AN ABSTRACT OF THE THESIS OF

Heidi S. Roe Goracke for the degree of Master of Science in Forest Resources presented on January 15, 2010.
Title: Temporal Effect of Vegetation Management on Growth and Wood Quality of Conifers in a Western Oregon Plantation.

Abstract approved:

Robert W. Rose

Concern over the increasing proportion of juvenile wood grown in second-growth plantations has led to a large amount of research on the effects of common silvicultural practices on wood quality. Lacking is research on the effect of timing and duration of vegetation control on wood quality near the pith of young trees. This study was designed to quantify differences in specific gravity, ring width, percent latewood, biomass increment and eight-year diameter growth of Douglas-fir seedlings among different vegetation control regimes applied over the first five years of stand establishment. Largest year-eight volumes were observed in plots having five consecutive years of vegetation control, resulting in 239% more volume than control plots with no vegetation control. Mean specific gravity values ranged from 0.41 to 0.45 in rings 3, 4, and 5 from the pith and from 0.37 to 0.41 in rings 6, 7, and 8, with no significant treatment effect. Average ring width increased with increasing years of

vegetation control for both ring segments, reaching consistent lengths of approximately 30 mm after three years of initial treatment. Percent latewood decreased with increasing years of vegetation control, ranging from 3.73% to11.13% in rings 3, 4, and 5. No significant treatment effect was observed for percent latewood in rings 6, 7, and 8, indicating consistent ring width production over time. Biomass increment was significantly affected by treatment, increasing by a maximum of 376% with increasing intensity of vegetation control. The lack of significant differences in specific gravity among treatments and the significant gains in volume and biomass from a greater intensity of vegetation control suggests a lack of adverse impacts on wood quality. Future silvicultural treatment and age at the time of harvest will likely have a more significant influence on the end-use quality of the wood.

Temporal Effect of Vegetation Management on Growth and Wood Quality of Conifers in a Western Oregon Plantation

by
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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented January 15, 2010
Commencement June 2010

Master of Science thesis of Heidi S. Roe Goracke presented on January 15, 2010.

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Heidi S. Roe Goracke, Author

ACKNOWLEDGEMENTS

I would like to begin by recognizing the Lord's incredible plan and design. It is because of His guidance and grace that I have been given this opportunity. I have met many wonderful people through my adventures in graduate school and I am thankful for every one of them. I am especially thankful for those who have taken an interest in me and helped guide me along the way. Thank you to Robin Rose for taking a chance on me and being the mentor I needed to succeed. Thank you to the rest of my committee as well for your contribution and support: Doug Maguire, Jennifer Kling, and Hannah Gosnell. Thank you to Eric Dinger for his constant availability and contagious enthusiasm when I needed a fresh perspective. The members of the VMRC are owed tremendous thanks for their consistent contribution to my research and academic success. Without their provision, I would not be here today. Thank you also to my fellow grad student friends, you know who you are, for being there to identify with, study with, and laugh with over the years. Thank you so much to Sean Smith, Crystal Perez-Gonzalez, Heidi Leib, Rebecca Burson, Nick Dellaca, Janine Burgess, Mike Collier, and Monica Ramirez for braving the cold and wet to help with my data collection and for offering your moral support. Finally, I thank my family, especially my mom, dad, Jeremy, Laurie, and my wonderfully patient husband, Paul for believing in me and praying for me through it all. Thank you from the bottom of my heart!

CONTRIBUTION OF AUTHORS

Robin Rose assisted in the development of procedures and design of the experiment. Eric Dinger also assisted in the development of procedures and approach to data collection. Scott Ketchum was involved in the study design and implementation of the experiment. Doug Maguire, Jennifer Kling, and Eric Dinger were helpful in offering assistance with statistical approach.

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CHAPTER 1.0 – LITERATURE REVIEW

1.1 Overview of critical period of weed competition and vegetation control

Vegetation management is the manipulation of plant presence and abundance to meet specific management goals, and includes the practice of weed control or suppression of non-crop plants, for enhancing the production of crop plants (Walstad and Kuch 1987; Radosevich et al. 1997). Weeds have been categorized as plants growing in a place where they are unwanted or where they interfere with the growth of a crop plant or tree (Harper 1960; Salisbury 1961; King 1966). The objectives and perspectives of the person managing the land determine plants that are considered weeds (King 1966; Walstad and Kuch 1987). The concept that certain plants are undesirable is even mentioned in the Bible in Genesis 3:18 when God says "…thorns and thistles it shall bring forth to you." The struggle between humans and weeds dates back to the earliest farmers, (Smith and Secoy 1976; Derpsch 1998) even though earliest experimentation on the detrimental effect of weeds on crop plant yields was not documented until the work of Jethro Tull in the early 18th century (Smith and Secoy 1976). Weed interference with the production of crop plants has been well documented, and much research is devoted to the interaction between weeds and crop plants, as well as mitigation of this effect.

The concept that there is a period of time during which weeds should be controlled in order to prevent significant losses to crop yield is known as "the critical period concept." Zimdahl (1988) considered the critical period to be the time period during crop development when interspecific competition between weed and crop plants is particularly acute. This concept was first developed for agricultural application in the late 1950s to early 1960s (Nieto et al. 1968). Nieto et al. (1968) studied corn under differing levels of weed infestation in Mexico, suggesting that weeds should be controlled during the first 35 days after planting to achieve maximum corn yields. This time period was termed as the "critical period for competition," and from this, it was realized that development of the critical period concept could aid managers in applying herbicides according to specific crop needs, to ensure that weeds were controlled purposefully and economically (Nieto et al. 1968). Weaver and Tan (1983) further developed the critical period concept for tomato crops when they identified two components of the critical period; the length of time weed control should be maintained in order to reduce loss in crop yield and the length of time weeds can be present before causing unacceptable reductions in crop yield.

The critical period concept first appeared in forestry literature in the late nineties when Robert Wagner tested the concept on four conifer species in northern Ontario, Canada (Wagner et al. 1996). An objective of Wagner's (2006) study was to determine the time of equal interference, i.e. the point of intersection between the weed-infested and weed-free curve when crop yield loss from interspecific competition is the same on both curves (Wagner and Robinson 2006). The results of Wagner and Robinson (2006) for several species were similar to those found by the Vegetation Management Research Cooperative (2008) for two conifer species in

Western Oregon, where the number of years of weed control rather than the timing of application (immediate vs. delayed) had a stronger influence on volume growth. Essential to identifying the critical period is observation of the growth response of seedlings to weed-free and weed-infested environments over a several year period (Rosner and Rose 2006, Wagner et al. 1996).

Earlier studies on height, diameter, and stem volume increment in the initial years of stand development (Cole and Newton 1988; Cole et al. 1989; Creighton et al. 1987; Newton and Preest 1988; Walstad and Kuch 1987), helped to focus research on optimizing seedling growth response during the establishment period and explored the use of herbicides for releasing seedlings from competition. Studies were conducted on a variety of facets including area of weed control (Cole and Newton 1989; Oester et al. 1995; Rose and Rosner 2005), fertilizer-vegetation control interactions (Rose and Ketchum 2002), vegetation management regime comparisons (Balandier et al. 2006; Dinger 2006; Lauer et al. 1993; Richardson 1993), and interaction between vegetation control and seedling size (Long and Carrier 1993; Rose and Ketchum 2003; Rosner and Rose 2006). These studies were designed to identify the elements essential to achieving forest regeneration goals. Common to all these studies was the conclusion that herbicides effectively reduced weed cover to give the desired crop trees a temporary competitive advantage during the critical period of establishment in the presence of interspecific competition (Dinger 2006).

1.2 Wood production

The concept of secondary growth was formed in the 1700's and further confirmed in the 1850's by Thomas Hartig (Fraser, D. 1952). Priestley (1935) and Avery et al. (1937) expanded on this concept further to explain that wood production begins in the spring at the apex of the stem and is directly related to the swelling of newly formed buds. Within these newly forming buds are growth hormones, or auxins, which trigger cambial growth from the top to the bottom of the stem (Snow 1935; Bailey 1952). It is known that high auxin levels produced in the terminal shoot and active buds are associated with large diameter, thinner-walled cells (Larson 1962; Larson 1969; Koch 1972; Megraw 1986; Zobel and van Buijtenen 1989). These cells, also known as tracheids, are developed early in the growing season and are thus part of the earlywood zone of cell formation. As the season progresses and environmental conditions vary, auxin levels decrease and moisture levels decrease, reducing cambial division and causing smaller-diameter, thicker-walled cells to be produced in conifers (Koch 1972; Jozsa and Middleton 1994). This zone of cell formation is known as latewood because it occurs in the later part of the growing season. Production of latewood cells begins at the base of the stem, farthest from the source of auxins, and progresses up the stem toward the apex as moisture stress increases and movement of auxins down the stem decreases (Koch 1972; Clark and Saucier 1989). Larson (1969) describes earlywood formation as the period when radial expansion is favored over secondary wall thickening and latewood formation as the period when secondary wall thickening is favored over radial expansion.

The mechanism that triggers latewood formation is still debated in the literature. Some studies have looked into the timing of crown and leader growth cessation in relation to transition to latewood formation (Larson 1969; Jayawickrama et al. 1997; Jozsa and Middleton 1994; Larson et al. 2001; Renninger et al. 2006). Renninger et al. (2006) measured height and transition to latewood of 14 Douglas-fir (*Pseudostuga menziesii* (Mirb.) Franco) trees after they reached age five. They found there to be no correlation between timing of leader growth cessation and initiation of latewood formation. Their results suggest that the timing of transition is not dependent on the development of the leader, but rather on foliar development in general. They also recognize that temperature, photoperiod, and precipitation also influence both leader growth cessation and transition to latewood. According to Larson (1969), the most important thing to understand about earlywood and latewood development is the crown-stem relationship and that events occurring in the crown, regardless of the cause, determine the pattern of wood formation on the stem.

Wood closest to the active crown and pith has been referred to as juvenile wood, pith wood, the juvenile core (Burdon et al. 2004), or as Trendelenburg termed it in 1935, crown-formed wood (Paul 1957). Juvenile wood is generally characterized by shorter fibers, larger micro-fibril angle, lower cellulose content, and lower density, depending on species. Gradually increasing trends of wood density from pith to bark have been reported most often in southern pines but also for Douglas-fir (McKimmy 1959). Several reports of an initial decreasing trend from the pith for several years, followed by a gradual increase have been reported as common for species such as fir, hemlock, spruce, cedars, and ponderosa pine (Zobel and van Buijtenen 1989; Koch and Fins 2000). This trend has been reported for Douglas-fir as well, (Megraw 1986; Jozsa et al. 1989; Abdel-Gadir et al. 1991) emphasizing the fact that no rule is steadfast and exceptions do exist. The characteristics of juvenile wood are generally unfavorable because they result in wood with low strength and high longitudinal shrinkage (Megraw 1986; Jozsa and Middleton 1994). Juvenile wood has generally been assigned to the first 10-15 rings of growth in radiata pine (*Pinus radiata*) (Cown et al. 1991) and the first 15 to 30 rings in Douglas-fir (Jozsa and Middleton 1994). The actual number of rings from the pith where the transition from juvenile wood to mature wood occurs varies widely by species, genetic makeup, and environmental conditions (Zobel and van Buijtenen 1989; Jozsa and Middleton 1994); thus the transition from the juvenile phase to the mature phase is said to be a function of distance from the active live-crown and/or age from the pith (Zobel 1959; Larson 1969).

In young trees with live branches growing along the stem all the way to the ground, radial growth is allocated along a gradient depending on longitudinal distance from the active crown and the time period in which it was formed (Jozsa and Middleton 1994), also defined by radial distance from the pith. As the lower branches die off or become less vigorous, the active crown moves up the stem and a greater proportion of wood having more mature characteristics (higher specific gravity, longer tracheids, decreased fibril angle, and increased uniformity) is produced in the lower part of the stem. Zobel and van Buijtenen (1989) emphasized that lower density juvenile wood is produced near the pith regardless of the growth rate in order to clear up the misconception that all fast grown wood has low density. Because of the concern over quality and extent of juvenile wood proportion influencing production of end-use products, Abdel-Gadir et al. (1993) developed a method of analysis of radial patterns in wood properties for the purpose of estimating the age of transition from juvenile to mature wood in Douglas-fir using piece-wise regression. X-ray densitometry was used to obtain density-profile data from increment cores taken at breast-height from 360 Douglas-fir trees (ages 38-50) in western Oregon. The results of the piece-wise regression analysis of ring density showed the onset of mature characteristics ranging from 15 to 38 rings from the pith. This range was found to fluctuate when the same model was applied to other tree ring components such as latewood proportion, earlywood density, or ring width, but the usefulness of the model in recognizing the transition from juvenile to mature wood is still evident.

A reduced proportion of wood with juvenile characteristics is desirable for certain end use products because of the large impact this type of wood can have on the mechanical properties of solid wood (Koch 1972; Green and McDonald 1997), thus it is important to understand the characteristics of juvenile wood and their effect on different end use products (Zobel and Jett 1995). Because it is assumed that juvenile wood does not have the desired characteristics, Zobel and Sprague (1998) and Jozsa et al. (1989) suggest the obvious way to achieve a reduced proportion of juvenile wood core is by extending the age of harvest. Bendtsen (1978) emphasized the importance of tree improvement research, improved screening systems for identification of trees with desirable mechanical properties, and changing end-use processing requirements.

1.3 Definition and importance of wood quality

According to the literature, wood quality is defined by the context of its end use (Briggs and Smith 1986; Jozsa and Middleton 1994; Haygreen and Bowyer 1996). Wood quality is the term used to describe the combined attributes for a particular wood product. The attribute referred to as wood density, also known as relative density or specific gravity, is of similar importance for all contexts of wood use because of its direct relationship to strength, stiffness, hardness, thermal conductivity, shrinkage, machinability, pulp yield, and paper making quality (Larson 1969; Koch 1972; Jozsa and Brix 1989; Vargas-Hernandez and Adams 1991; Jozsa and Middleton 1994; Zobel and Sprague 1998). Specific gravity is determined by the combination of percent latewood, cells per unit area, cell diameter, and cell wall thickness, as well as the amounts of various extractives (Zobel and van Buijtenen 1989). Other attributes often reported in combination with specific gravity are tracheid length, micro-fibril angle, and juvenile/mature wood distribution. Although studies have looked into using other measures, such as modulus of elasticity (MOE) rather than specific gravity for the prediction of wood quality (Green and McDonald 1997), the literature overwhelmingly indicates that specific gravity is the primary attribute by which wood quality is determined (Koch 1972; Cown 1976; Zobel and van Buijtenen 1989; Zobel and Sprague 1998; Jozsa et al. 1989). It has been thought that the utility of specific gravity as a principle wood quality attribute is its moderate to high heritability ranging from 0.5 to 0.9 (Zobel 1961), and thus its potential for inclusion in breeding programs which are focused on meeting end-use requirements (Zobel and van Buijtenen 1989).

Relationships between factors influencing radial growth patterns and wood quality of Douglas-fir such as climatic and geographic influences have been studied (Kennedy 1961; Lassen and Okkonen 1969; Robertson et al. 1989; Zhang and Hebda 2004). Lassen and Okkonen (1969) investigated the effect of elevation and summer precipitation on specific gravity of ~50 year-old coastal Douglas-fir in Washington and Oregon. Eight-mm increment cores were sampled from five trees at each of the 45 sampling locations. They found that specific gravity was highest at sites with low summer precipitation and low elevation; conversely, sites with high summer precipitation and high elevation had the lowest specific gravity. When describing the variation among and within trees, it is important to recognize the geographic and climatic factors that also have a strong influence on the variability. Other studies call for recognition of the within-tree and within-ring genetic variation that influences wood quality attributes (Resch and Arganbright 1968; Ivkovic and Rozenberg 2004).

Study of the causes of within-ring variation is important because within-ring uniformity is an important factor for meeting wood product processing requirements (Larson 1969; Zobel and van Buijtenen 1989). Studies by DeBell et al. (2004) and

Zhang (1998) discovered that ring width in western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and black spruce (*Picea mariana*) was negatively correlated with ring density at younger ages (less than 21 years for western hemlock and less than 7 years for black spruce), but was less negatively correlated with density at older ages. This result indicates that rapid growth may only have a significant effect on wood density up to a certain age, after which, increases in growth rate have a less profound effect on wood density.

1.4 Silviculture and wood quality

Sivicultural practices such as initial spacing, genetic improvement, thinning, and fertilization can have a strong influence on early development of wood characteristics and the volume and quality of wood ultimately produced in a stand (Megraw 1986; Jozsa and Brix 1989; Hermann and Lavender 1999; Watson et al. 2003; Lundgren 2004). Only one study could be found that investigated the effect of weed control on wood quality. A 2 × 2 factorial in a randomized block design tested the effects of 10 years of sustained weed control and various applications of fertilizer on the productivity of 18-year old loblolly pine (*Pinus taeda* L.) (Martin and Jokela 2004). Specific gravity was calculated indirectly and resulted in average increases by ring associated with weed control. Typically, stocking density influences the proportion and vigor of the live crown, in turn affecting the juvenile and mature wood distribution at a given age. Trees with a larger and more vigorous crown tend to grow faster and have a greater proportion of juvenile wood for any given diameter than trees that have already experienced crown recession (Jozsa and Middleton 1994). Because of the influence of the crown size and vigor on wood distribution along the stem, open grown trees have a more conical shaped stem and a very low percentage of mature wood, whereas densely stocked trees have a more cylindrical shaped stem and a higher percentage of mature wood (Paul 1957; Zahner 1963; Jozsa and Middleton 1994).

