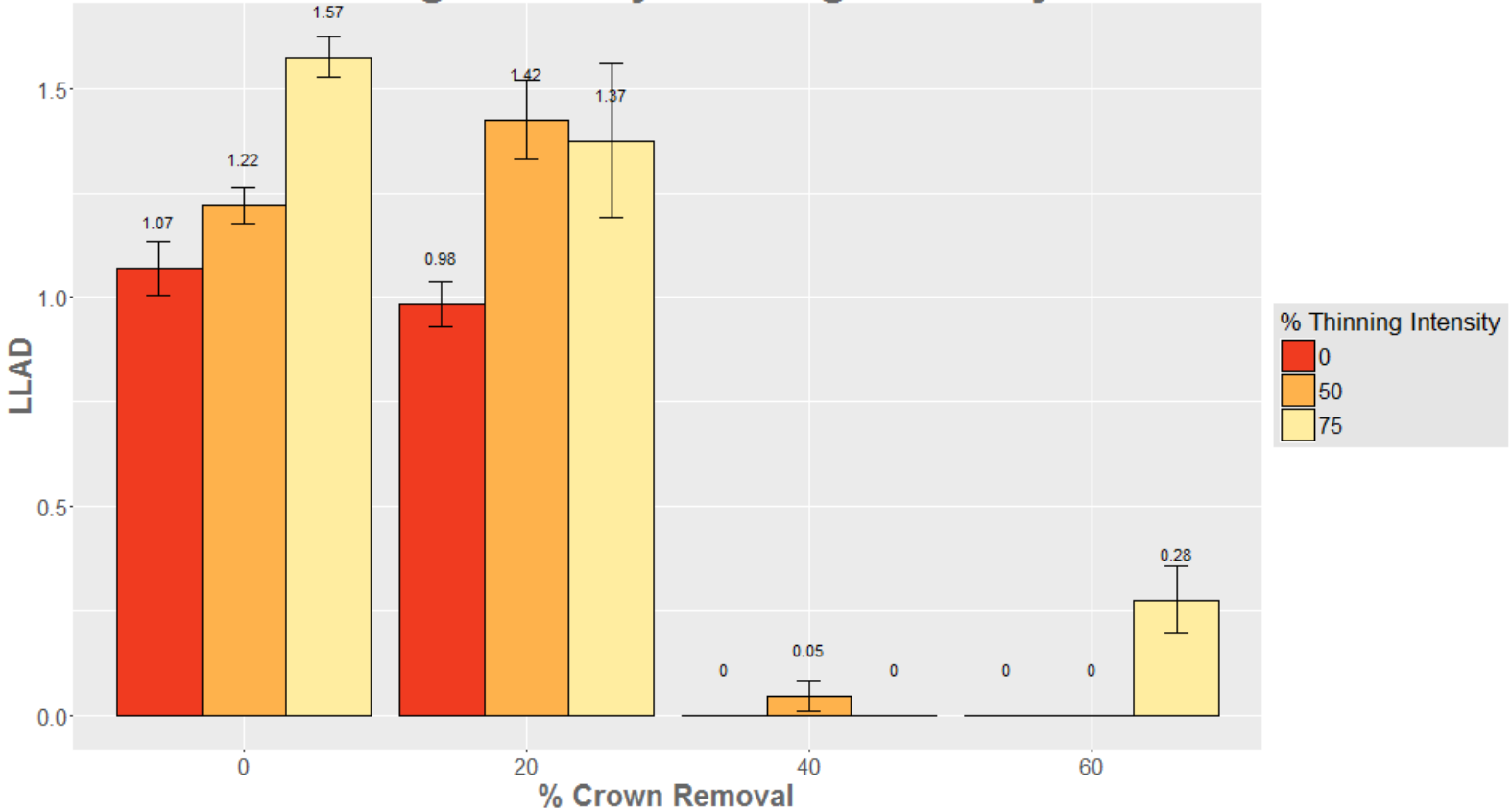
## Log Taper by Log Number



**Figure 15:** Mean log taper of each specific log by pruning descriptor averaged across the three stand densities. Followers show increased taper over the controls whereas both types of pruned tree show a reduction in taper. Further evidence that the followers are becoming “wolf trees” by having poor form and commanding the sites resources. Means of each pruning descriptor are averaged across (planted) stand densities as follows: Control (100,200,300 TPA), Followers (200 and 300 TPA), Pruned w/ Followers (200 and 300 TPA) and All Pruned (100 and 200 TPA). Error bars are  $\pm 1$  SE.

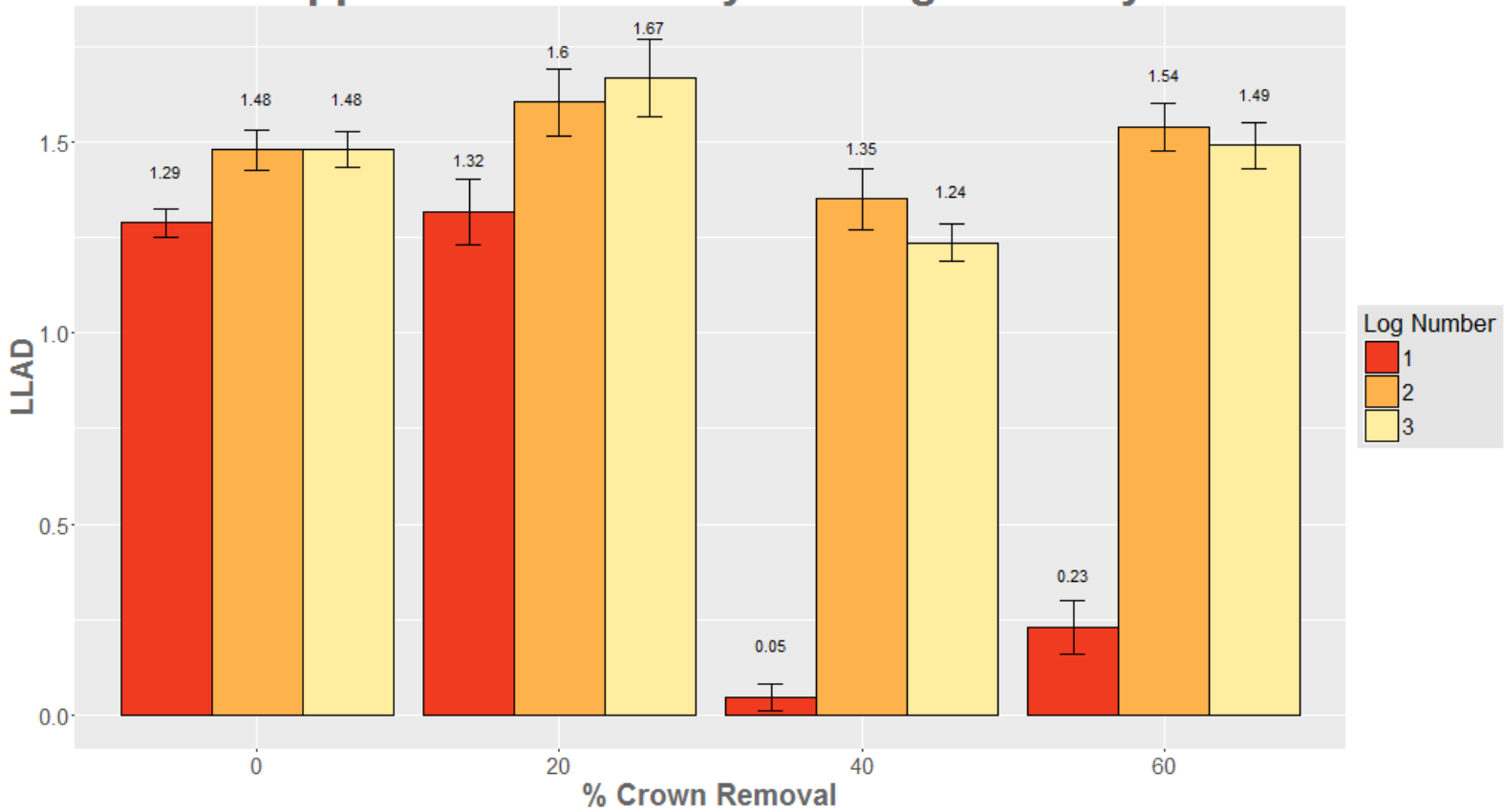
## Type I: Branch Diameters

### 1st Log LLAD by Pruning Intensity



**Figure 16:** First log (butt log) largest limb average diameter (LLAD) by pruning intensity and thinning intensity in Type I installations. Trees pruned with 20% crown removal tended to have equivalent LLAD at the initial spacing (ISPA), slightly larger LLAD than the controls at the 50% thinning intensity (ISPA/2) and slightly smaller LLAD at the plots with 75% thinning (ISPA/4). However, note that all differences were 0.2 inches or less. Note also that at 40 and 60% crown removal, the only branches to measure were epicormic branches, hence the small to nonexistent diameters shown. Evidence of increasing epicormic branch size and occurrence (likely) with increasing pruning intensity. Error bars are  $\pm 1$  SE.

## Upper Stem LLAD by Pruning Intensity



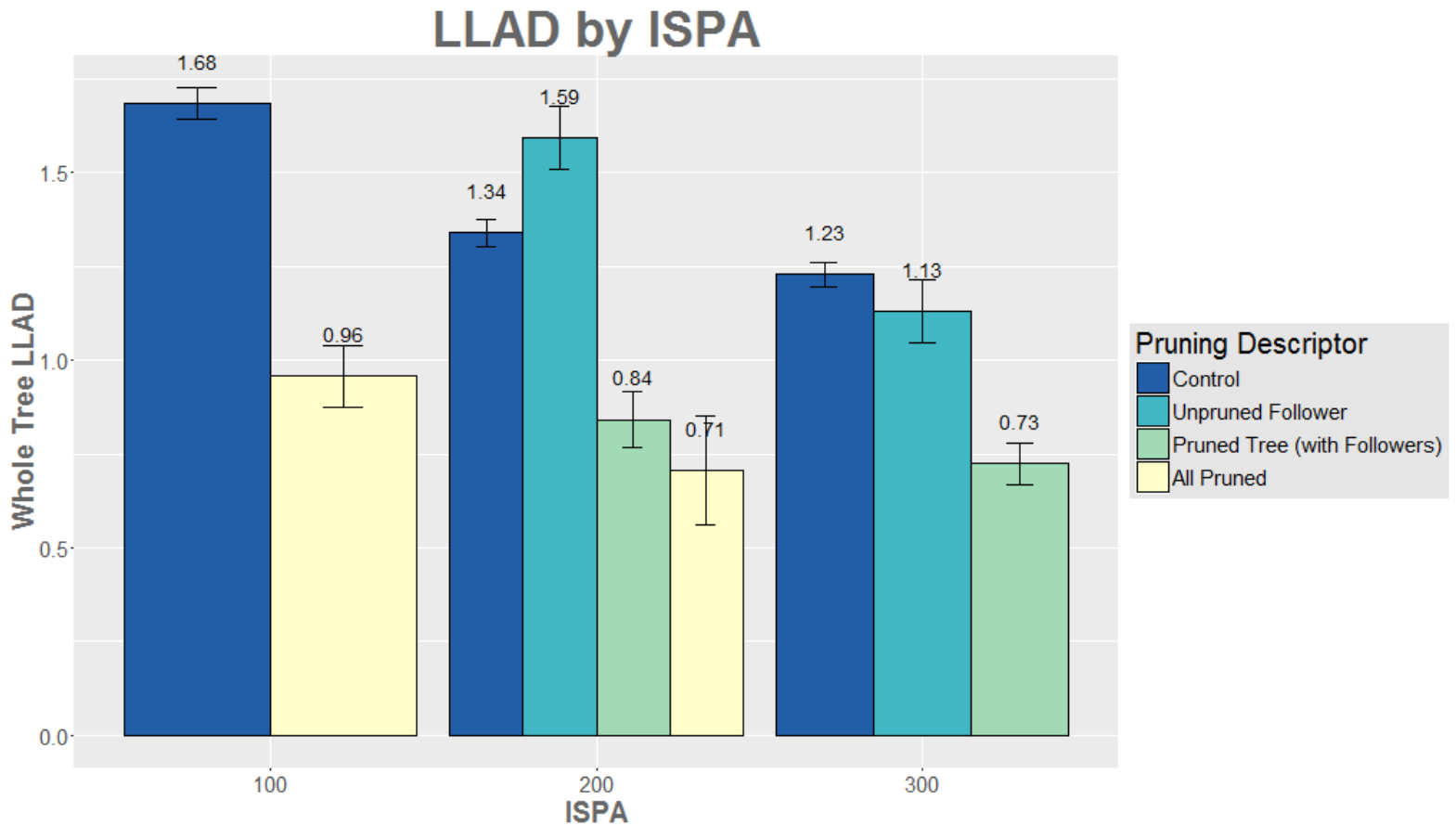
**Figure 17:** Upper stem LLAD of the three logs by pruning intensity, based on the raw data. Labels denote mean LLAD in inches. The largest increase in LLAD is seen in the 20% crown removal with an increase of 0.5 inches compared to the control; however, this increase is also associated with large error bars ( $\pm 1$  SE). Note this figure does not take stand density into account, therefore, shows that LLAD across all the thinning regimes. The small diameter branches size seen in the first logs of the 40 and 60% crown removal are simply epicormic branches that have sprouted since pruning. Error bars are  $\pm 1$  SE.