Numerous successful studies have been conducted to investigate the influence of spacing and thinning on wood density and quality. A study by Watson et al. (2003), designed to investigate the effect of stand density on 38-year old western hemlock in the context of effect on pulp fibre properties, showed that extremely wide spacing (4.6 m) had a negative effect on wood quality as far as increasing the juvenile wood proportion, but mature wood density was not affected by spacing (0.9 m, 1.8 m, 2.7 m, and 3.7 m). This result may be attributable to relatively low survival on the site, lack of adequate replication, or to insensitivity of wood density in this instance to a decrease in tree-to-tree competition for reasons related to genetics or environmental conditions. A study conducted by DeBell et al. (2004) comparing a wide range of stand density conditions for western hemlock found tree ring components of earlywood and latewood density to become less affected by increased growth rate as age increased beyond 21 years. Percent latewood, however, continued to decrease significantly with increasing growth rate after 21 years of age. Climatic factors such as an increase in early summer rainfall may have some influence on not only the increased growth rate, but also the reduced proportion of latewood associated with it

(Chalk 1953). It is observed that increases in latewood proportion are often associated with spring moisture stress as well as with high levels of late summer rainfall (Paul and Smith 1950; Zahner 1963). In Douglas-fir, the former serves to expedite the transition to latewood, therefore reducing the proportion of earlywood, and the latter serves to extend the period of latewood formation (Chalk 1951; Kennedy 1961). A statistical comparison of three thinning intensities (low, 40 m^2/ha; normal, 27m^2/ha; and high, 24 m^2/ha) in mature Norway spruce (*Picea abies* (L.) Karst.) resulted in a significant increase in basal area increment (increasing ring width by 41%) with greater intensity, but no significant difference in wood density among treatments (Jaakkola et al. 2005). Common to these studies is the effect of spacing among trees on the radial growth and its relationship to ring density, with the result that radial growth is affected by silvicultural treatments but when rings of the same age are compared, specific gravity or density is relatively unchanged (Jozsa et al. 1989; Megraw 1986).

Studies have found that there is no relationship between ring width and relative density (specific gravity) when rings of the same cambial age are evaluated for Douglas-fir, southern pines, western hemlock, and Norway spruce (Megraw 1986; Jozsa et al. 1989; Watson et al. 2003; DeBell et al. 2004; Jaakola et al. 2005). Despite these findings, studies on the influence of age and vertical or radial position on wood quality and density have shown that increased growth rate will greatly affect the proportion of juvenile wood depending on the age of harvest, which does have a significant effect on wood quality regardless of the effect on density at a particular age (Bendtsen 1978; Megraw 1986). Jozsa et al. (1989) and Larson (1962) in a review of auxin gradient regulation on cell size reported that average wood properties are affected by tree age and height position in the stem rather than growth rate. He also stated that low density and wide rings near the pith are the inherent physiological result of the crown's influence on wood formation. Reason for this is associated with the distribution of auxin taking place in the buds. Nonetheless, it is emphasized that plantation growers in general must understand the impact of fast-grown wood on end-use quality and how to select trees and management strategies that will optimize the quality of wood produced in shorter rotations to meet the demand of an ever-growing resource need (Bendtsen 1978).

1.5 Genetics and wood quality

In addition to manipulating the growing environment to achieve desirable stem form, branch size and growth rates, tree improvement programs can be a useful tool for silviculturists to select individual trees having the desired heritable characteristics that will produce quality end products (Vargas-Hernandez and Adams 1991; Jozsa and Middleton 1994). Specific gravity has been reported to be a moderately to highly heritable trait in conifers (Zobel 1961; King et al. 1988). Some reported heritabilities for specific gravity are 0.59 in Douglas-fir (Vargas-Hernandez and Adams 1991), 0.5-0.7 in radiata pine, (Dadswell et al. 1961) and >0.9 in Douglas-fir (King et al. 1988). Many studies have focused on the genetic variation of ring specific gravity and its appropriateness for inclusion in a tree breeding program for various species. Cown (1976) studied variation in radial patterns of 13-year old Douglas-fir growth ring components using gravimetric and densitometric techniques from different seed sources by sampling increment cores from ten trees from five seed sources at five sites in Oregon and British Columbia. Cown reported that wood quality attributes were highly variable among and within individual stems, but reported non-significant differences in specific gravity among seed sources. A similar result was found for specific gravity and tracheid length from increment cores sampled from 27-year old Tawain incense cedar (*Calocedrus formosana*) (Yang and Chiu 2006). From these results, it would seem that solid evidence of the supposed great potential for genetic improvement of wood quality has yet to be established.

Other studies have focused on the genetic relationship between wood quality traits and growth patterns and characteristics in conifers. Jayawickrama et al. (1997) evaluated the genetic relationships between height and diameter growth cessation and percent latewood, transition to latewood date, and specific gravity of five and six year-old loblolly pine among and within provenances. Significant differences for specific gravity were observed only within provenances with specific gravity values ranging from ~0.42-0.50. They also found that trees within provenances having faster height and diameter growth tended to have lower specific gravity. They suggest that selecting provenances having suitable growth rate and adaptability combined with selecting trees within provenances for high specific gravity has potential to be a useful improvement strategy for loblolly pine, but do not offer any statistics related to the gains in either volume or specific gravity that have been achieved. In another study, Douglas-fir stem strength was studied indirectly through evaluation of genetic variation of the density and ring-width trend (McKimmy and Campbell 1981). Two increment cores were sampled at breast height from 90 64-year old trees from a genetics study in Washington and Oregon. Juvenile and mature wood were analyzed separately. Their results revealed significant genetic variability for ring width and wood density, though the structure of the variability was quite different. Despite limitations in sampling design and the indirect nature of the experiment, McKimmy and Campbell (1981) concluded that stem strength properties are influenced by genetic variation and that because of the apparent family×plantation interaction the density and ring width trend should be considered in Douglas-fir tree breeding programs. Though these studies provide some evidence that the potential for genetic improvement of wood quality exists, there is little numerical evidence offered in terms of the potential gains that could be achieved.

Some research has shown that specific wood quality attributes are more heritable than others, which has importance in terms of focusing goals for improvement breeding. Louzada and Fonseca (2001) reported ring-by-ring earlywood density using x-ray densitometry at breast-height of 18-year old maritime pine (*Pinus pinaster*). Based on three completely randomized blocks, earlywood density was determined to be more highly heritable than latewood density (0.52-1.01 vs. 0.03-

0.52), and perhaps even an improvement over average ring density (0.53-0.74) when included in a tree breeding program. They note however, that more work is needed on the genetic correlations of these characteristics within juvenile/mature wood. Another recent study found a similar result from breast-high cores taken from 26-year old Douglas-fir (Ukrainetz et al. 2008), suggesting that gains in wood quality achieved through breeding for higher density earlywood (heritability = 0.54), because of its supposed correlation with micro-fibril angle, would outweigh any losses in volume produced. Somewhat contradictory to the previous two studies, in their study on ring density components of breast-high increment cores from 15-year old Douglas-fir from 60 open-pollinated families, Vargas Hernandez and Adams (1991) reported that ring density components of earlywood and latewood density and percent latewood were not any more highly heritable than overall ring density. Earlywood, latewood, and overall density heritability were reported to be 0.51, 0.46, and 0.55, respectively. Heritability values were averaged across rings in this study rather than presented ring-by-ring, possibly contributing to the incongruity with results of Louzada and Fonseca (2001).

Results from studies of heritability of wood density and its components vary widely in the literature (Zobel and van Buijtenen 1989; Fugimoto et al. 2005) because of variation among species and environmental conditions. There is an emphasis on understanding the effect of tree age on genetic and phenotypic correlations among wood quality components (Zobel and Sprague 1998; Bendtsen 1978). Chemical components of lignin and cellulose are thought to be under genetic control, but the patterns and variability are less understood (Zobel 1971). Improvement of juvenile wood through vegetative propagation for increased cellulose content and reduced lignin content has been proposed (Zobel and van Buijtenen 1989), however little is known regarding the potential effects on overall wood quality. Vargas-Hernandez and Adams (1991) state that decreases as little as 2.41% in specific gravity can manifest losses in dry fiber yield as great as 11,000 kg/hectare, emphasizing the importance of balancing wood quality and volume growth when selecting traits for tree improvement programs. They also conclude that changes made to any one trait will affect all traits and maximum gains cannot be achieved for any two traits simultaneously. It is important to consider the tradeoffs associated with growing higher density wood and the potential that free-to-grow status may not be achievable with the slower growth that could be associated with genetically improved trees.

Cown (1976) notes the need for more detailed and comprehensive research in the arena of genetic improvement of wood quality with sufficient replications in space and time. Although, there does seem to be potential for genetic improvement in wood quality in plantations, there is still much work that needs to be done to understand the consequences and tradeoffs involved with genetic modification.

1.6 Methods for measuring specific gravity

Specific gravity is the most commonly used criterion for assessing wood quality. It is a unitless measurement similar to but derived differently than relative density or basic density. It is the ratio of the density of a wood sample to the density of an equal volume of water at a given temperature, usually 4°C because at this temperature, the density of water is equal to 1 g/cm^3 (Haygreen and Bowyer 1996; Larson et al. 2001). Specific gravity is always reported using the oven-dry weight of a wood sample; however, volume of the sample can be reported at green, oven-dry, or any other specified moisture content (Haygreen and Bowyer 1996). This standard method of measurement makes it a desirable tool for comparison among researchers.

Several methods exist for the purpose of measuring specific gravity of wood samples. The objective driving the development of new methods has been to more accurately and easily estimate the specific gravity of wood samples. Traditionally, small wood samples were most commonly measured using the water immersion method based on Archimedes principle of floating bodies or buoyancy which states that "if a solid lighter than a fluid be forcibly immersed in it, the solid will be driven upwards by a force equal to the difference between its weight and the weight of the fluid displaced" (Heath 1897). This method was considered ideal for measuring volume and density of irregularly shaped wood samples. In 1954 and 1955, Diane Smith described a method called the maximum moisture method which estimates specific gravity using an equation with a correction factor that assumes the standard density of wood substance to be 1.53. This method was considered by Smith to be a much simpler and more reliable approach to estimating specific gravity because it eliminated the separate measurements of volume and weight of the sample.

A study by Valencia-Manzo and Vargas-Hernandez (1997) looked into the use of the empirical method for estimating specific gravity of regularly shaped wood samples (measurement of volume using the formula for the volume of a cylinder = length × (πr^2)) and its correlation with the water immersion method and the maximum moisture method. They found significant correlations among mean values, standard deviations, and specific gravity minimum and maximum values for the three methods, suggesting that for regularly shaped increment core samples, the empirical method can be used as a reliable and simple approach.

Because simple and economical methods may not always yield the kind of accurate results one may be seeking, methods have been developed to assess tree ring density using x-ray densitometry. The Geological Survey of Canada developed the prototype which was designed to produce density plots, ring-width measurements, maximum density bar graphs, and ring-width bar graphs (Jones and Parker 1970). Most research in the study of wood science currently utilizes x-ray densitometry because of the wide range of wood properties it captures and the degree of accuracy with which they can be estimated; however, the use of older methods is still practical depending on the objectives of the research study (Swenson and Enquist 2008).

1.7 Thesis objectives and research approach

Copious amounts of research have been conducted to study the effects of manipulation of the growing environment and genetic improvement on tree wood quality components, however; no research study exists demonstrating the effects of vegetation control regimes on wood quality in Douglas-fir. Two research objectives were developed to begin to approach this topic in the present study. The first objective was to evaluate the cumulative eight-year growth response of the Sweet Home, Critical Period Threshold Study, including Douglas-fir and western redcedar (*Thuja plicata* Donn ex D. Don) growing under vegetation control treatments with varied timing and duration. The second objective was to investigate the effect of these treatments on wood quality of Douglas-fir and relate growth rate to wood quality attributes. Wood quality was specifically represented by differences in specific gravity, ring segment length, percent latewood, and biomass increment, and cells per unit area among the various weed control treatments.

It is hoped that this study will contribute some new information to the body of knowledge surrounding vegetation management in the establishment phase of young plantations and will spur further research of the effect that timing and duration of controlling interspecific competition has on young tree wood quality, and hence on the core of juvenile wood within eight years from the pith for mature trees grown under the same regimes. Knowledge of the effect of vegetation control on wood quality attributes as well as volume growth is essential for plantation growers and the forest products industry to develop appropriate silvicultural strategies to meet their objectives.

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CHAPTER 2.0 – EFFECT OF VARIED TIMING AND DURATION OF WEED CONTROL ON GROWTH OF DOUGLAS-FIR AND WESTERN REDCEDAR SEEDLINGS IN WESTERN OREGON

2.1 Introduction

With increasing demand for wood volume comes the need for a strategy that will optimize growth of conifer species. Many silvicultural techniques will increase growth, but the best way to avoid losses in crop yield from interspecific competition is through the application of herbicide early on in stand development. After disturbance, colonizing species compete for resources aggressively with target conifer species (Radosevich 1997). Control of these competitors early on in stand establishment is necessary to achieve a consistent gain in volume (Wagner et al. 1999).

The critical period is the time during crop development when intense interspecific competition occurs between crop plants and weed plants. It is the period when weeds should be controlled to avoid critical losses in crop yield. This concept was developed for agricultural use in the 1960's (Zimdahl 1988) and was applied to forest plantations in the 1990's (Wagner et al. 1996, Wagner et al.1999). Research by Wagner et al. (1999) in northern Ontario, Canada, showed increases in stem volume with increased duration of weed control that varied among northern conifer species. The response of Pacific Northwest conifer species after three and four years of varied timing and duration of vegetation control has been studied by Chen (2004) and Rosner and Rose (2006). The current study evaluated the eighth year growth response of Douglas-fir and western redcedar at the Sweet Home, Oregon site with specific objectives to 1) estimate the duration of continuous weed control needed to maximize early plantation growth and 2) quantify growth losses resulting from delaying vegetation control for one or two years after planting.

2.2 Materials and Methods

2.2.1 Study Site

Four different sites were selected in western Oregon, USA based on vegetation and climatic type, such that they covered a range of habitat types. The four sites, known as the Critical Period Threshold study (CPT), were selected to represent the range of sites that most private timber companies manage in the Pacific Northwest. The Sweet Home site is located at 44° 28’ 32” N, 122° 43’ 16” W, on the western slope of the Cascade Range on flat terrain with an elevation of about 200 m. Figure 2.1 shows a map of Oregon and the locations of each of the CPT study sites. Figure 2.2 shows the block and plot layout of the Sweet Home site. The soils at this site range from deep and well-drained to poorly drained and are composed of silty clay loams from recent alluvial deposits. Average annual precipitation is 100-150 cm. Average annual temperature is 12 °C with a frost-free period of about 165-210 days. Vegetation composition is variable but many species tend to invade quickly. The typical competing species are sword fern (*Polystichummunitum* (Kaulf.) K. Presl), salal (*Gaultheria shallon* Pursh), Oregon grape (*Mahonia nervosa* (Pursh) Nutt.), and various small shrubs and trees. The previous stand was dominated by 60-70 year-old Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), bitter cherry (*Prunus emarginata*

(Dougl. Ex Hook.) D. Dietr.), and bigleaf maple (*Acer macrophyllum* Pursh). The previous stand's understory was composed of sword fern, salal, and evergreen blackberry (*Rubus lacinaiatus* Willd.). In March 2000, a feller-buncher was used to harvest the site. To alleviate harvesting compaction, an excavator was used to subsoil the site using a one tooth tool following the completion of excavator piling.

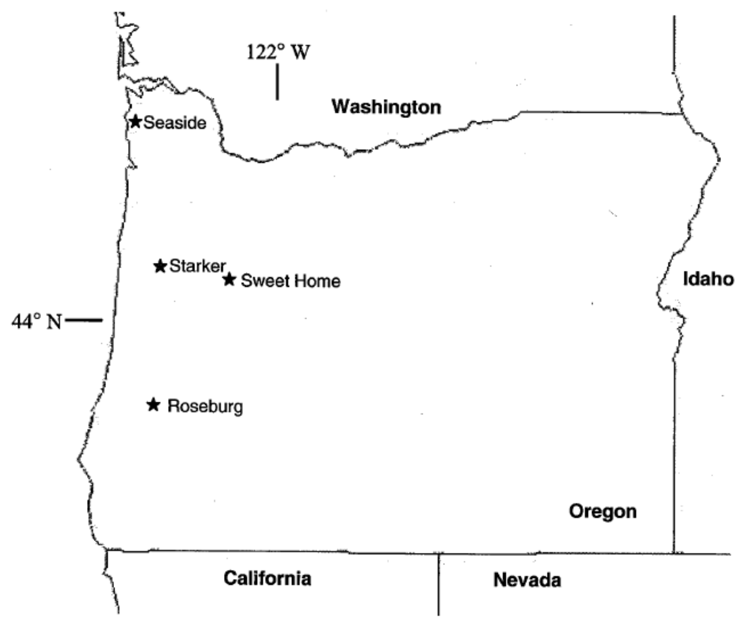

Figure 2.1. Map of Oregon and four Critical Period Threshold study sites.