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## Type III: Branch Diameters

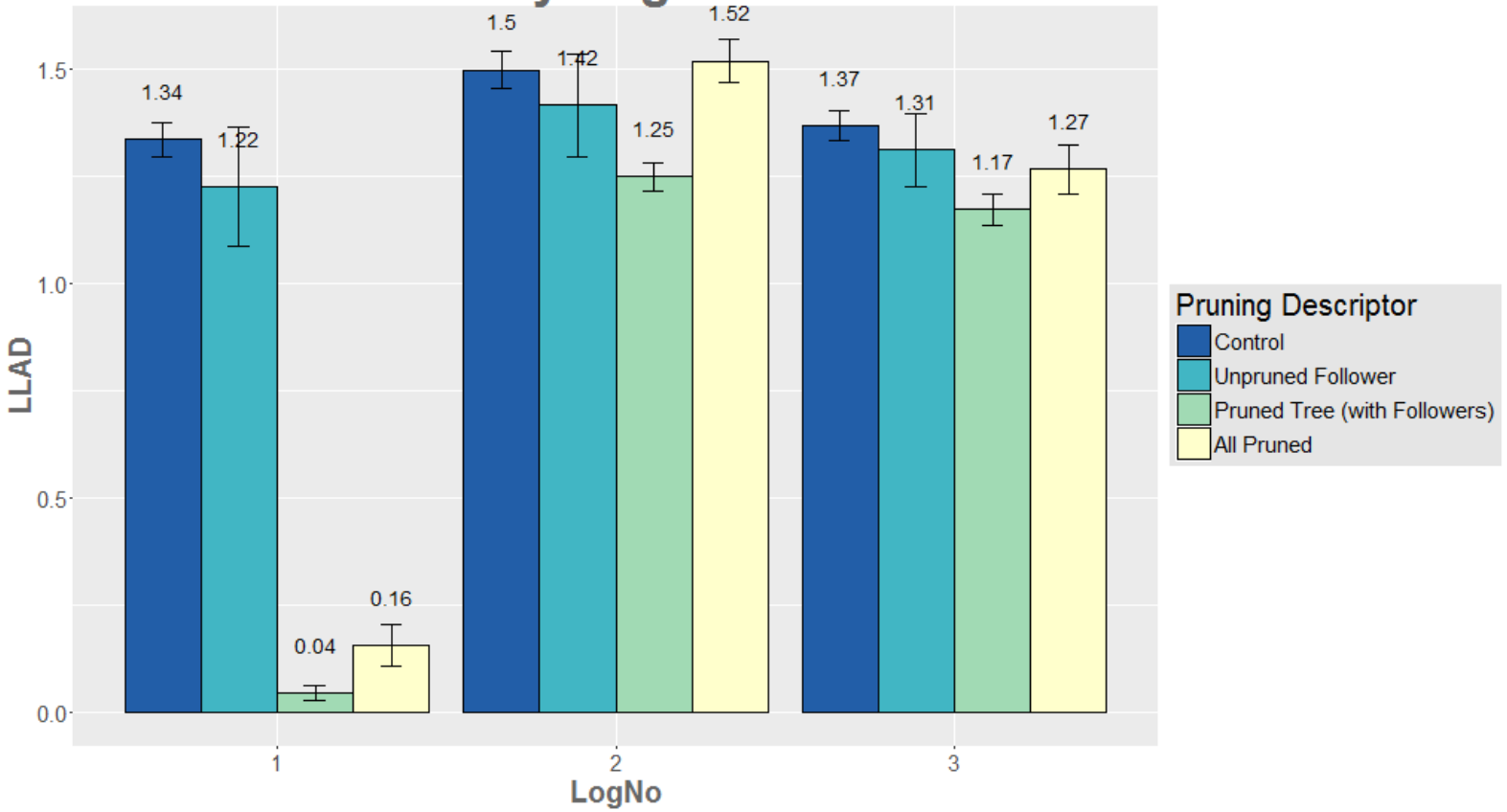
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\*\*\* **Note:** A figure showing pruned tree LLAD in the first log was uninformative in the Type III dataset as pruning eliminated all branches in that log except for epicormic branches. \*\*\*



**Figure 18:** Whole tree LLAD (average LLAD across the three logs) by initial stems planted per acre (ISPA). In general, branch size decreases with increasing density and the smallest branch sizes were seen in trees that had been pruned likely due to small or nonexistent branches in the first log with the Type III pruning regime. Note: This is not the typical way in which determine the quality of timber as each log is individually graded. However, the figure serves to show the overall differences in LLAD by pruning descriptor across varying densities which cannot be done without averaging the LLAD of the logs. Error bars are  $\pm 1$  SE.

## LLAD by Log Number

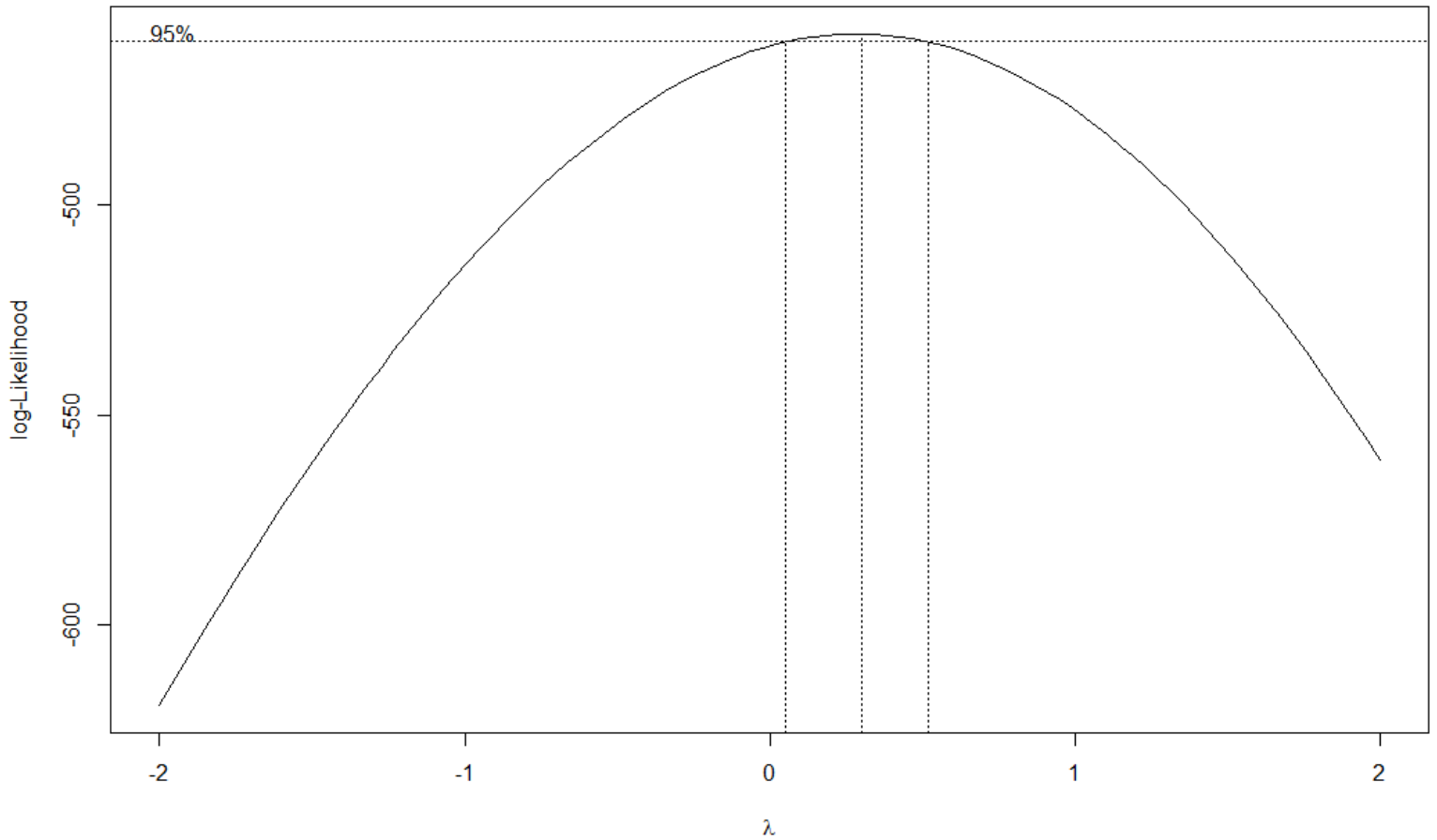


**Figure 19:** LLAD by log and pruning descriptor. Small LLAD in the pruned trees of the first log are due to epicormic branches following the complete removal of branches in that log. On average, the second log tended to have slightly larger branches than the first or third logs, however, the increase was only slight, 0.1-0.2 inches. Means of each pruning descriptor are averaged across (planted) stand densities as follows: Control (100,200,300 TPA), Followers (200 and 300 TPA), Pruned w/ Followers (200 and 300 TPA), and All Pruned (100 and 200 TPA). Error bars are  $\pm 1$  SE.

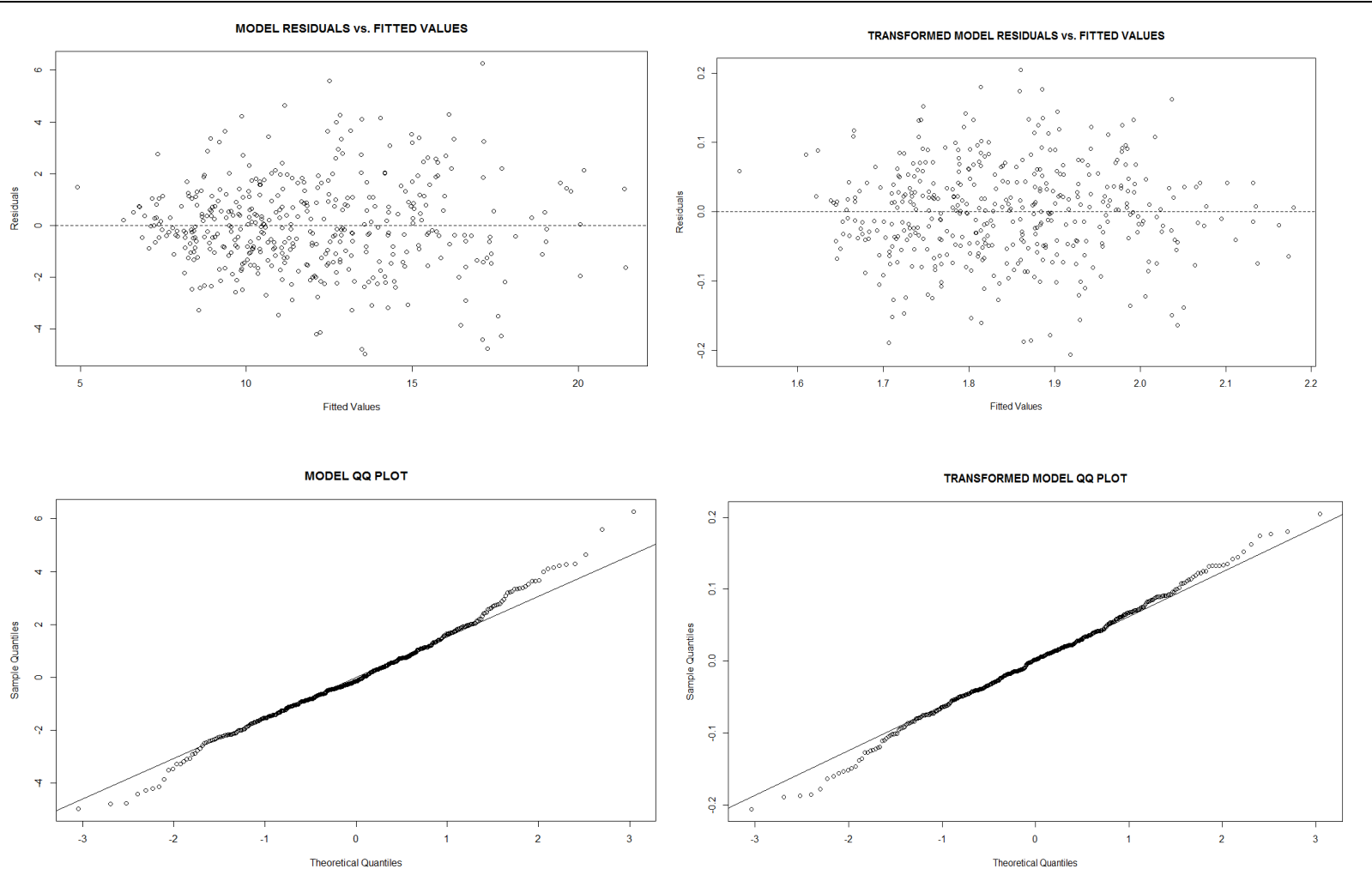
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## Model Figures