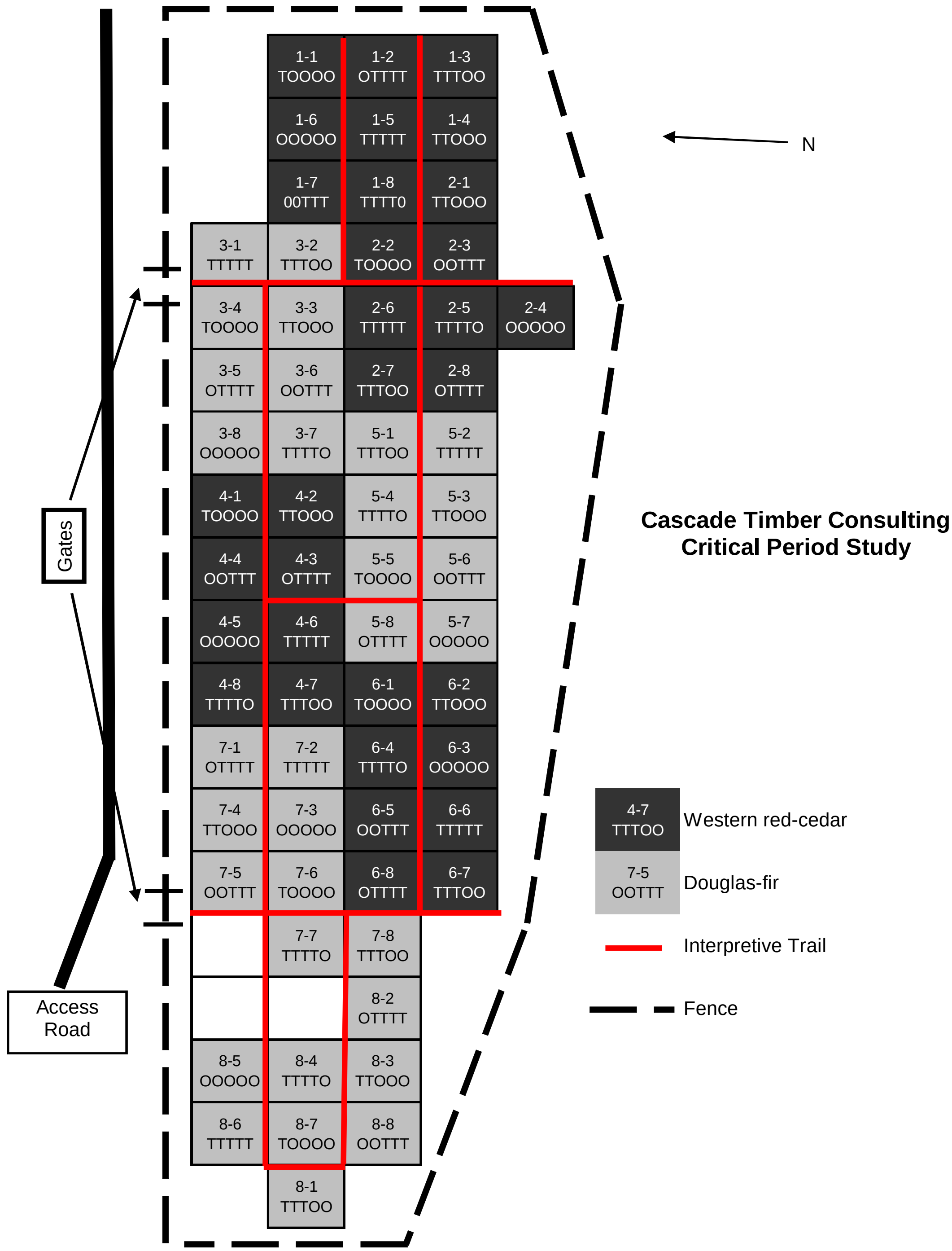

Figure 2.2. Sweet Home site block and plot layout. (Courtesy of Eric Dinger.)

2.2.2 Experimental Design

This study conformed to a complete randomized block design with 8 treatments and 4 replications (blocks). The species of interest at the Sweet Home site were Douglas-fir and western redcedar (*Thuja plicata* Donn ex D. Don).

Each treatment plot was 24 m × 24 m in size and planted in winter 2001 with 36 seedlings at a spacing of 3 m × 3 m with 6 trees in each of 6 rows. Each treatment plot was surrounded by a row of buffer trees planted at the same spacing. Plots were arranged as contiguously as possible, excluding wet areas. Figure 2.3 shows a graphic of the layout of two plots within a block and trees within each treatment plot.

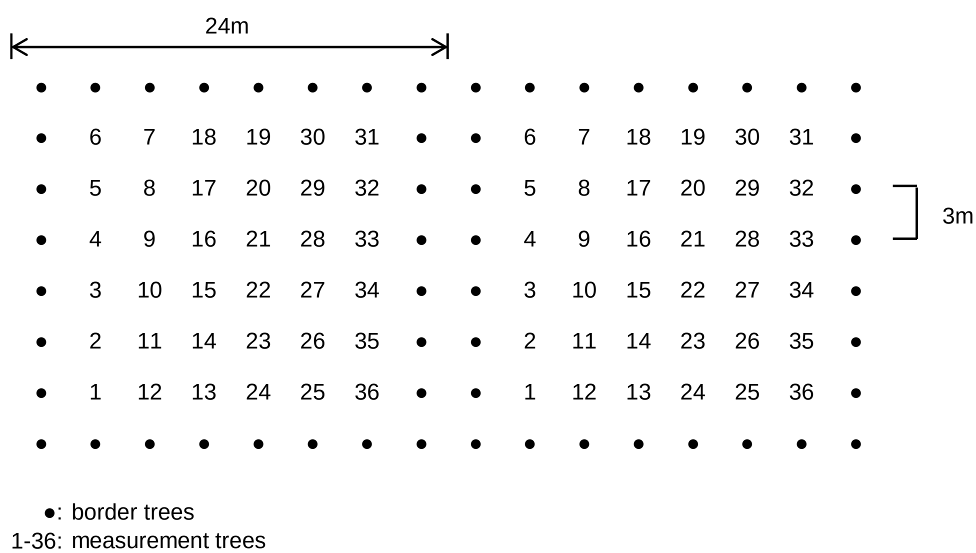

Figure 2.3. Plot layout showing 36 measurement trees, border trees, and excavator routes.

The 2000 site preparation at Sweet Home consisted of piling excavator slash outside of the treatment areas. Most slash was removed in order to plant seedlings in a strict grid pattern without causing extensive soil disturbance. Prior to piling, block boundaries and excavator routes were marked to minimize compaction within the treatment areas. Excavator routes were limited to the centermost 6 m of the buffer rows. Large shrub clumps were removed during excavation. The slash piled in the 6 m zone was burned prior to planting. All treatment plots, including the controls, received a follow up herbicide treatment application if there were potentially sprouting hardwoods (e.g., bigleaf maple, cottonwood, and madrone) present. For plots receiving herbicide treatment in the first year, there was an additional fall site prep herbicide application of a mixture containing sulfometuron, metsulfuron, and glyphosate (0.15 L/ha (2.0/ounces/acre), 0.04 L/ha (0.5 ounces/acre), and 4.68 L/ha (64 ounces/acre), respectively.) (Chen 2004).

All seedlings were grown in the same greenhouse at the same nursery, Plum Creek in Cottage Grove, Oregon, in order to limit the inherent variability associated with nursery stock. For the same reason, all seedlings were grown in Styroblock 60/250 ml containers (Beaver Plastics, Edmonton, Alberta, Canada) in media containing the same slow-release fertilizer.

The entire site was fenced to reduce confounding results due to elk or deer browse and Vexar® (Conwed Plastics, LLC, Minneapolis, MN) tubing was used in the western red cedar plots to protect seedlings from potential rodent damage.

2.2.3 Vegetation Treatments

Vegetation control was implemented with the goal of maintaining <25% weed cover throughout the season by applying spring and fall treatments.   All spring herbicide treatments consisted of the application of atrazine (2 kg/ha) and clopyralid (0.58 L/ha) using a waving wand operated by a trained applicator.

Weed control treatments at the Sweet Home site were first conducted in 2001 and over the subsequent four years. Plots were either treated (“T”) or untreated (O”) in each year of the study. Seven treatments were implemented along with an eighth no treatment “control” (OOOOO) that received only a site preparation treatment and no herbicide release. One set of treatments received herbicide treatment in the first year (TOOOO); first two (TTOOO); first three years (TTTOO); first four years (TTTTO); first five years (TTTTT). In addition, vegetation control treatments were delayed for one year followed by 4 years of herbicide treatment (OTTTT) or for two years followed by 3 years of herbicide treatment (OOTTT). Table 2.1 shows the treatment regimes explicitly. The treatments were randomly assigned to plots within each replication.

Table 2.1. Treatment by year of application.

	year				
	2001	**2002**	**2003**	**2004**	**2005**
treatment	O	O	O	O	O
	T	O	O	O	O
	T	T	O	O	O
	T	T	T	O	O
	T	T	T	T	O
	T	T	T	T	T
	O	T	T	T	T
	O	O	T	T	T

2.2.4 Data Collection

Initial height and basal diameter of conifer seedlings were measured within a few weeks after planting in 2001. In August of each year of the study (years 1-5) and in November 2008, survival and size (height, basal diameter, and diameter at breast height when applicable) of all seedlings were recorded. Crown radius was measured in years 4, 5, and 8.

In November 2008, crews were assembled to measure growth response of the entire Sweet Home study site. Each crew was assigned a block and was instructed to measure height, basal diameter, diameter at breast height (dbh), and crown radius.

2.2.4.1 Height

Height was measured in centimeters using a telescoping height pole. The person recording the data walked away from the tree being measured in order to get a good vantage point and then watched for the height pole to reach the top of the tree, notifying the person operating the height pole when the height pole was properly positioned and the height reading could be observed.

2.2.4.2 Basal Diameter

Basal diameter was measured in centimeters at roughly 15 cm above ground using a small diameter tape. The person measuring diameter was careful to keep the tape parallel to the ground, weaving the tape through the lower branches to get an accurate reading of the stem diameter.

2.2.4.3 Diameter at Breast Height (dbh)

Dbh was measured to the 0.1 centimeter breast height (1.37 m above ground) using a small diameter tape. The person measuring dbh was also careful to keep the tape parallel to the ground, weaving the tape through the branches where necessary.

2.2.4.4 Crown Radius

Crown radius was measured to the nearest 0.1 centimeter. The length of the longest branch was measured using a cm stick by holding the stick horizontally from the tree stem to the end of the branch, being careful not to stretch the branch out, but only measuring the length of the natural drip line of the branch. Then the branch most perpendicular to the first branch was measured in the same way. The two branch length measurements were averaged to obtain mean crown radius.

2.2.4.5 Vegetation

Vegetation was assessed at each site in July of each year of the study (years 1-5) (Chen 2004). No vegetation data were measured in 2008.

2.2.5 Derived Variables

2.2.5.1 Conifer Growth

Stem volume and height/diameter ratio were calculated from height and basal diameter for each conifer seedling through year 5 and again in year 8. Volume was calculated in cubic centimeters (cm^3) using the formula for a cone (Rosner and Rose 2006) and converted to cubic decimeters (dm^3) by dividing volume in cm^3 by 1000.

2.2.6 Statistical Approach

Treatment effects were tested by ANOVA under a randomized complete block design using Statistical Analysis Software version 9.1 (SAS Institute Inc. Cary, North Carolina). The ANOVA model assumptions of normality, homogeneity of variance, and linearity of the residuals were satisfied. Analyses of tree growth response variables were analyzed separately for each species using analysis of variance general linear models in SAS (Proc GLM) to determine treatment effects. Fisher's protected least significant difference tests were used to identify treatment differences ($\alpha \leq 0.05$). Standard errors for all variables were calculated for treatment means across replications.

2.2.6.1 Conifer Growth

Differences in seedling volume, basal stem diameter, diameter at breast height (dbh), height, height/diameter ratio, and crown radius were tested independently for each conifer species using standard analysis of variance procedures (ANOVA) for a completely randomized block design as shown in Table 2.2.

Table 2.2. Basic ANOVA table used for all conifer growth analysis.

Source of variation	df
Total	(8*4)-1 = 31
Block	(4-1) = 3
Treatment	(8-1) = 7
Error	(31-3-7) = 21

2.2.6.2 Vegetation

Difference in vegetation response at the Sweet Home site was analyzed for the first 5 years of the study by pooling the data from the different conifer species. Vegetation was not assessed in 2008 but the influence of vegetation composition on tree growth early on in the study and can be read in detail in Chen (2004) and Rosner and Rose (2006).

2.3 Results

2.3.1. Douglas-fir

In the Douglas-fir plots, eight years after the beginning of the study and three years following its completion, plots with three or more consecutive years of weed control showed consistently higher values for volume, basal diameter, dbh, height and crown radius and consistently lower values for height to diameter ratio ($p < 0.05$, Table 2.3, Figure 2.4).

Table 2.3. ANOVA table for all growth variables volume (dm^3), basal diameter (cm), dbh (cm), height (cm), height/diameter ratio, crown radius (cm), and survival (%) for Douglas-fir ($\alpha \leq 0.05$).

Douglas-fir						
Parameter	**Source**	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
Volume 08	block	3	212.57	70.86	1.70	0.1982
	treatment	7	4510.80	644.40	15.43	<0.0001
Basal diameter 08	block	3	8.42	2.81	1.72	0.1939
	treatment	7	189.93	27.13	16.60	<0.0001
DBH 08	block	3	2.33	0.78	0.95	0.4337
	treatment	7	56.29	8.04	9.86	<0.0001
Height 08	block	3	15740.71	5246.90	1.96	0.1506
	treatment	7	96104.97	13729.28	5.13	0.0016
Height/ Diameter Ratio 08	block	3	139.60	46.53	6.54	0.0027
	treatment	7	1064.47	152.07	21.38	<0.0001
Crown Radius 08	block	3	272.05	90.68	0.44	0.7268
	treatment	7	14819.09	2117.01	10.27	<0.0001
Survival 08	block	3	79.58	26.53	4.42	0.0043
	treatment	7	80.22	11.46	1.91	0.0649

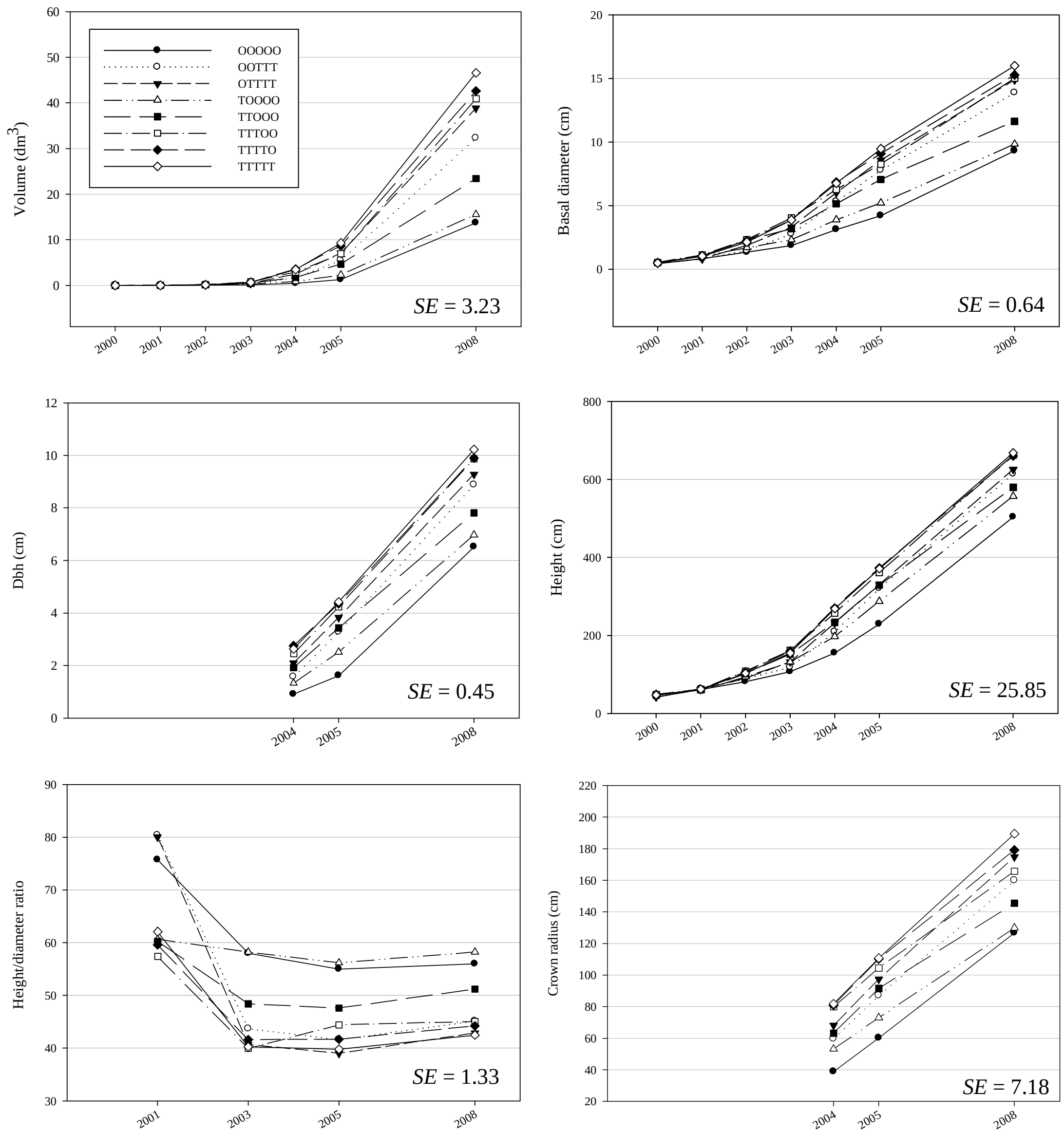

Figure 2.4. Douglas-fir mean volume (dm^3), basal diameter (cm), dbh (cm), height (cm), crown radius (cm) and height/diameter ratio measured from 2000 to 2008. SE shown refers only to analysis of year eight.

Treatments TTTTT, TTTTO, and TTTOO showed a 239%, 211%, and 199% increase in volume over the OOOOO, respectively. For all growth variables, there was no significant improvement over the control (OOOOO) by adding one year of weed control (TOOOO). Delaying weed control in the first year (OTTTT) did not prove to have any significant effect on growth relative to the TTTTO or TTTTT treatments for all growth variables. All growth variables for treatments having the same number of treatment years did not vary significantly regardless of the timing of weed control, in other words, delaying treatment for two years and applying treatment in the last three years (OOTTT) was not significantly different from applying treatment in the first three years only (TTTOO). All Douglas-fir growth variable estimates are shown in Table 2.4. Douglas-fir survival was not significantly affected by treatments and ranged from 88% in the OOTTT treatment to 97% in the TTTTO treatment (Figure 2.5).