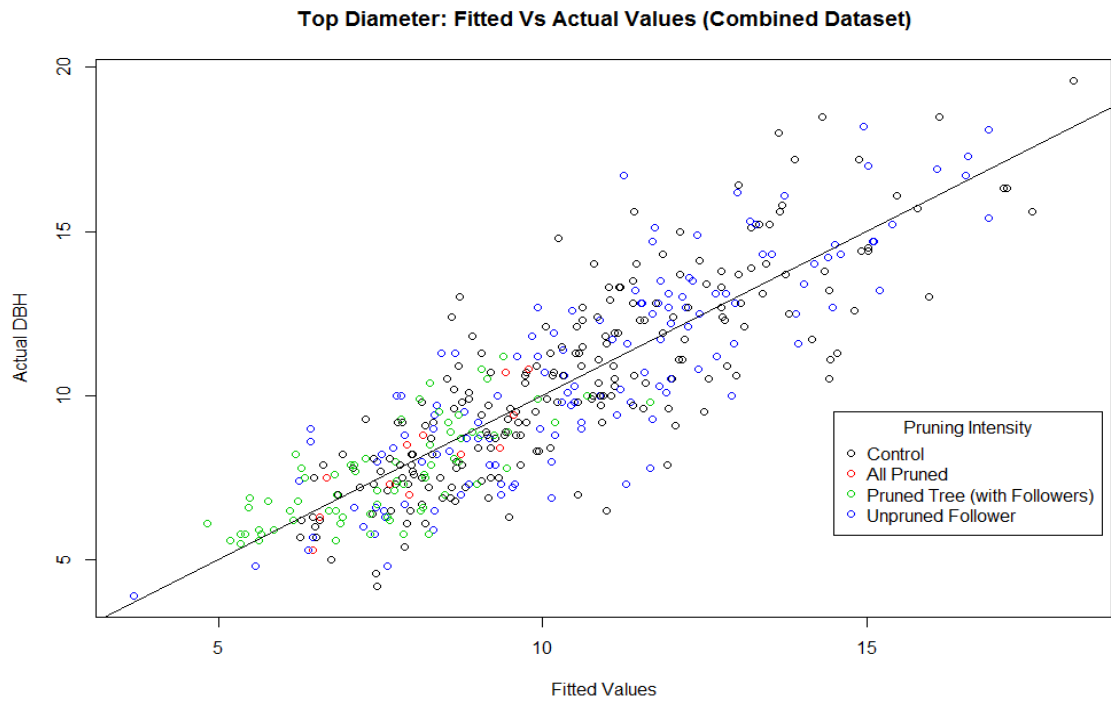
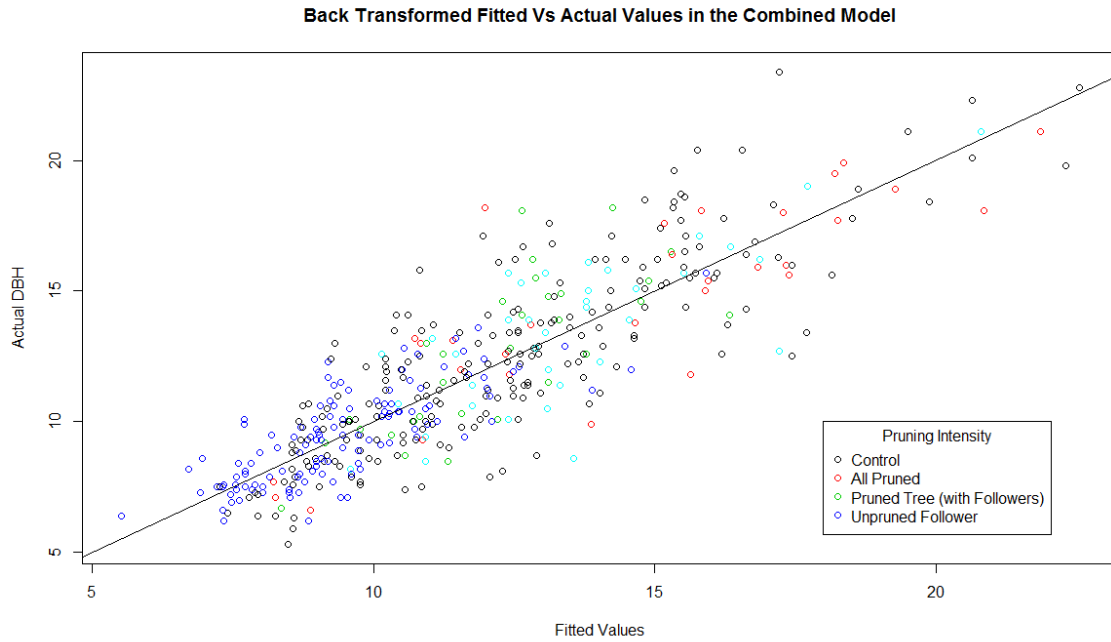
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**Figure 20:** Plot of the log-likelihood of the Box-Cox power transformation. The plot suggests that the model could benefit from a slight transformation to the  $\frac{1}{4}$  power.