Table 2.4. Total mean volume, basal diameter, dbh, height, height/diameter ratio, crown radius, and volume growth 2005–2008 of Douglas-fir for data collected in year 8 at the Sweet Home site. Standard errors (1 SE) of treatment means are shown in parentheses. Values within a column with different letters are significantly different ($\alpha \leq 0.05$).

Species	Treatment	Volume (dm^3)	Basal diam (cm)	DBH (cm)	Height (cm)	Height/ diam ratio	Crown radius (cm)	Survival (%)
Douglas-fir	*(SE)*	*(3.23)*	*(0.64)*	*(0.45)*	*(25.85)*	*(1.33)*	*(7.18)*	*(0.02)*
	OOOOO	13.7 *e*	9.3 *d*	6.5 *d*	503 *c*	56.0 *a*	126.7 *d*	0.93
	OOTTT	32.3 *bc*	13.9 *b*	8.9 *cb*	614 *ab*	45.1 *c*	159.8 *bc*	0.88
	OTTTT	38.8 *ab*	14.9 *ab*	9.0 *ab*	625 *ab*	42.9 *c*	174.7 *ab*	0.92
	TOOOO	15.6 *de*	9.8 *cd*	7.0 *d*	557 *bc*	58.2 *a*	129.9 *d*	0.93
	TTOOO	23.4 cd	11.6 *c*	7.8 *cd*	580 *b*	51.2 *b*	145.4 *cd*	0.95
	TTTOO	40.9 *ab*	15.0 *ab*	9.9 *ab*	663 *a*	45.1 *c*	165.7 *bc*	0.91
	TTTTO	42.6 *a*	15.3 *ab*	9.9 *ab*	660 *a*	44.2 *c*	179.2 *ab*	0.97
	TTTTT	46.5 *a*	15.0 *a*	10.2 *a*	668 *a*	42.5 *c*	189.5 *a*	0.94

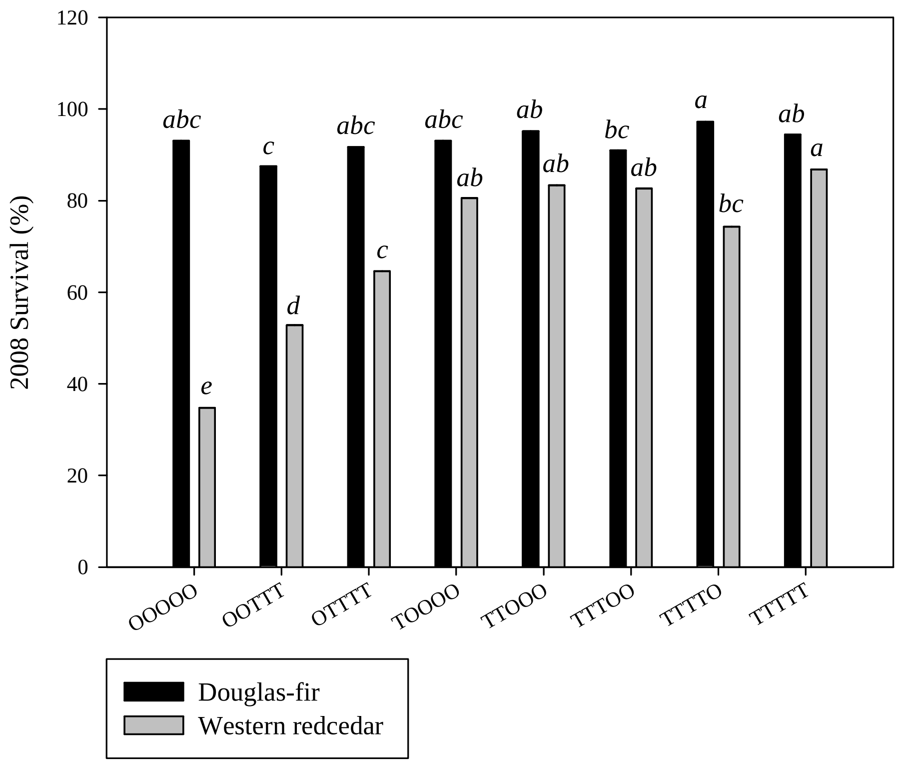

Figure 2.5. Douglas-fir and western redcedar survival (%) for 2008. Means labeled with different letters within species represent significant differences at ($\alpha \leq 0.05$).

2.3.2 Western redcedar

In the western redcedar plots after eight years, plots with three or more consecutive years of weed control showed consistently higher values for volume, basal diameter, dbh, height and crown radius and consistently lower values for height to diameter ratio ($p < 0.05$, Table 2.5, Figure 2.6).

Table 2.5. ANOVA table for all growth variables volume (dm^3), basal diameter (cm), dbh (cm), height (cm), height/diameter ratio, crown radius (cm), and survival (%) for western redcedar ($\alpha \leq 0.05$).

Western redcedar						
Parameter	**Source**	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
Volume 08	block	3	320.82	106.94	3.76	0.0264
	treatment	7	802.77	114.68	4.03	0.006
Basal diameter 08	block	3	56.50	18.83	5.33	0.0069
	treatment	7	125.32	17.90	5.06	0.0017
DBH 08	block	3	3.39	1.13	1.46	0.2530
	treatment	7	37.98	5.43	7.03	0.0002
Height 08	block	3	8431.01	2810.34	1.77	0.1840
	treatment	7	76549.49	10935.64	6.88	0.0003
Height/ Diameter Ratio 08	block	3	626.33	208.78	5.02	0.0089
	treatment	7	736.05	105.15	2.53	0.0471
Crown Radius 08	block	3	652.60	217.53	1.19	0.3372
	treatment	7	4724.66	674.95	3.70	0.0093
Survival 08	block	3	450.32	150.11	9.13	<0.0001
	treatment	7	3075.51	439.36	26.73	<0.0001

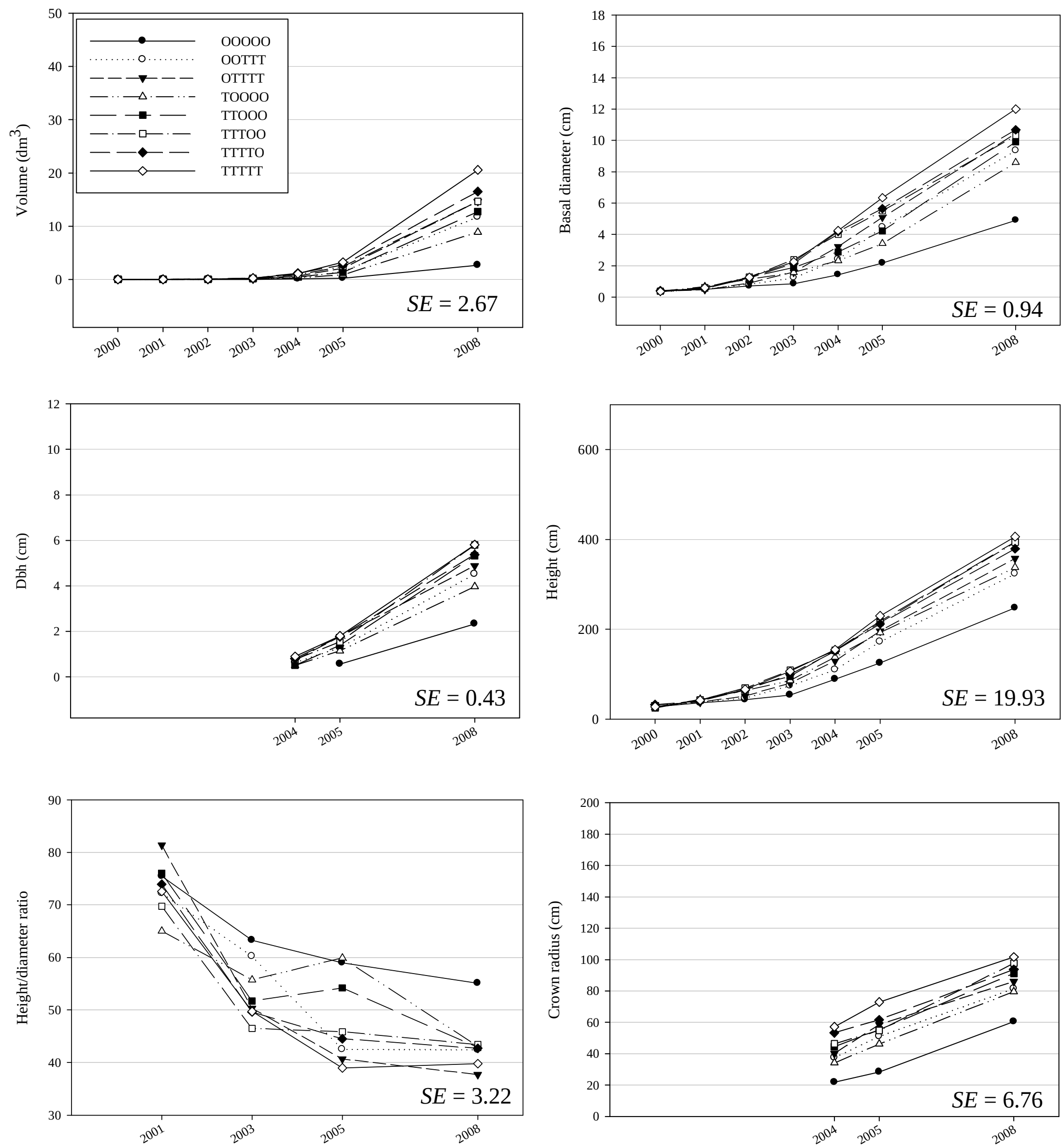

Figure 2.6. Western redcedar mean volume (dm^3), basal diameter (cm), dbh (cm), height (cm), crown radius (cm) and height/diameter ratio measured from 2000 to 2008. SE shown refers only to analysis of year eight.

Volume proved to be sensitive to an increase in number of years of weed control for both species. This variable showed an increase of 692% for five consecutive years of treatment (TTTTT) over the control (OOOOO). For all growth variables, there was no significant difference between delaying one (OTTTT) or two (OOTTT) years. When treatment was delayed for one year only, there was no significant difference between 5, 4, and 3 years of initial weed control for all growth variables. For volume, dbh, height, and crown radius, delaying treatment for two years (OOTTT) showed significant losses in growth compared to five consecutive years of treatment (TTTTT) but the OOTTT treatment was not significantly different from three or four years of initial or delayed treatment. Adding a first year release treatment (TOOOO) caused significant increases of 76%, 74%, and 37%, respectively, over the control (OOOOO) for basal diameter, dbh, and height, and a 28%, decrease for height/diameter ratio.

With the exception of height, growth variables for treatments having the same number of treatment years did not vary significantly regardless of the timing of weed control. Interesting to note is that for height/diameter ratio, there was no significant difference between any of the treatments with one or more years of weed control, but there was a significant decrease of 32% in height/diameter ratio of the treatments with one or more years of weed control compared to the control condition (OOOOO) (Table 2.6). Survival in the Western redcedar plots was significantly affected by treatment, ranging from 35% in the OOOOO to 87% in the TTTTT. Figure 2.5

illustrates the pronounced decreased survival in plots that did not receive herbicide in the first two years of establishment.

Table 2.6. Total mean volume, basal diameter, dbh, height, height/diameter ratio, crown radius, and volume growth 2005–2008 of western redcedar for data collected in year 8 at the Sweet Home site. Standard errors (1 SE) of treatment means are shown in parentheses. Values within a column with different letters are significantly different ($\alpha \leq 0.05$).

Species	Treatment	Volume (dm^3)	Basal diam (cm)	DBH (cm)	Height (cm)	Height/ diam ratio	Crown radius (cm)	Survival (%)
Western redcedar	*(SE)*	*(2.67)*	*(0.94)*	*(0.43)*	*(19.93)*	*(3.22)*	*(6.76)*	*(0.04)*
	OOOOO	2.6 *c*	4.9 *c*	2.3 *d*	247 *d*	55.1 *a*	60.4 *c*	0.35 *e*
	OOTTT	11.7 *b*	9.3 *ab*	4.5 *bc*	323 *c*	42.4 *b*	81.4 *b*	0.53 *d*
	OTTTT	14.6 *ab*	10.4 *ab*	4.9 *abc*	357 *abc*	37.7 *b*	86.1 *ab*	0.65 *c*
	TOOOO	8.9 *bc*	8.6 *b*	4.0 *c*	338 *bc*	43.0 *b*	79.5 *bc*	0.81 *ab*
	TTOOO	12.7 *b*	9.9 *ab*	5.3 *ab*	394 *ab*	42.9 *b*	91.1 *ab*	0.83 *ab*
	TTTOO	14.6 *ab*	10.3 *ab*	5.8 *ab*	393 *ab*	43.4 *b*	97.6 *ab*	0.83 *ab*
	TTTTO	16.5 *ab*	10.7 *ab*	5.4 *ab*	379 *abc*	42.7 *b*	93.7 *ab*	0.74 *bc*
	TTTTT	20.6 *a*	12.0 *a*	5.8 *a*	406 *a*	39.8 *b*	101.6 *a*	0.87 *a*

2.4 Discussion

The eighth year growth results show that increasing duration of weed control still had a strong effect on conifer growth at the Sweet Home CPT site (Chen 2004). The trend of increasing volume, diameter, height, dbh, and crown radius along with a decreasing height/diameter ratio is supported by other studies (Lauer 1993; Wagner 1999; Wagner 2006). Consistent with Chen's (2004) results, as well as with studies of several other species (Wagner et al. 1999; Richardson et al. 1999), height growth was consistently less sensitive to weed control than was basal diameter or dbh.

As competition for light increases, height/diameter ratio typically increases because tree crowns are allocating more resources to primary or height growth (Cole and Newton 1987; Lieffers and Stadt 1994). The mean values of height/diameter ratio for Douglas-fir and western redcedar (44 and 42, respectively) achieved in plots having increasing years of weed control are desirable because they indicate greater mechanical stability. Trees with a lower height/diameter ratio are more stable and less prone to wind throw than are those trees with greater height/diameter ratio (Smith et al. 1997). At this age and height, susceptibility to wind throw damage is not a major concern; however, as trees grow in height, maintaining a height/diameter ratio less than 100 is increasingly important.

Thinning is used in closed stands to reduce competition and encourage lower height/diameter ratios; however, stands grown in higher density conditions (2000 trees/hectare) have a narrower window for thinning before the stand becomes too unstable to thin (Wilson and Oliver 2000). Conversely, stands planted at lower densities (1000 trees/hectare) have a larger window for thinning without mechanical damage. The reduction in early vegetation competition in this study mimics a condition of lower initial stand density, potentially allowing for greater flexibility in thinning for future stand stability. Year eight results for height/diameter ratio for Douglas-fir showed a slight increase over year five results, suggesting that competition among trees for light is beginning to occur now that tree crowns have enlarged enough to overlap in some of the treatments. Western redcedar height/diameter ratios show an obvious decrease from year 5 to year 8 which suggests that competition for light among trees is not occurring yet in these plots. The decrease in height/diameter ratio associated with increasing duration of vegetation control may have added long-term benefits in relation to the health of the stand; specifically it is recommended that height/diameter ratio and stand stability be considered among other objectives in plantation management (Wilson and Oliver 2000).

The number of years of continuous competition control proved to have a greater influence on year-8 growth than whether or not herbicide application was delayed, but the initial years of stand development proved to be critical for western redcedar survival. Douglas-fir survival was unaffected by delaying treatment; which can be attributed to differences in growth ecology among the two species (Walters and Reich 1996). The fact that Douglas-fir is a shade-intolerant, pioneer species and western redcedar is a shade-tolerant, secondary seral species contributes to the differences observed in each species' growth response.

2.5 Conclusions and Recommendations

Obtaining maximized growth of conifer species in western Oregon plantations is achieved through the control of competing vegetation during the critical years of stand development. At the Sweet Home site, control of competing vegetation in the first three years of stand establishment maximized the growth of both species. Allowing seedlings to have an advantage over weeds continuously for several years at the beginning of their lives offers them the competitive advantage they need to compete with weeds and gain a large amount of crown and stem volume. This early growth advantage sets them on a trajectory to continue to increase in volume. It is recommended that the economic tradeoff associated with increasing the number of years of weed control over the industry standard of one or two years be assessed in each particular instance; however, gaining an understanding of the critical period of weed competition during which growth is maximized and loss of crop yield is minimized allows forest plantation managers to make informed decisions when choosing a vegetation management regime that will produce the most economical and efficient results.

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CHAPTER 3.0 – EFFECT OF VARIED TIMING AND DURATION OF WEED CONTROL ON WOOD QUALITY PROPERTIES OF DOUGLAS-FIR SEEDLINGS IN WESTERN OREGON

3.1 Introduction

Wood quality for any given species is broadly determined by the quality of the site (ie. soil type, aspect, elevation) (Paul and Smith 1950) and the events, either climatological or anthropogenic, that influence the growth characteristics of a tree or stand. Wood quality is also determined by cellular structure and is considered a complex of several traits: specific gravity, percent latewood, fiber length, and micro-fibril angle. Each of these traits is closely related to clear wood strength and pulp yield. As the forest products industry depends more heavily on second growth and plantation forests to supply the world's growing demand for wood and pulp products, concern over wood quality has become increasingly widespread (Bendtsen 1978; Jozsa and Brix 1989; Cown 1992; Cown 2001). This concern is justified in the PNW given that Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) plantations are among the most economically important forests in the world, supplying timber grown in New Zealand, North America, and Europe (Hermann and Lavender 1999; Gartner et al. 2002). In addition to the increase in demand for wood the proportion of juvenile wood being sent to mills is increasing. For clearwood end-use purposes, the strength characteristics of juvenile wood formed near the pith and crown of the tree are undesirable (Bendtsen 1978; Megraw 1986; Clark and Saucier 1989; Jozsa and Middleton 1994). It is for this reason that wood quality has become increasingly important as a key objective in plantation management and tree improvement programs.

Wood quality traits are influenced by a tree's age, as well as by silvicultural manipulation, genetics, and environmental conditions (Megraw 1986; Jozsa etal. 1989; Jozsa and Brix 1989; and Jozsa and Middleton 1994). A majority of the literature on silvicultural manipulation of wood quality is concerned with stand density management. Control of competing vegetation through the use of herbicides during early stand development may also have some impact on wood quality attributes; however, little experimental evidence exists to support this possible effect (Zobel and van Buijtenen 1989). The limited research in loblolly pine (*Pinus taeda* L.) conducted by Martin and Jokela (2004) suggested a trend from ring four (0.39) to ring ten (0.54) of higher specific gravity and lower earlywood/latewood ratio under a regime of consecutive years of weed control and fertilization. Significant differences, however, were only found at ring age six. Wood specific gravity was also looked at by Smith and Anderson (1977) in relation to various site preparation treatments in slash pine (*Pinus elliottii* Englm. var. *elliottii*) stands in the Georgia Coastal Plain. A significant difference was reported between the most intense site preparation treatment and the three less intense treatments, however, mean specific gravity values did not exhibit a significant difference (0.487 vs. 0.492). The effects of common practices employed by forest managers in the Pacific Northwest as a means to increase wood volume production must also be understood in respect to their impacts on wood quality.

Although it is important to understand the growth effects of competition among older trees for growing space, it is equally important to understand the impact of a tree's first encounter with competition for resources. Early control of competing vegetation does influence the quantity wood produced, and so may also affect quality. Having a statistical comparison of the effects of various vegetation control regimes on both growth and wood quality is essential for gaining a better understanding of wood formation in response to silvicultural manipulations.

3.2 Objectives and Hypotheses

3.2.1 Objectives

The objective of this study was to quantify Douglas-fir juvenile wood quality as influenced by timing and duration of weed control. Specific objectives were as follows:

1. To evaluate the effect of timing and duration of weed control on selected tree growth, specific gravity, ring segment length, percent latewood, and biomass increment of the pre-treatment (rings 3, 4, & 5) and post-treatment (rings 6, 7, & 8) growth periods.

2. To observe the difference in cell size within earlywood and latewood resulting from varied timing and duration of weed control between pre-treatment and post-treatment growth periods.

3.2.2 Hypotheses

The following hypotheses were developed into response to the first objective stated above.

1. There is no treatment effect on specific gravity of wood formed during the 3-year growth period prior to the end of treatment (rings 3, 4, and 5).

2. There is no treatment effect on specific gravity of wood formed during the 3-year growth period following termination of treatment (rings 6, 7, and 8).

3. There is no treatment effect on post/pre treatment specific gravity ratio (the three year period of post-treatment growth divided by the three year period of growth prior to the end of treatment).

4. There is no treatment effect on radial growth during the three year growth period prior to the end of treatment.

5. There is no treatment effect on radial growth during the three year growth period following termination of treatment.

6. There is no treatment effect on percent latewood during the three year growth period prior to the end of treatment.

7. There is no treatment effect on percent latewood during the three year growth period following termination of treatment.

8. There is no treatment effect on biomass increment during the three year growth period prior to the end of treatment.

9. There is no treatment effect on biomass increment during the three year growth period following termination of treatment.

3.3 Materials and Methods

3.3.1 Study Site

The Sweet Home CPT site is located on Cascade Timber Company land, on the western slope of the Cascade Range at 44° 28’ 32” N, 122° 43’ 16” W at an elevation of about 200 m. The soils at this site range from deep and well-drained to poorly drained and are composed of level silty clay loams from recent alluvial deposits. Average annual precipitation is 100-150 cm. Average annual temperature is 12 °C with a frost-free period of about 165-210 days.

Vegetation composition is variable, but most species tend to invade quickly. The typical competing species are sword fern, salal, Oregon grape, and various small shrubs and trees. The previous stand was dominated by 60-70 year-old Douglas-fir, bitter cherry (*Prunus emarginata* (Dougl. Ex Hook.) D. Dietr.), and bigleaf maple (*Acer macrophyllum* Pursh). The previous stand’s understory was composed of sword fern, salal, and evergreen blackberry (*Rubus lacinaiatus* Willd.). In March 2000, a feller-buncher harvested the site. To alleviate harvesting compaction, an excavator subsoiled the site using a one tooth tool following the completion of excavator piling.

The site was planted with Douglas-fir and western red cedar, however; only the Douglas-fir was selected for wood quality testing.

3.3.2 Vegetation Treatments

Weed control treatments at the Sweet Home site were first conducted in 2001 and over the subsequent four years. Plots were either treated (“T”) or untreated (O”) in each year of the study. Seven treatments were implemented along with an eighth no treatment “control” (OOOOO) that received only a site preparation treatment and no herbicide release. One set of treatments received herbicide treatment in the first year (TOOOO); first two (TTOOO); first three years (TTTOO); first four years (TTTTO); first five years (TTTTT). In addition, vegetation control treatments were delayed for one year followed by 4 years of herbicide treatment (OTTTT) or for two years followed by 3 years of herbicide treatment (OOTTT). Table 3.1 shows the treatment regimes explicitly. The treatments were randomly assigned to plots within each replication. Vegetation control was implemented with the goal of maintaining <25% weed cover throughout the season by applying spring and fall treatments.

Table 3.1. Treatment by year of application.

	year				
	2001	2002	2003	2004	2005
treatment	O	O	O	O	O
	T	O	O	O	O
	T	T	O	O	O
	T	T	T	O	O
	T	T	T	T	O
	T	T	T	T	T
	O	T	T	T	T
	O	O	T	T	T

3.3.3 Tree Selection

Three sample trees were randomly selected for coring in each treatment plot from a group of the “top 50%” of trees (based on largest basal diameter) grown at 10-foot spacing in each plot (i.e. all neighboring trees were present.) This method for tree selection was chosen because the trees in the top 50%, grown at 10-foot spacing adequately represent a high percentage of the volume and value present in the plots, which is of interest to timberland owners. In addition this method was considered very repeatable. In the few cases where there were not enough trees that met the criteria, the remaining trees were selected at random from the top 50% of trees with a maximum of one missing neighbor. Justification for selecting trees with missing neighbors is in the fact that competition among trees is minimal at this stage in development. To expedite the collection of cores, the trees selected for coring were identified, flagged, and limbs that would impede the turning of an increment borer were removed on the southern half of each tree stem prior to core collection.

3.3.4 Selected Tree Growth

Tree growth variables of volume, basal diameter, dbh, height, height/diameter ratio, and crown radius were analyzed and graphed for the trees selected for wood quality assessment in the same way as the whole plot growth variables in order to verify the growth pattern of the selected tree mean growth in relation to the whole plot mean growth. Figures 3.1-3.6 show the comparison of selected tree growth and average whole plot growth.

3.3.5 Experimental Design

The experiment followed a complete randomized block design with four replications (blocks) of 8 treatments per block. Each treatment plot consisted of 36 seedlings planted on a 3 m × 3 m grid, with a row of buffer trees surrounding each treatment plot. A sub-sample of three trees from each treatment plot was selected to be cored, making a total of 96 sample cores.

3.3.6 Data Collection

3.3.6.1 Tree Cores

During dormancy, between the beginning of January and the end of February 2009, all 4 blocks were visited and three increment cores were taken from each of the 8 treatments in each block.

Using a sharpened 5.15 mm (0.25 in) diameter increment borer, each selected tree was cored between 15 and 20 cm above ground line on the southern half of the stem. Diameter at the location of the core was measured and recorded in millimeters for each tree using a small diameter tape. This location was chosen because it receives the most direct sunlight over the course of the day and year. Allowing the measurement to be taken anywhere within the southern hemisphere also allowed some flexibility for the crew member taking the core to avoid any barriers or obstacles (e.g. stumps) present, while still maintaining consistency in the collection of the cores. Obstacles large enough to completely obstruct the extraction of a core were noticed prior to final tree selection, so that an alternative tree could be randomly selected. Only the branches that directly inhibited the turning of the handle on the increment borer were removed to avoid unnecessary damage to the tree. Best proper use of the increment borer was followed as closely as possible; though, sampling at the base of the tree required some adjustment of body position in order to obtain a straight core all the way to the pith (Maeglin 1979; Jozsa 1988). As much as possible, the increment borer was inserted into the tree so that the center pith would be sampled, while keeping the instrument as level as possible so a clear radial section could be viewed. Perfect cores were not extracted every time, but the sampling protocol and procedures were carefully followed in order to reduce sampling error as much as possible. Once extracted, each tree core was promptly placed in a properly labeled straw showing the block, plot, and tree number on a piece of masking tape. The ends of the straw were folded and then taped tightly with blue painter’s masking tape so as to create an airtight seal. Any broken pieces of the core were placed in the straw in their correct position along the core, though this only occurred when the bark broke off the end of a core. The straws were kept in Ziploc bags to control moisture level and avoid loss of cores. Samples from each block were collected in 2- 4 hours depending on weather conditions.

3.3.6.2 Ring Width

Width of rings 1-8 was measured using the Velmex "TA" UniSlide System (Velmex Inc., Bloomfield, NY) with a position readout linear encoder (Acu-rite Inc., Jamestown, NY). Upon returning to the lab after field collection, each set of 24 cores was prepared for ring width measurement. Although standard procedure for measuring ring width calls for drying, mounting, and sanding of tree cores so that the rings are easy to distinguish, it was necessary to keep the cores in the green condition during ring width measurement so that further analysis of the cores would not be compromised. The green cores were allowed to become saturated in a 1.5% ethyl alcohol solution before sanding the radial surface slightly using 600-grit sandpaper. This procedure achieved a transverse surface that could be easily viewed using the Velmex "TA" UniSlide System which displays the enlarged microscope image onto a monitor screen. A cross hair was drawn on a clear plastic sheet taped to the monitor to use for tree ring delineation. Ring delineation was also achieved by using the cross-hair reticle inside the microscope eyepiece. Prior to viewing through the Velmex System, the rings were identified by use of a dissecting microscope and marked with a #2 pencil. The linear encoder allowed the position along each tree core to be displayed and recorded easily.

Within one day after sample preparation, ring width for each core was measured using the Velmex "TA" System located in the Wood Science and Engineering lab. Ring width measurements were performed with the help of a crew member who recorded the measurements of earlywood and latewood for each core, from which total ring width was calculated. Rings 1-8 were measured so that percent latewood estimates could be made for each growth ring even though other estimates were only made for rings 3, 4, and 5 and 6, 7, and 8. After the ring width was measured for each of the 24 cores in one block, a razor blade was used to cut each core into three segments. The segment composed of rings 3, 4, and 5 was termed the "pre-segment" because it represents the growth occurring prior to the end of the treatment regimes on the site. The segment composed of rings 6, 7, and 8 was termed the "post-segment" because it represents the growth that occurred after treatment regimes had ceased. Rings 1 and 2, closest to the pith were not used again. The ends of each core segment were labeled as the year of the growth ring using an ultra-fine point Sharpie pen. The respective core segments were placed in a vial containing the same 1.5% alcohol solution to maintain fiber saturation for measurement of green volume and also to keep the samples from growing mold. Each vial contained a label including block, plot, tree number, and years of growth hand written on "rite in the-rain" paper.

3.3.6.3 Photographs

Photographs of the cores were taken prior to ring width measurement in the Forest Research Lab at the time of sanding to serve not only as a back-up for ring width measurement in case something should happen to the cores, but also as a study catalog for future reference. Each core was photographed with a Canon SD digital camera (Canon U.S.A., Inc., Lake Success, NY) with a close-up setting. The cores were placed in a notched block of wood built specifically to hold them still during analysis. A millimeter ruler was positioned next to the core, with zero on the left, positioned at the pith, to indicate the scale of the photograph. A label showing block, plot and tree was visible in each photograph as well.

3.3.6.4 Specific Gravity

Specific gravity was one of several attributes chosen to represent wood quality in this study. Specific gravity of the pre-segment and post-segment of each core was determined on an oven-dry weight and green volume basis using the water-immersion method (Smith 1954; Smith 1955; Haygreen and Bowyer 1996; ASTM Standard 2007). Specific gravity was calculated from green volume and oven-dry weight which were measured for each segment using the following procedure.

The equipment used to measure specific gravity is:

Mettler balance
Tray of labeled vials containing alcohol solution for samples to remain in before and after water weighing
Metal rig for suspending sample in tank
Plastic tank containing water
Labeled plastic trays for oven drying
Tongs for handling samples
Tissue for blotting samples
Ultra-fine point Sharpie pen for labeling samples

Procedure for weighing the samples:

1) Level and zero the balance.

2) Place the stand and water tank on the balance and position rig in the water suspended from the stand.

3) Before inserting each core sample in the metal rig, zero the balance with the empty rig suspended in the water tank to eliminate the volume of the rig from the core volume. Weigh each sample being careful not to touch the sample to the sides or bottom of the tank. After weighing, each sample must be put back in its respective vial until all are weighed.

4) After all volumes are complete, place samples in a plastic tray to air-dry overnight.

5) The following day, place samples in an oven at 75 °C for 48 hours. Remove samples from oven and cool for 30 minutes in $CaSO_4$ desiccator and weigh again as quickly as possible to avoid absorption of moisture by the samples.

6) Calculate specific gravity according to equation 1:

[1] $$\text{specific gravity} = \left(\frac{oven\ dry\ weight\ (g)}{green\ volume\ (cm^3)}\right) / \text{density of water } (1\ \text{g/cm}^3)$$

As a way of validating the water-immersion method, the volume of each ring segment was also measured using the empirical method described by Valencia-Manzo and Vargas-Hernandez (1997). This method of volume measurement requires knowledge of the inside diameter of the increment borer used to collect samples as well as the length of each sample in the same units. The inside diameter of the increment borer used for this study was 5.15 mm which was converted to cm for the purpose of calculating specific gravity which is based on a g/cm^3 scale. Equation 2 was then used to calculate the volume:

[2] $$\text{volume of ring segment in cm}^3 = \pi r^2 \times \text{length}$$

Specific gravity determined by the empirical method was then calculated by dividing the oven-dry weight by the calculated volume. Correlation analysis was used to assess the relationship between the volumes and specific gravity values for both methods for validation of the procedures used to report specific gravity.

3.3.6.5 Scanning Electron Microscopy (SEM)

Following the specific gravity measurement procedures, the core segments were stored in air tight containers until SEM could be performed at the end of May 2009. Electron microscopy uses a beam of electrons to create a highly magnified image of a specimen according to the correlation between wavelength and resolution; reducing wavelength results in increasing resolution. Traditional methods required a skilled technician as well as biological and non-conductive samples to be prepared with a metallic coating; however the newest technology utilizes a variable pressure vacuum and does not require coated samples or a skilled operator. This makes the use of SEM much more accessible to a broad range of interested parties.

Using the Hitachi TM-1000 Table-top SEM (Hitachi High Technologies America, Inc.) provided by Marine Reef International in Costa Mesa, California, images were obtained of several tree core segments. The Hitachi TM-1000 utilizes scanning electron microscope technologies to provide users with a quick and straightforward system that supplies the same high powered images as the traditional SEM technology. Two trees were selected for imaging from treatment TTTTT (tree 31 from block 8 and tree 33 from block 3) and two trees were selected from treatment OOOOO (tree 15 from block 8 and tree 32 from block 3). Both the pre- and post-segments were imaged from each tree. Tree cores were selected for SEM imaging based on their having the largest difference in specific gravity between the two same-tree core segments (pre-segment > post-segment). Originally, trees from treatments TTOOO and OOTTT were to be imaged as well, but time was limited, so only the TTTTT and OOOOO treatments were observed.

There was difficulty seeing the samples projected on the monitor at first and it was determined that a clean cut radial surface of the core was necessary for viewing the cell structure. Each core to be sampled was carefully cut using a sharp razor blade. It was not possible to achieve a perfectly clean surface every time, so some images had rough areas where the blade damaged the viewing surface. It is recommended for future studies that a sliding microtome be used to prepare the surface of the cores prior to ring width and specific gravity measurement. After the cores were prepared for imaging, a core segment was positioned on the sample stage using double sided tape so that the pith end was on the left and the bark end was on the right. The sample could then be moved from left to right along a constant Y axis, using the manual dials on the TM-1000. Because of the limited traverse capacity of the TM-1000, multiple images were obtained of each sample segment. Between 15 and 40 images of each segment were obtained at a magnification of ×150 so that rows of cells could be seen as well as transitions from earlywood to latewood. Care was taken to identify markers at the edge of each image, so that the images could later be stitched together manually after they were printed.

Evaluation of the images consisted of laying out the stitched images of opposing treatments side by side. The distinct boundary between ring 4 and ring 5 from the pre-segment was selected for evaluation because these images were of the highest visual quality, best capturing the boundary between latewood and earlywood in both treatments of interest. Next, a square frame, representing a 250 $\mu m \times$ 250 μm (micrometer) square area (1 mm = 1,000 μm), was placed on the image so that the one edge of the opening was lined up with the border between ring 4 latewood and ring 5 earlywood. The number of cells inside the frame was estimated by multiplying the number counted on the vertical axis by the number counted on the horizontal axis. Ray cells were excluded from the count. This procedure was completed for the latewood of ring 4 and earlywood of ring 5 for the two trees in the TTTTT and the two trees in the OOOOO, and then averaged across blocks 3 and 8. The images of the post-segments did not turn out well enough to obtain averages from the two blocks.