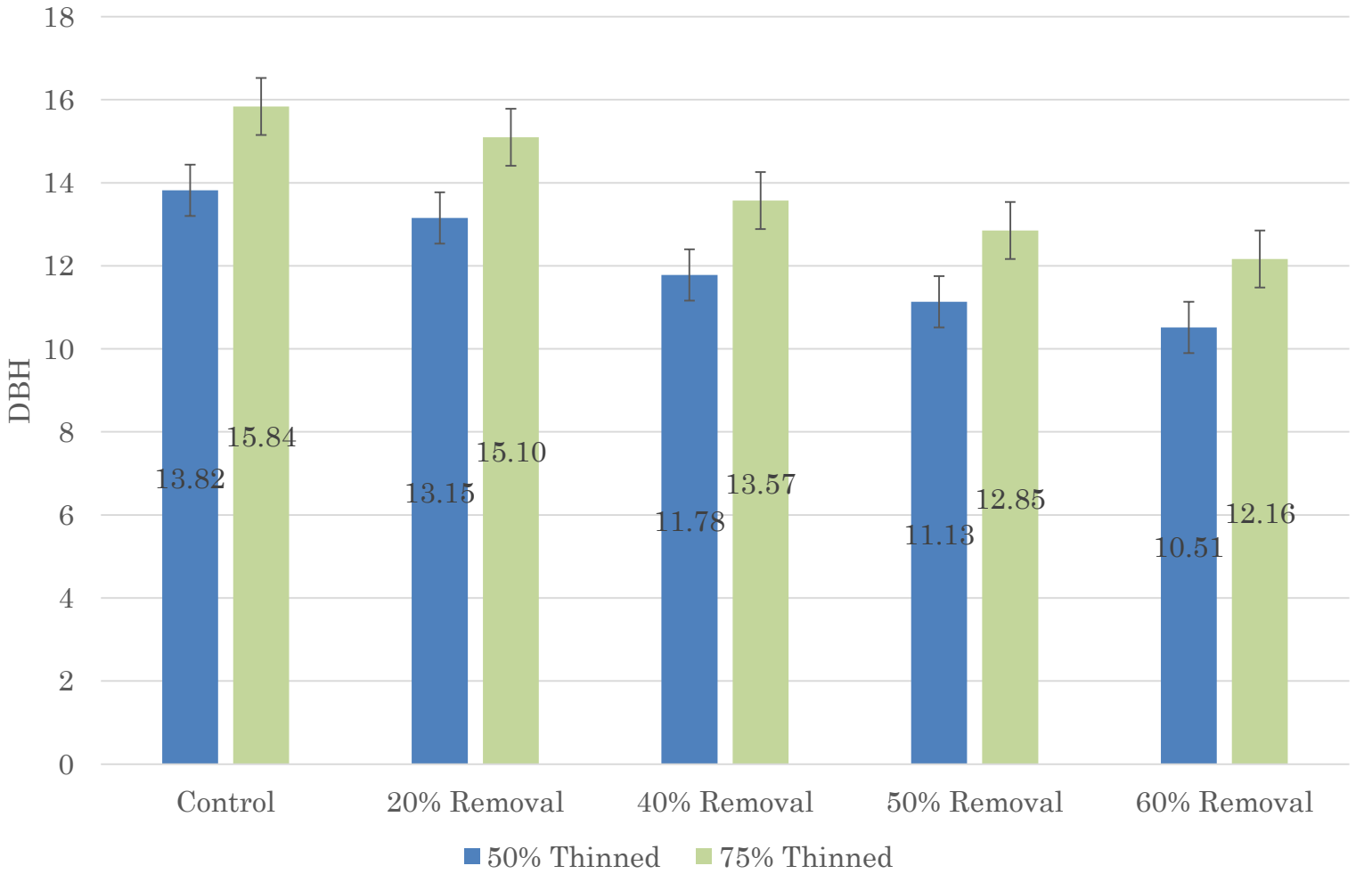


**Figure 21:** Comparison of the combined data (Type I and III) and untransformed (left) and transformed (right) model residuals (Observed-Predicted) and QQ plots. Model was transformed by taking the response variable (Dbh) to the 4<sup>th</sup> root and then refitted to the data.



**Figure 22: (Top)** Examination of the 1:1 line (Model fitted values Vs. measured DBH) for the transformed DBH model. Transformed fitted values were back transformed. No obvious patterns are apparent. **(Bottom)** Actual versus fitted values in the untransformed top diameter model.  $R^2$  is .751 for the DBH model and .7256 for the top diameter model.