3.3.7 Derived Variables

3.3.7.1 Specific Gravity post/pre Ratio

To illustrate the trend of specific gravity over time, the ratio of specific gravity calculated for the post-segment was divided by the specific gravity calculated for the pre-segment for each treatment regime.

3.3.7.2 Segment Length

Ring segment length was derived from the individual ring width measurements taken using the Velmex “TA” system. The sum of rings 3, 4, and 5 constitute the pre-segment length and the sum of rings 6, 7, and 8 constitute the post-segment length.

The summation of ring widths into ring segment lengths was of particular interest because specific gravity was calculated for these segments rather than for individual rings.

3.3.7.3 Percent Latewood

Percent latewood is an attribute that also contributes to wood quality. It was derived by multiplying the sum of the latewood in the pre- and post-segments by the total length of each segment (Vargas-Hernandez and Adams 1991; Koch and Fins 2000).

3.3.7.4 Biomass Increment

Biomass is considered to be any carbon-based material produced by autotrophic or heterotrophic organisms (Haygreen and Bowyer 1996). In the context of this study, biomass refers to the mass of stem wood produced by Douglas-fir trees. Biomass increment is the amount of stem wood mass produced in a given time period. This response variable provides an estimate of the potential biomass (of which, 50% is carbon) that is being stored in the Sweet Home CPT treatment plots. To calculate biomass from wood volume, either wood density or specific gravity must also be known, and the latter supplemented with density of water. (Bettinger et al. 2009). Because wood volume was calculated in cubic centimeters, the density of water is known to be 1 g/cm^3, and specific gravity is a unitless value, the volume units cancel leaving biomass in grams. The specific gravity of the pre- and post-segments were obtained from increment cores taken at 15-20cm above the ground line. This single value for specific gravity was used to estimate biomass, despite the fact that specific gravity is known to change vertically within a tree.

The pre- and post-volume increments are the segments for which specific gravity was measured. In order to calculate stem volume corresponding to each radial increment, it was first necessary to calculate the basal area increments for wood only. All diameters were measured outside bark (DOB), so the conversion formula based on prediction equations developed by Larsen and Hann (1985), shown in equation 3, was used to convert the values to diameter inside bark (DIB) to achieve wood only increments:

[3] $$DIB = 0.903563 \times DOB^{0.989388}$$

Using the diameter outside bark (DIB) field measurements for basal diameter collected at the end of years two (basal area$_1$) and five (basal area$_2$) for the pre-increment and at the end of years five (basal area$_1$) and eight (basal area$_2$) for the post-increment, basal area was calculated using the formula found in Avery and Burkhart (2002), shown in equation 4:

[4] $$basal\ area\ inside\ bark = \frac{\pi}{4} \times\ basal\ diameter^2$$

Once all basal area values for the pre- and post-increments were calculated, basal $area_1$ and basal $area_2$ for pre- and post-increments were multiplied by the corresponding $height_1$ and $height_2$. Like basal area, $height_1$ was measured at the end of year two and $height_2$ was measured at the end of year five for the pre-increment. For the post-increment, $height_1$ was measured at the end of year five and $height_2$ was measured at the end of year eight. Volume increment was then calculated for pre- and post-increments using equation 5 assuming a conical shape of the seedlings:

[5]
$$\text{volume increment } (cm^3) = \frac{1}{3}(\text{basal area}_2 \times \text{height}_2 \text{- basal area}_1 \times \text{height}_1)$$

Calculation of the biomass increment was similar to the method used by Bouriaud et al. (2005) in which volume increment was multiplied by corresponding ring specific gravity to obtain direct measurements rather than model estimates. The volume increments in the present study were multiplied by specific gravity for the corresponding ring segment to provide an estimate of the amount of biomass being produced in for each growth period on these treatment plots.

In order to present the biomass increment data in terms of the EPA standard for greenhouse gas emissions equivalency, it was necessary to convert biomass from grams to kilograms so that it could be converted to metric tons more easily (1 kilogram = 0.001 metric tons). This is because the metric ton is the common unit for reporting CO_2 emissions. Because dry biomass is approximately 50% carbon

(Bettinger et al. 2009; EPA 2009), the biomass increment was multiplied by 0.5 to determine the stored carbon equivalent. Once the stored carbon equivalent was calculated, the equivalent CO_2 could be calculated using the following basic equation (Fried and Zhou 2008).

[6] $$CO_2\ equivalent = 3.67 \times (0.5 \times biomass)$$

One unit of stored carbon equates to 3.67 units of CO_2 emission equivalent. This factor is based on the ratio of the atomic mass of the CO_2 molecule (44) to the atomic mass of the carbon atom (12) (44/12 = 3.67) (EPA 2005).

In addition to estimates of carbon and CO_2 equivalent for each biomass increment, an estimate of whole tree CO_2 equivalent across treatments was computed. In order to calculate whole tree biomass, mean tree volumes obtained from the results of the selected tree growth (Figure 3.1) and the mean of pre- and post-segment specific gravity were multiplied. Equation 6 was applied to estimate the amount of whole tree carbon and CO_2 equivalent.

3.3.8 Statistical Approach

Treatment effects on average tree increment were analyzed under a randomized complete block design using Statistical Analysis Software version 9.1 (SAS Institute Inc. Cary, North Carolina). The ANOVA model assumptions of normality, homogeneity of variance, and linearity of the residuals were checked for each variable analyzed. Analyses of the growth period three years prior to the end of treatment (pre-segment) and the growth period three-years after termination of treatment (post-segment) were conducted separately using analysis of variance to test treatment effects for specific gravity, specific gravity post/pre ratio, segment length, percent latewood, and biomass increment. Fisher's protected least significant difference tests were used to identify treatment differences for all variables. Standard errors for all variables were calculated for treatment means across replications.

3.4 Results

Year-eight Douglas-fir growth was significantly increased by controlling competing vegetation for three or more years. No significant treatment effect on specific gravity was detected, only a gradual negative trend. Ring width of pre- and post-segments and pre-segment percent latewood were significantly increased and reduced, respectively, by control of competing vegetation. Biomass accumulation or increment was also significantly increased by competing vegetation control for three or more years. Three years is the apparent threshold for maximizing growth at the Sweet Home CPT site.

3.4.1 Selected Tree Growth

Growth attributes for the trees selected for wood quality assessment were on average higher (or lower in the case of height/diameter ratio) than for the same attributes for all plot trees. All growth attributes for the selected wood quality trees were significantly affected by treatment (Table 3.2; Fig. 3.1-3.6).

Table 3.2. ANOVA table for volume (dm^3), basal diameter (cm), dbh (cm), height (cm), height/diameter ratio, and crown radius (cm) for Douglas-fir trees selected for wood quality assessment ($\alpha \leq 0.05$).

Douglas-fir: Trees selected for wood quality testing						
Parameter	**Source**	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
Volume 08	block	3	779.11	259.70	1.79	0.1550
	trt	7	17058.97	2437.00	16.81	<0.0001
Basal diameter 08	block	3	19.78	6.59	1.77	0.1597
	trt	7	509.39	72.77	19.50	<0.0001
DBH 08	block	3	4.47	1.49	0.40	0.7510
	trt	7	130.83	18.69	5.06	<0.0001
Height 08	block	3	53909.00	17969.67	2.78	0.0460
	trt	7	213636.17	30519.45	4.72	0.0002
Height-Diameter Ratio 08	block	3	560.34	186.78	5.28	0.0022
	trt	7	2335.91	333.70	9.44	<0.0001
Crown Radius 08	block	3	1810.07	603.36	1.16	0.3314
	trt	7	50441.02	7205.86	13.81	<0.0001

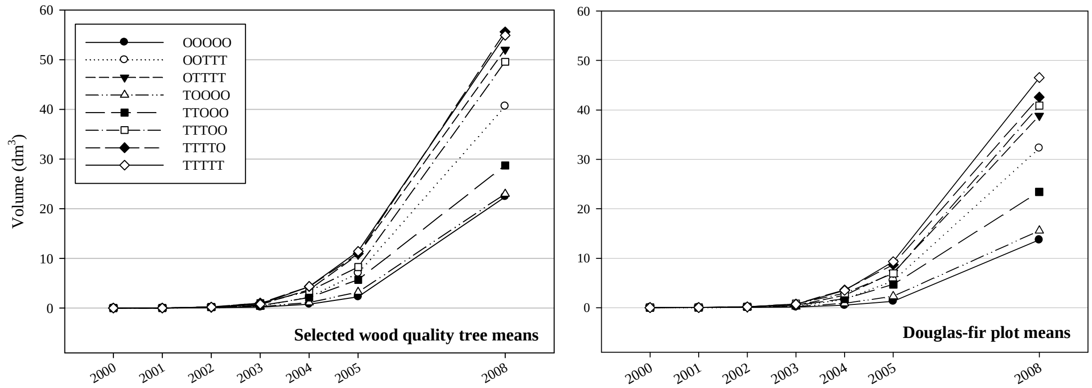

Figure 3.1. Mean volume (dm^3) growth for Douglas-fir trees selected for wood quality compared to the mean volume (dm^3) growth for all Douglas-fir from each treatment.

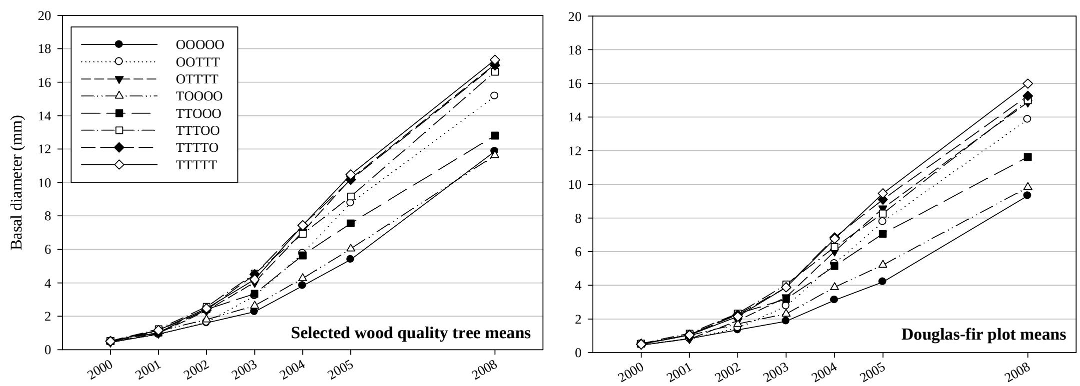

Figure 3.2. Mean basal diameter (cm) growth for Douglas-fir trees selected for wood quality compared to the mean basal diameter (cm) growth for all Douglas-fir from each treatment.

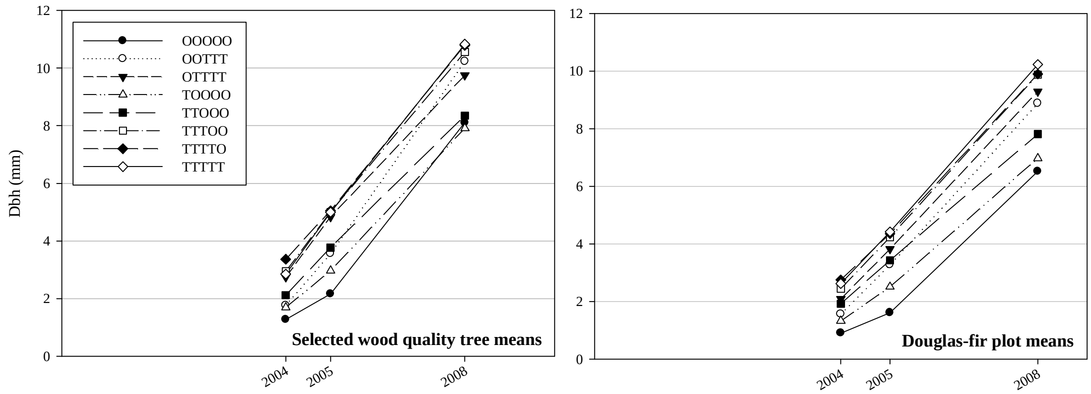

Figure 3.3. Mean dbh (cm) growth for Douglas-fir trees selected for wood quality compared to the mean dbh (cm) growth for all Douglas-fir from each treatment.

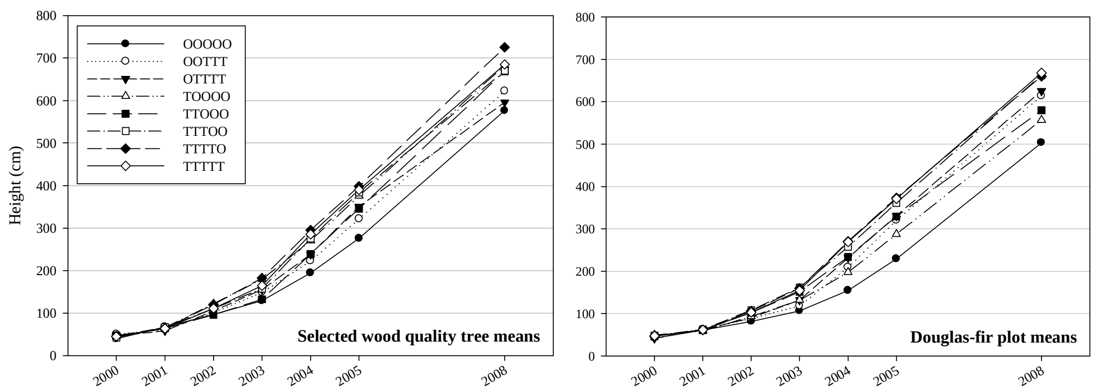

Figure 3.4. Mean height (cm) growth for Douglas-fir trees selected for wood quality compared to the mean height (cm) growth for all Douglas-fir from each treatment.

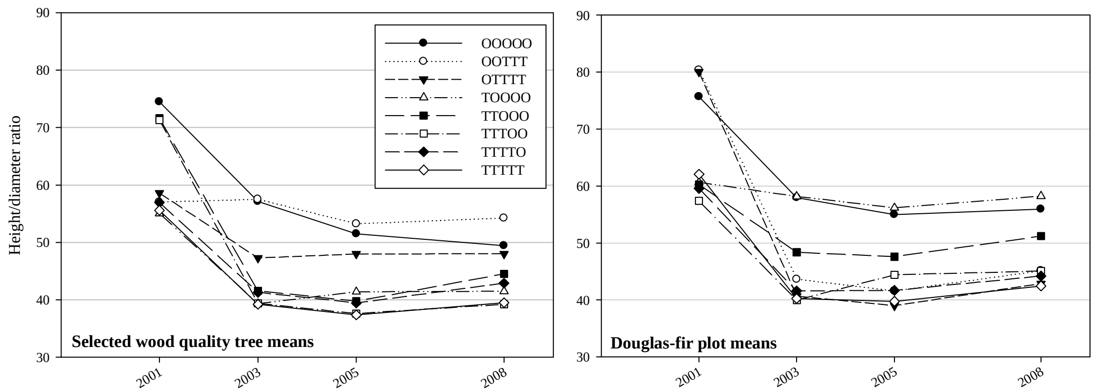

Figure 3.5. Mean height/diameter ratio for Douglas-fir trees selected for wood quality compared to the mean height/diameter ratio for all Douglas-fir from each treatment.

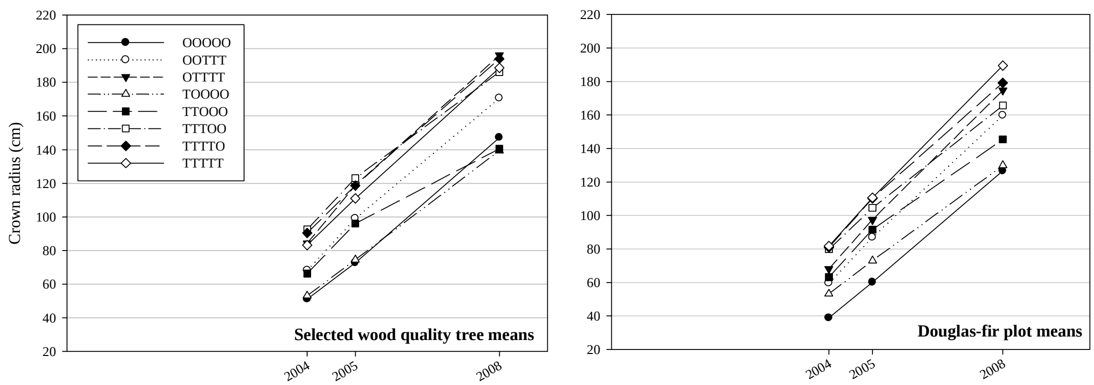

Figure 3.6. Mean crown radius (cm) growth for Douglas-fir trees selected for wood quality compared to the mean crown radius (cm) growth for all Douglas-fir from each treatment.

Treatment effects (most noticeably for volume, basal diameter, and dbh) appear smaller for the selected tree means than for whole plot means. There is some shift in the pattern of treatments for the different variables, but in general treatments having more continuous intensive competing vegetation control have greater growth response and lower height/diameter ratio.

3.4.2 Specific Gravity

Comparison of the water immersion method and the empirical method resulted in a strong positive correlation, verifying the virtual equivalence of the two methods. Ring segment volumes calculated using the empirical method and the water immersion method were highly correlated having an R^2 = 0.94 for both pre- and post-segments (Figure 3.7). Specific gravity values for both methods were also correlated, though not as highly, having R^2 = 0.59 for the pre-segments and R^2 = 0.51 for the post-segments (Figure 3.8). Specific gravity from the water immersion method were used for all subsequent analyses.

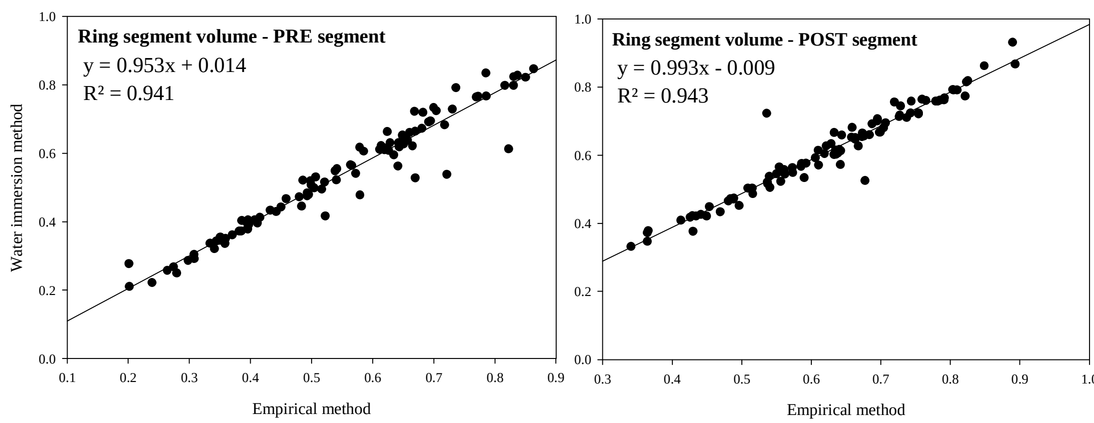

Figure 3.7. Scatterplots and regression equations for volume of PRE (rings 3, 4, and 5) and POST (rings 6, 7, and 8) ring segments using the water immersion method vs. the empirical method.

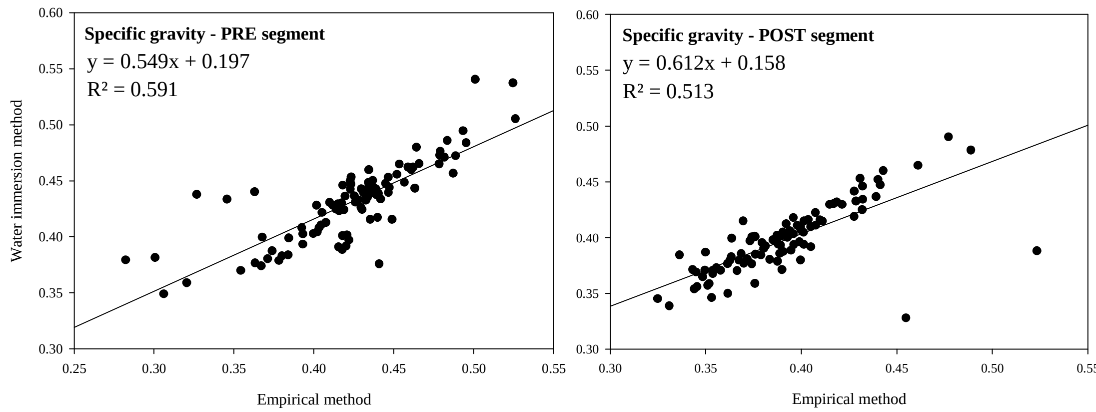

Figure 3.8. Scatterplots and regression equations for specific gravity of PRE (rings 3, 4, and 5) and POST (rings 6, 7, and 8) ring segments using the water immersion method vs. the empirical method.

In regard to hypotheses 1 and 2, results from the ANOVA showed that there were no statistically significant treatment effects on specific gravity of either the pre- or post-segments of growth at $\alpha = 0.05$ (*p values* = 0.0843 and 0.0984, Table 3.3). As vegetation was controlled for an increasing number of consecutive years, there was a trend of lower specific gravity for both segments (Figure 3.9). Pre-segment specific gravity was significantly greater than for the post-segment in all treatments. Mean specific gravity in the pre-segment ranged from 0.45 in the TOOOO treatment to 0.41 in the TTTTT treatment, and in the post-segment, from 0.41 in the OOOOO treatment to 0.37 in the TTTTO treatment. All treatment mean specific gravity values were within the range (0.36-0.54) of expected values for Douglas-fir (Haygreen and Bowyer 1996, Table 3.4).

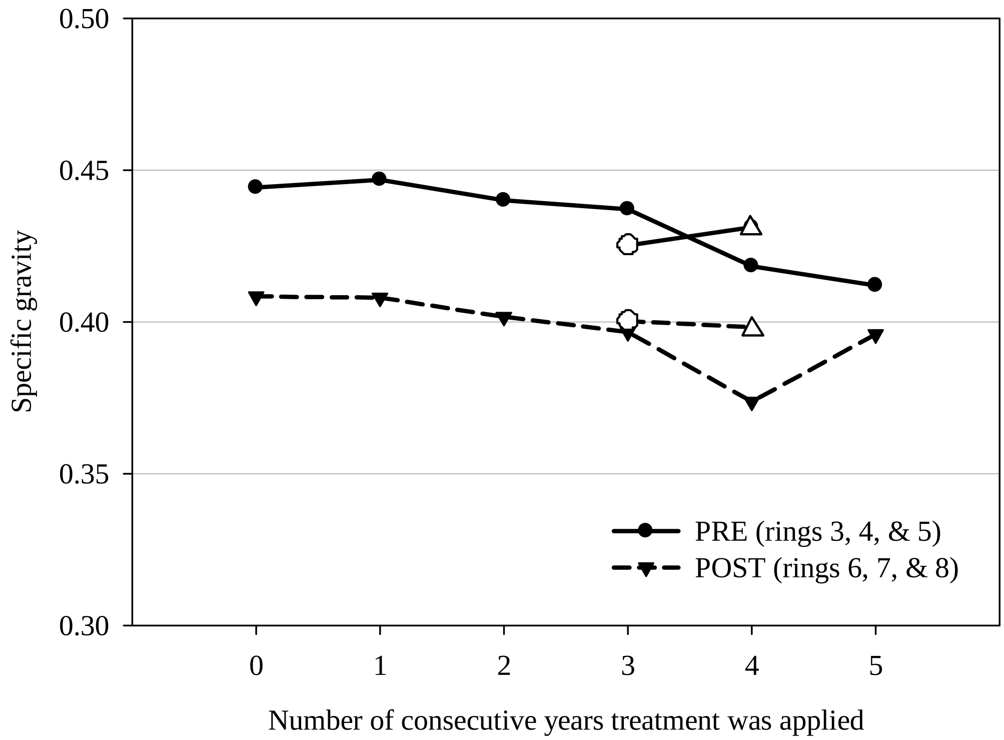

Figure 3.9. Comparison of specific gravity of PRE (rings 3, 4, & 5) and POST (rings 6, 7, & 8) segments by number of consecutive years of treatment. The two delayed treatments were OTTTT and OOTTT and are represented by the symbols △ and ⬡, respectively.

Table 3.3. ANOVA table for Douglas-fir specific gravity, specific gravity POST/PRE ratio, segment length (mm), [1]biomass increment (kg), and latewood (%) for PRE and POST segments ($\alpha \leq 0.05$).

Parameter	DF	Type III SS	Mean Square	F Value	Pr > F
PRE Specific gravity					
block	3	0.0063	0.0021	6.11	0.0037
trt	7	0.0051	0.0007	2.14	0.0843
POST Specific gravity					
block	3	0.0041	0.0014	5.99	0.0041
trt	7	0.0033	0.0005	2.03	0.0984
Specific gravity POST/PRE Ratio					
block	3	0.0062	0.0021	2.03	0.141
trt	7	0.0105	0.0015	1.46	0.2334
PRE Segment length					
block	3	33.15	11.05	1.65	0.2071
trt	7	1390.05	198.58	29.74	<0.0001
POST Segment length					
block	3	149.73	49.91	5.74	0.005
trt	7	333.29	47.61	5.47	0.0011
PRE Latewood (%)					
block	3	1.00	0.33	0.05	0.9864
trt	7	229.40	32.77	4.54	0.0032
POST Latewood (%)					
block	3	56.37	18.79	2.73	0.0695
trt	7	38.70	5.53	0.8	0.5934
PRE Biomass increment					
block	3	1.38	0.46	0.83	0.4793
trt	7	106.28	15.18	27.45	<0.0001
POST Biomass increment					
block	3	35.93	11.98	0.99	0.4023
trt	7	815.28	116.47	9.61	<0.0001

[1]Biomass increment was derived from the product of the volume increment in the PRE and POST segments and the corresponding specific gravity for those segments by treatment regime.

Table 3.4. Mean Douglas-fir specific gravity, specific gravity post/pre ratio, segment length (mm), latewood (%), and biomass increment (kg) for data collected in year-eight at the Sweet Home CPT site. Standard errors of treatment means are shown in parentheses. Values within a column with different letters are significantly different ($\alpha \leq 0.05$).

Treatment	Specific gravity		Specific gravity post/pre ratio	Segment length (mm)		Latewood (%)		Biomass increment (kg)	
	pre[1]	post[2]		pre	post	pre	post	pre	post
(SE)	*(0.009)*	*(0.008)*	*(0.016)*	*(1.29)*	*(1.47)*	*(1.34)*	*(1.31)*	*(0.21)*	*(1.00)*
OOOOO	0.444	0.408	0.92	15.13 *d*	24.10 *b*	10.80 *a*	7.35	0.76 *d*	6.63 *c*
OOTTT	0.425	0.400	0.94	28.19 *b*	30.63 *a*	6.00 *bc*	8.71	2.34 *bc*	10.50 *b*
OTTTT	0.431	0.398	0.93	32.38 *a*	30.98 *a*	4.36 *c*	8.69	3.62 *a*	12.77 *ab*
TOOOO	0.447	0.408	0.92	17.41 *d*	25.06 *b*	11.13 *a*	9.09	1.10 *d*	6.29 *c*
TTOOO	0.440	0.402	0.91	22.31 *c*	31.86 *a*	9.89 *ab*	7.79	1.94 *c*	7.27 *c*
TTTOO	0.437	0.397	0.91	28.91 *ab*	32.54 *a*	6.39 *bc*	7.00	2.80 *b*	12.80 *ab*
TTTTO	0.412	0.374	0.91	32.70 *a*	32.74 *a*	7.44 *abc*	8.67	3.50 *a*	13.03 *ab*
TTTTT	0.412	0.396	0.96	32.58 *a*	32.31 *a*	3.73 *c*	5.60	3.60 *a*	13.37 *a*

[1] pre = rings 3, 4, and 5 were combined into a single segment for measurement.

[2] post = rings 6, 7, and 8 were combined into a single segment for measurement.

Correlation analysis between specific gravity and each of the growth variables analyzed for the trees selected for wood quality assessment revealed very weak negative linear relationship for all variables ($R^2 \leq 0.07$), with the exception of height/diameter ratio, which had a very weak positive relationship with specific gravity ($R^2 \leq 0.02$). The relationships between specific gravity and segment length and specific gravity and percent latewood were analyzed, resulting in very weak positive linear relationship between specific gravity and percent latewood ($R^2 \leq 0.07$) and a very weak negative relationship between specific gravity and segment length ($R^2 \leq 0.07$).

3.4.3 Specific Gravity post/pre Ratio

With respect to hypothesis 3, results of the ANOVA revealed there were no treatment effects on the specific gravity post/pre ratio (*p value* = 0.2334, Table 3.3). The ratio of post- to pre-segment specific gravity was very close to 1, (ranging from 0.91-0.96) for all treatments (Figure 3.10.A and 3.10.B) because the post-segment specific gravity values were lower than those of the pre-segment across all treatments (Table 3.4.)

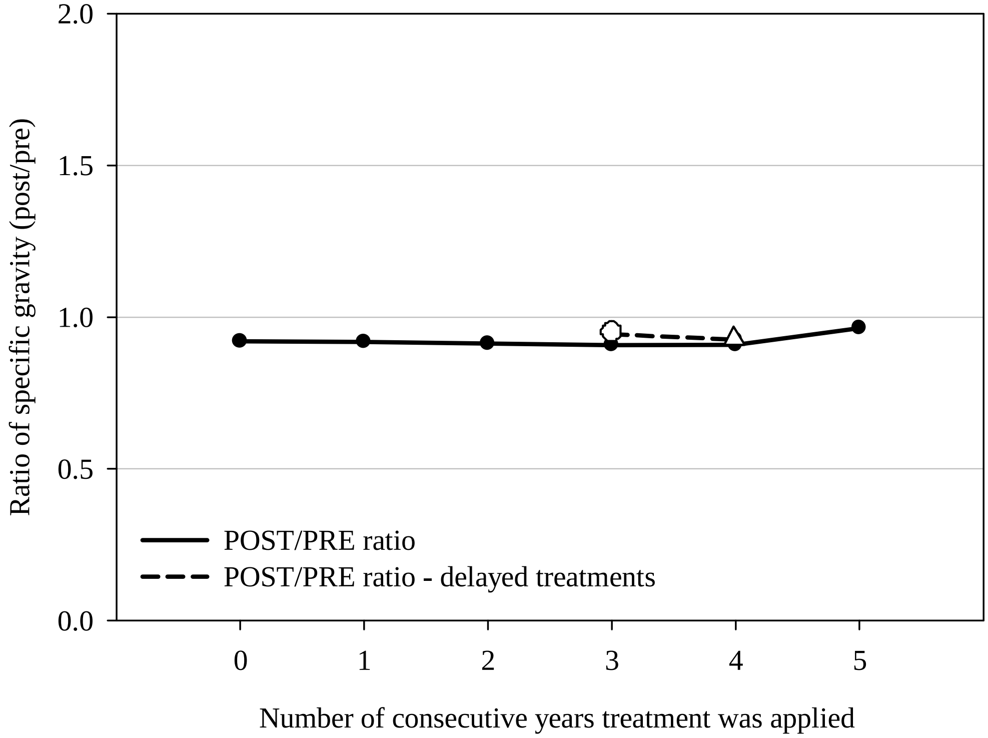

Figure 3.10.A. Comparison of specific gravity POST/PRE ratio by number of consecutive years of treatment, broad scale. The dashed line represents the delayed treatments which were OTTTT and OOTTT and are represented by the symbols △ and ○, respectively.

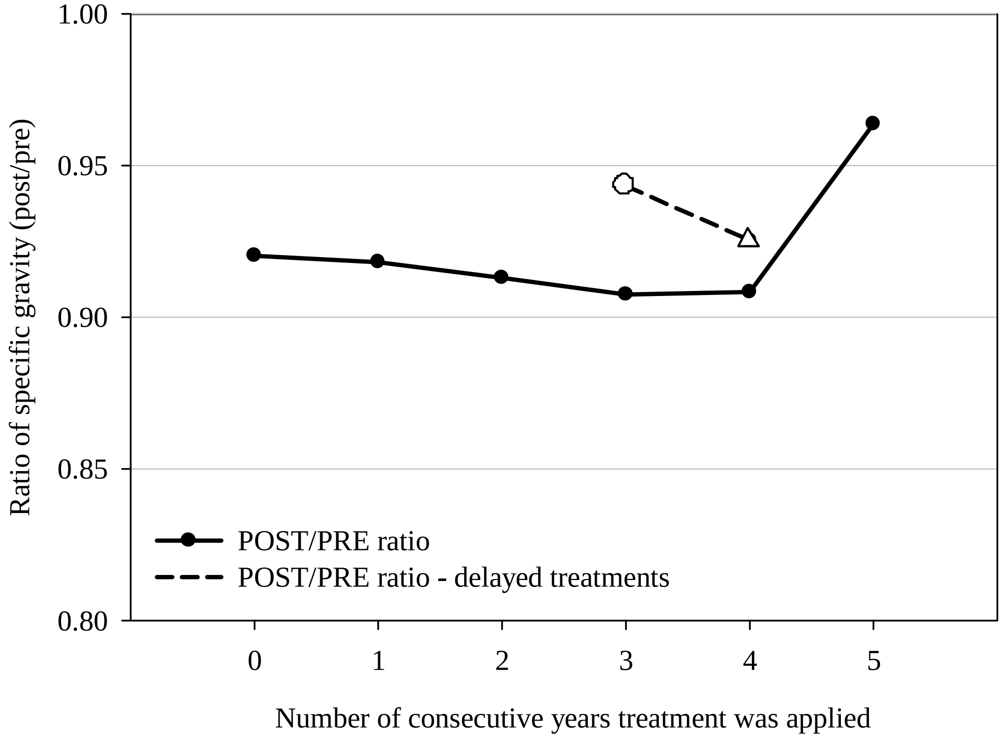

Figure 3.10.B. Comparison of specific gravity POST/PRE ratio by number of consecutive years of treatment, fine scale. The dashed line represents the delayed treatments which were OTTTT and OOTTT and are represented by the symbols △ and ○, respectively.

3.4.4 Segment Length

With respect to hypotheses 4 and 5, results of the ANOVA for both pre- and post-segments revealed that segment length was affected by the treatments (*p value* < 0.0001 and 0.0011, respectively, Table 3.3). Pre-segment lengths ranged from 15.13 mm in the OOOOO treatment to 32.70 mm in the TTTTO treatment. Post-segment lengths ranged from 24.10 mm in the OOOOO to 32.74 mm in the TTTTO treatment. Lengths for both segments increased with increasing duration of vegetation control, reaching a plateau at approximately 3 consecutive years of competing vegetation control (Figure 3.11).