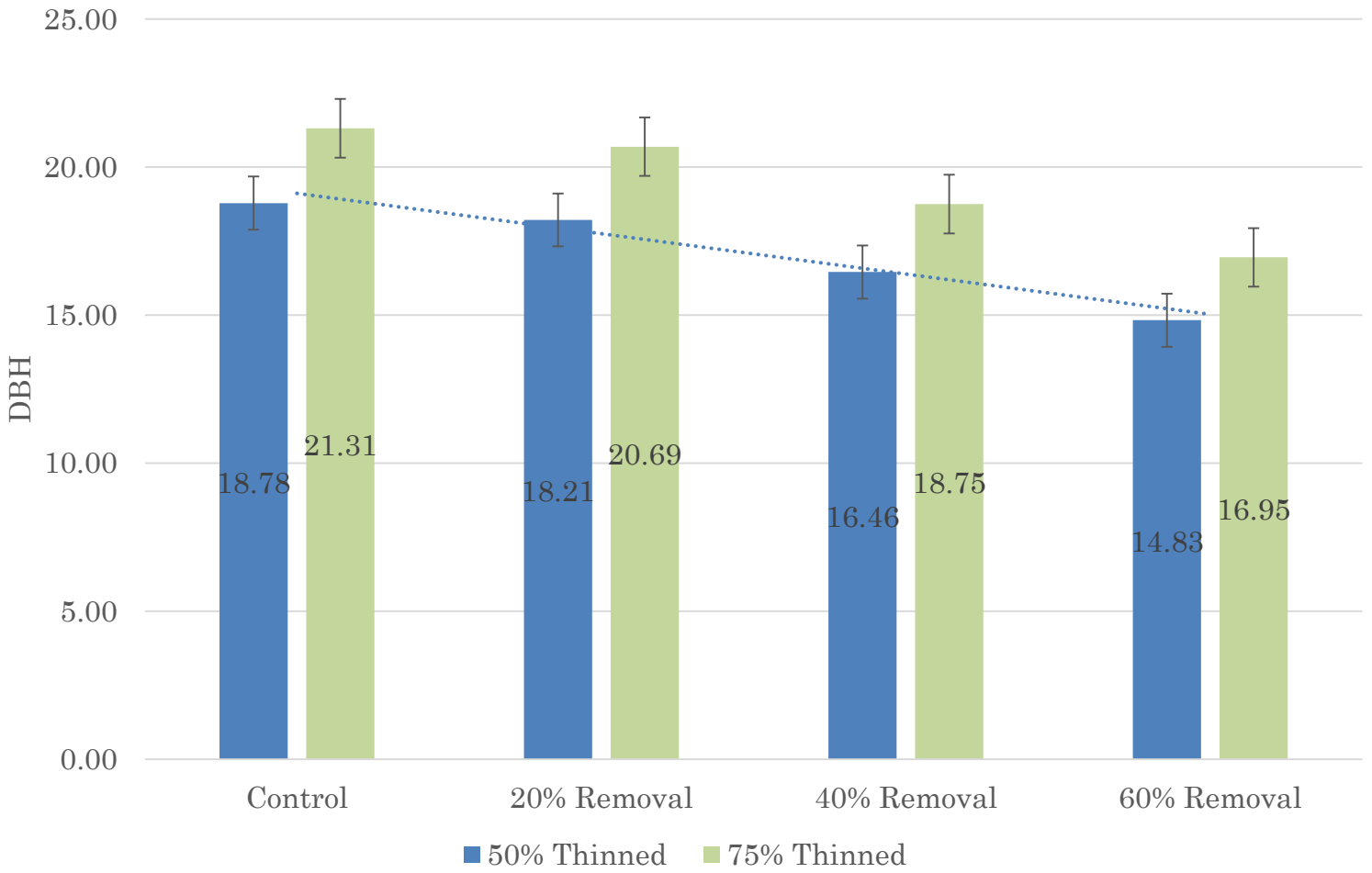
### Estimate of Current Pruning DBH Response



yrstrt	ISPA	stDbh	SDI	stAge	Dq
23	496	4.5	165	10	5

**Figure 23:** Using the model, current estimates were drawn based on holding all variables equal (chart below) and only changing pruning intensity. When the model accounts for all the variables, it estimates that pruning the live crown causes increasing reductions in DBH as the pruning intensity increases. Error bars are  $\pm 1$  SE.

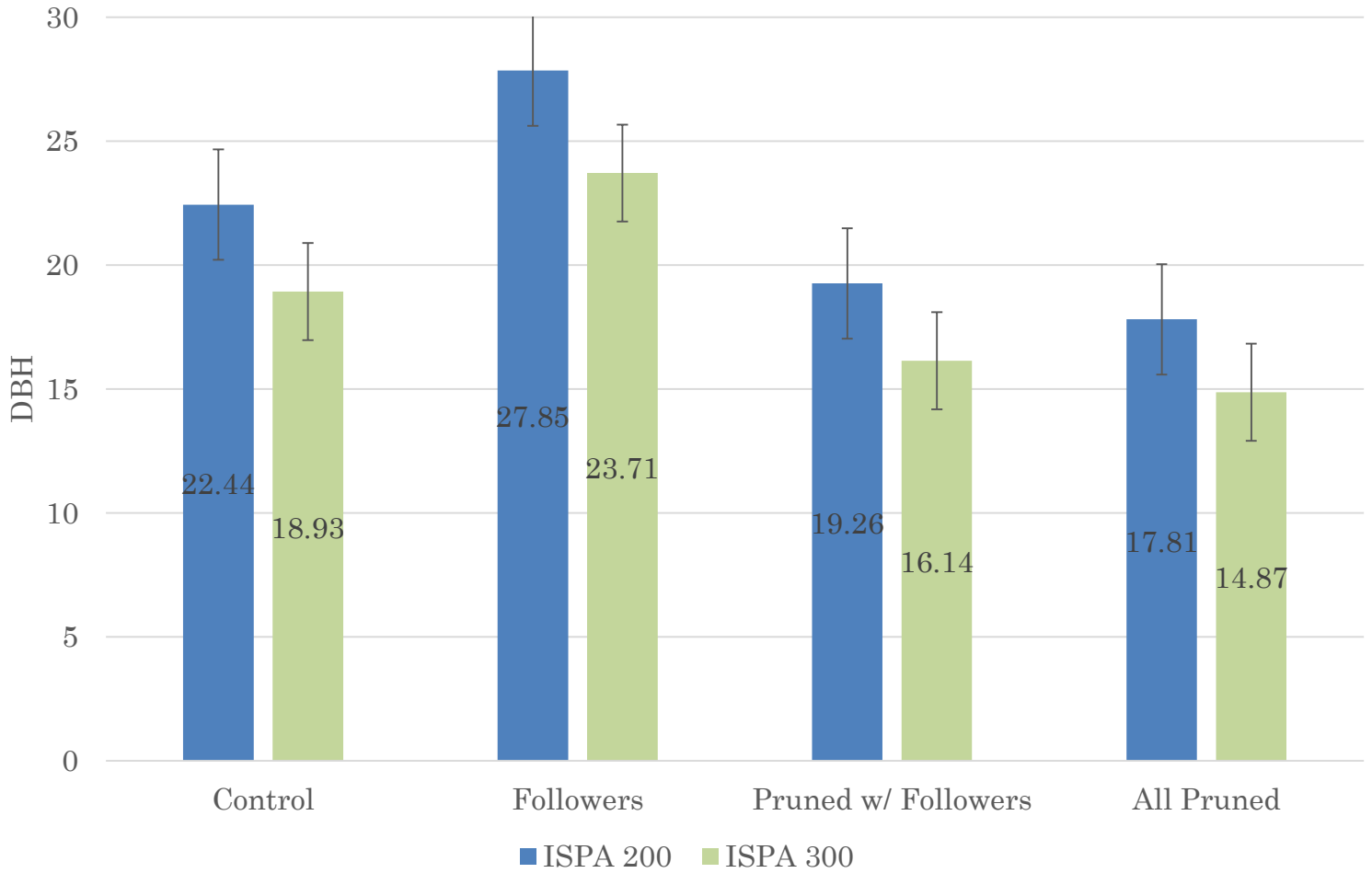
### 30 Year Post-Pruning Intensity Predictions: Stand Age 40



yrsTrt	ISPA	stDbh	SDI	stAge	Dq
30	500	5	165	10	5

**Figure 24:** Model DBH Predictions by increasing pruning intensity when density is held at ISPA/2 (blue) and ISPA/4 (green). Note the decreasing diameter predictions with increasing pruning intensity. Chart above details the values that were entered into the model. Error bars are  $\pm 1$  SE.

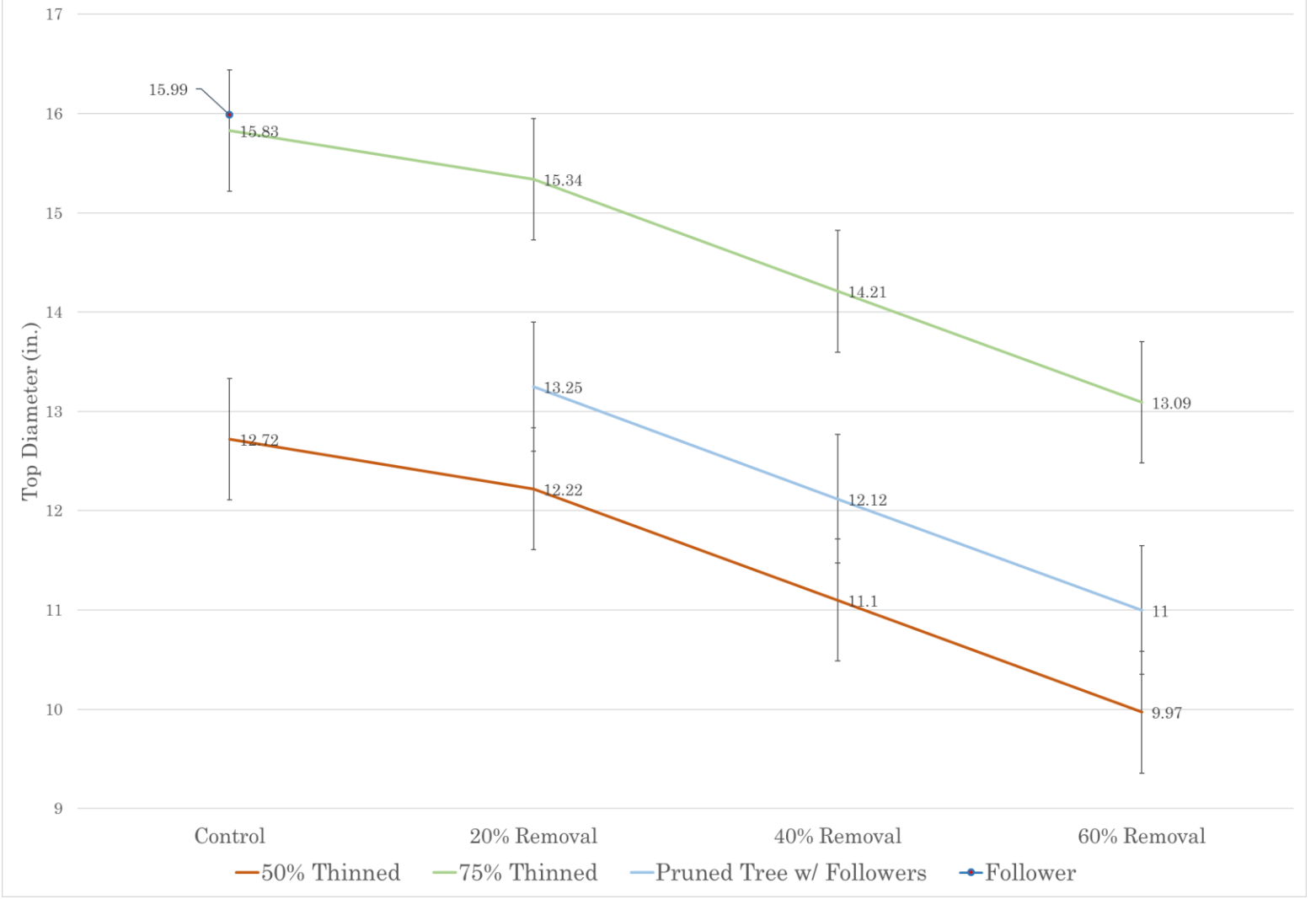
### 30 Year Post-Pruning Predictions: Pruning w/ Followers



yrsTrt	ISPA	stDbh	SDI	stAge	Dq
30	200/300	3.2	34.5	10	3.2

**Figure 25:** Dbh predictions of the transformed model after 30 yrs. of treatment. The followers tended to be significantly larger than the controls whereas the other pruning regimes were slightly reduced after 30 years since treatment. If a tree received a pruning treatment it was set to 20%. Chart above details the values that were entered into the model. Error bars are  $\pm 1$  SE.

### Model Predictions for Top Diameters of 1st Log



**Figure 26:** Linear model predictions for the top diameter of the 1st log based on current averages of the significant variables in the data (23 years since treatment at age 10). Note in general, with increasing pruning intensity the top diameter decreases. Evidence suggests that the reduction in taper is not enough to account for the loss in volume associated with the pruning treatment. An exception to this is seen in the 20% removal when pruning with followers. Here there is a slight increase in the top diameter, possibly due to either the effect of the followers or due to error in the model predictions as this combination was not actually measured in the field.