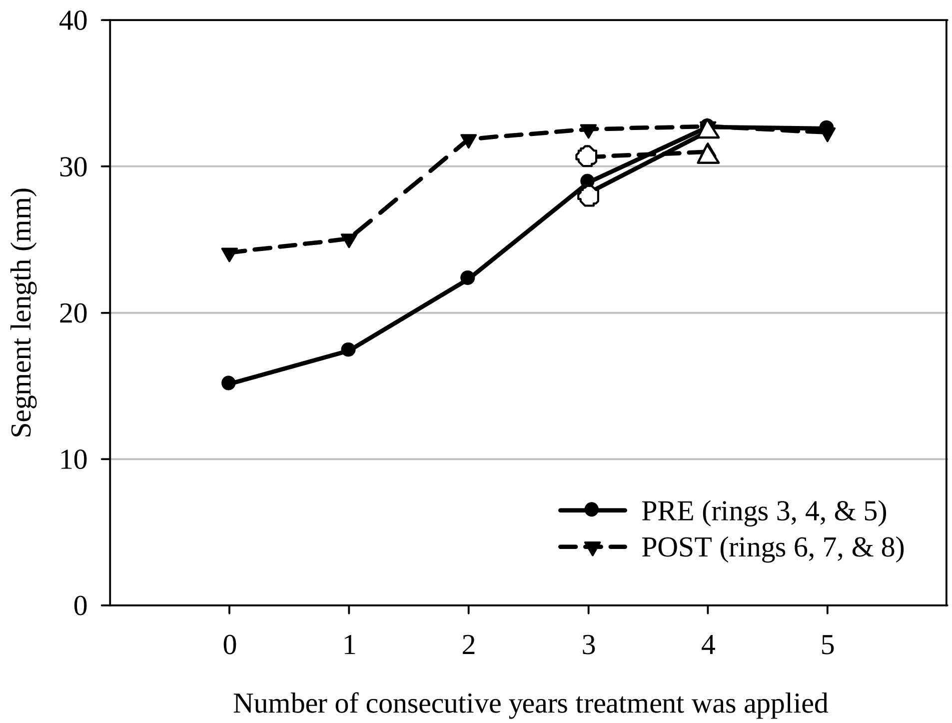

Figure 3.11. Comparison of segment length of PRE (rings 3, 4, & 5) and POST (rings 6, 7, & 8) segments by number of consecutive years of treatment. The two delayed treatments were OTTTT and OOTTT and are represented by the symbols △ and ⬡, respectively.

In the pre-segment, treatments having three initial years of vegetation control or more did not differ from each other but had significantly greater segment lengths than treatments having less than 3 initial years of vegetation control. The treatments having 3 years of initial control with a 1- or 2-year delay did not differ from each other. Two years of vegetation control had significantly shorter segment lengths than those treatments having longer duration of vegetation control. Treatments having zero or 1 initial year of vegetation control did not differ from each other and had the shortest segment lengths of all the treatments.

For the post-segment, treatments having 2 or more years of vegetation control did not differ in segment length from each other but were significantly greater than treatments having zero to one year of vegetation control. Mean segment length for 2+ years of vegetation control was 31.84 mm, a 30% increase in segment length over treatments having zero or 1 initial year of vegetation control, with the latter having a mean segment length of 24.58 mm (Table 3.4).

3.4.5 Percent Latewood

In regard to hypotheses 6 and 7, results of the ANOVA revealed that for the pre-segment, percent latewood was significantly affected by the treatments (*p value* = 0.0032, Table 3.3). No treatment effects were detected in percent latewood of the post-segment (*p value* = 0.5934, Table 3.3). Treatment estimates are shown in Table 3.4. Percent latewood in the pre-segment ranged from 3.73% in treatment TTTTT to 11.13% in treatment TOOOO. For the same treatments the post-segment ranged from 9.1% to 5.6%. For the pre-segment, treatments OOOOO, TOOOO, TTOOO, and TTTTO were not statistically different from each other, having a mean percent latewood of 9.8%. A 192% decrease in percent latewood was observed for TTTTT relative to OOOOO, corresponding to an increase in segment length of 115%.

Both segments demonstrated a general trend of decreasing percent latewood with increasing duration of vegetation control. The post-segment percent latewood, however, increased slightly over the pre-segment percent latewood with the application of three or more years of vegetation control (Figure 3.12.A). Figure 3.12.B shows the percent latewood per ring averaged over treatment with a sharp decline from ring 1 to ring 3, followed by a less steep decline from ring 3 to ring 5, after which, percent latewood seems to be relatively constant for rings 6, 7, and 8.

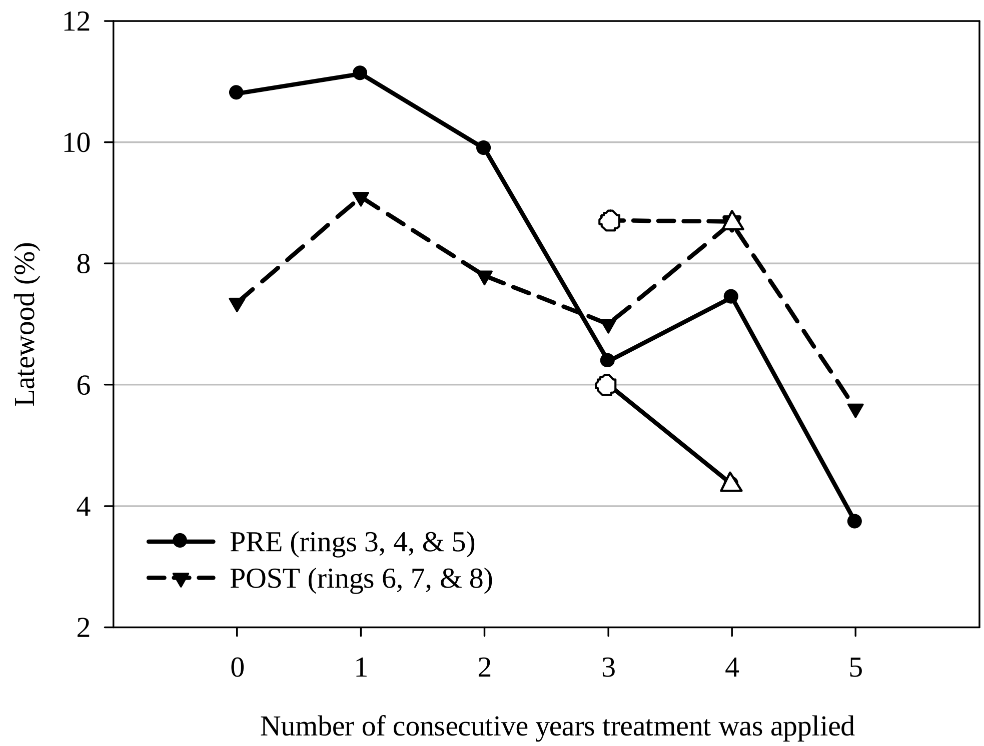

Figure 3.12.A. Comparison of percent latewood of PRE (rings 3, 4, & 5) and POST (rings 6, 7, & 8) segments by number of consecutive years of treatment. The two delayed treatments were OTTTT and OOTTT and are represented by the symbols △ and ⬡, respectively.

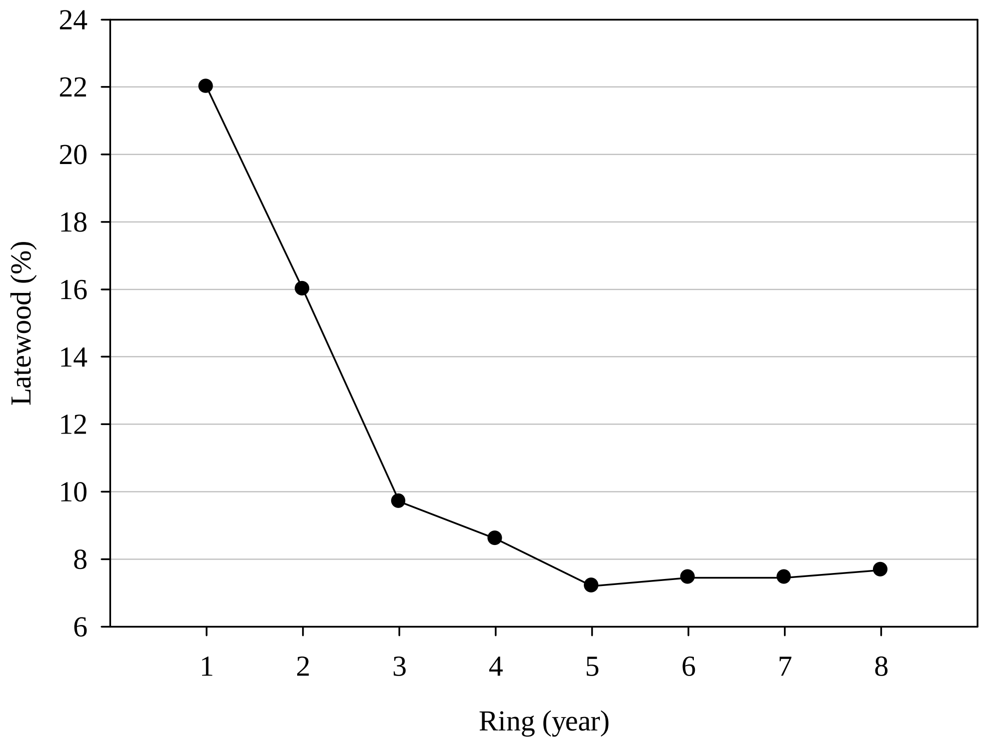

Figure 3.12.B. Percent latewood present in rings 1-8 averaged across all treatments.

3.4.6 Biomass Increment

In regard to hypotheses 8 and 9, ANOVA revealed that biomass increment for both the pre- and post-segments were significantly affected by treatment (*p values* < 0.0001 and < 0.0001, Table 3.3). Generally, biomass increment increased with increasing years of competing vegetation control (Figure 3.13). For the pre-segment, the OOOOO and TOOOO treatments did not differ significantly from each other and had a mean biomass increment of 0.93 kg. The TTOOO did not differ significantly from the OOTTT which did not differ significantly from TTTOO; however, TTOOO and TTTOO were significantly different from each other. The mean biomass increment of these three treatments was 2.36 kg, a 156% increase over the control and the TOOOO. Treatments TTTTO, OTTTT, and TTTTT were not significantly different from each other and had a mean biomass increment of 3.57 kg, a 283% increase over the control and the TOOOO.

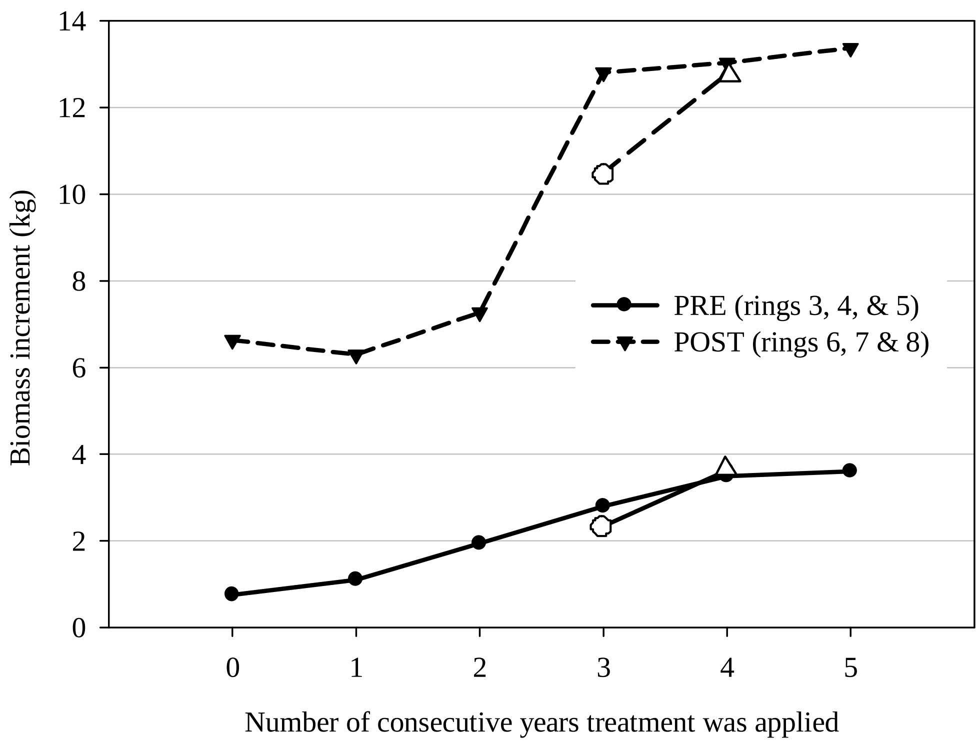

Figure 3.13. Comparison of biomass increment (kg) of PRE (rings 3, 4, & 5) and POST (rings 6, 7, & 8) segments by number of consecutive years of treatment. The two delayed treatments were OTTTT and OOTTT and are represented by the symbols △ and ⬡, respectively.

For the post-segment, treatments OOOOO, TOOOO, and TTOOO had the lowest mean biomass increment (6.73 kg), and these treatments did not differ significantly from each other (Table 3.4). Treatments having three or four years of treatment regardless of timing did not differ from each other, but had a mean biomass increment of 12.27 kg, a 77% increase over the treatments yielding the lowest biomass increment. A 113% increase from the highest yielding treatment (TTTTT) over the lowest yielding treatment (TOOOO) was observed (Table 3.4).

The equivalent stored carbon and CO_2 absorption in the wood quality Douglas-fir trees was greater in the post-treatment than in the pre-treatment period at the Sweet Home CPT site (Figure 3.14). Tests for treatment differences would be identical to the results for biomass increment because the response variables were biomass increment multiplied by a constant (0.5 and 3.67) for carbon and CO_2, respectively.

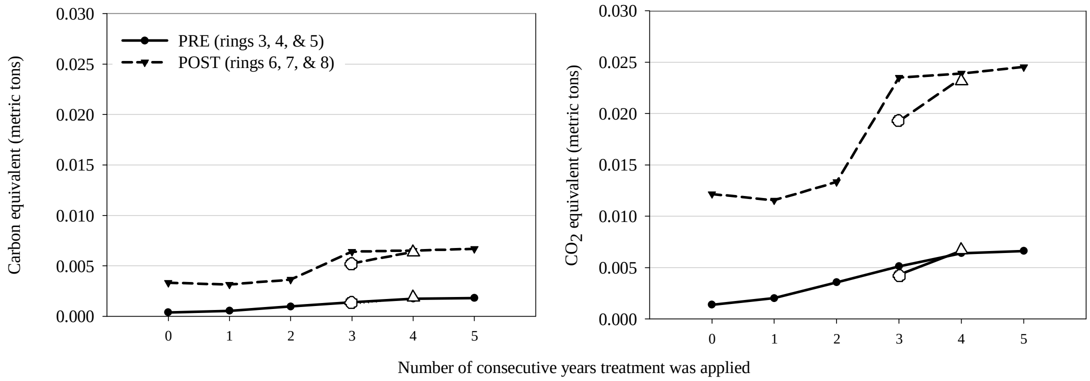

Figure 3.14. Equivalent stored carbon and CO_2 in metric tons for the PRE and POST treatment periods of the Douglas-fir trees selected for wood quality measurement at the Sweet Home CPT site. The two delayed treatments were OTTTT and OOTTT and are represented by the symbols △ and ○, respectively.

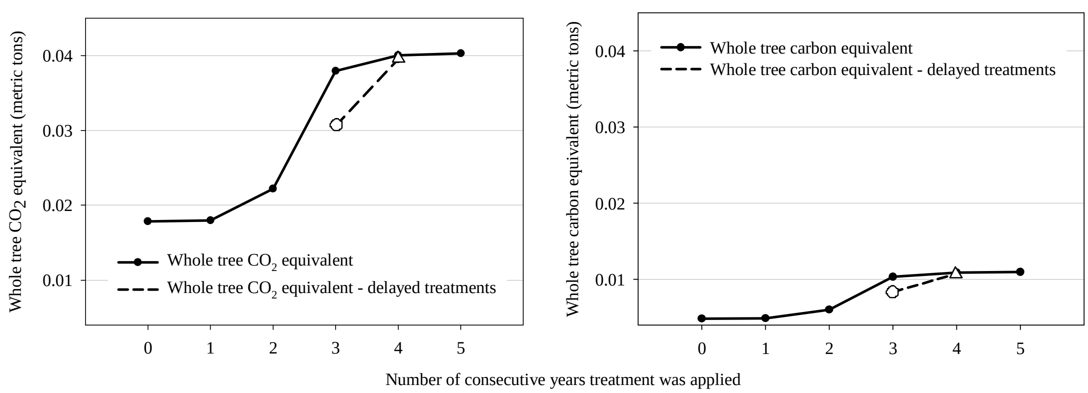

Figure 3.15. Equivalent stored carbon and CO_2 in metric tons for the entire growth period (2001-2008) of Douglas-fir trees selected for wood quality measurement at the Sweet Home CPT site. The dashed line represents the delayed treatments which were OTTTT and OOTTT and are represented by the symbols △ and ○, respectively.

3.4.7 Scanning Electron Microscopy

Assessment of the SEM images in regard to objective 2 revealed that ring 5 earlywood in treatment OOOOO compared to ring 5 earlywood in treatment TTTTT had a 50% greater mean number of cells per 62,500 μm^2. Similarly, ring 4 latewood in the OOOOO compared to ring 4 latewood in the TTTTT had a 47% greater mean number of cells per 62,500 μm^2. Table 3.5 displays the mean cells per 62,500 μm^2 for both treatments. Images from block 3 used for cells per 62,500 μm^2 estimation can be seen in Figures 3.16-3.19 and block 8 images can be seen in Figures 3.20-3.23.

Table 3.5. Mean number of cells per 62,500 μm^2 by treatment for ring 4 latewood and ring 5 earlywood for two trees in each treatment.

	Treatment	
n=2	TTTTT (cells/62,500μm^2)	OOOOO (cells/62,500μm^2)
Earlywood	72	108
Latewood	168	247

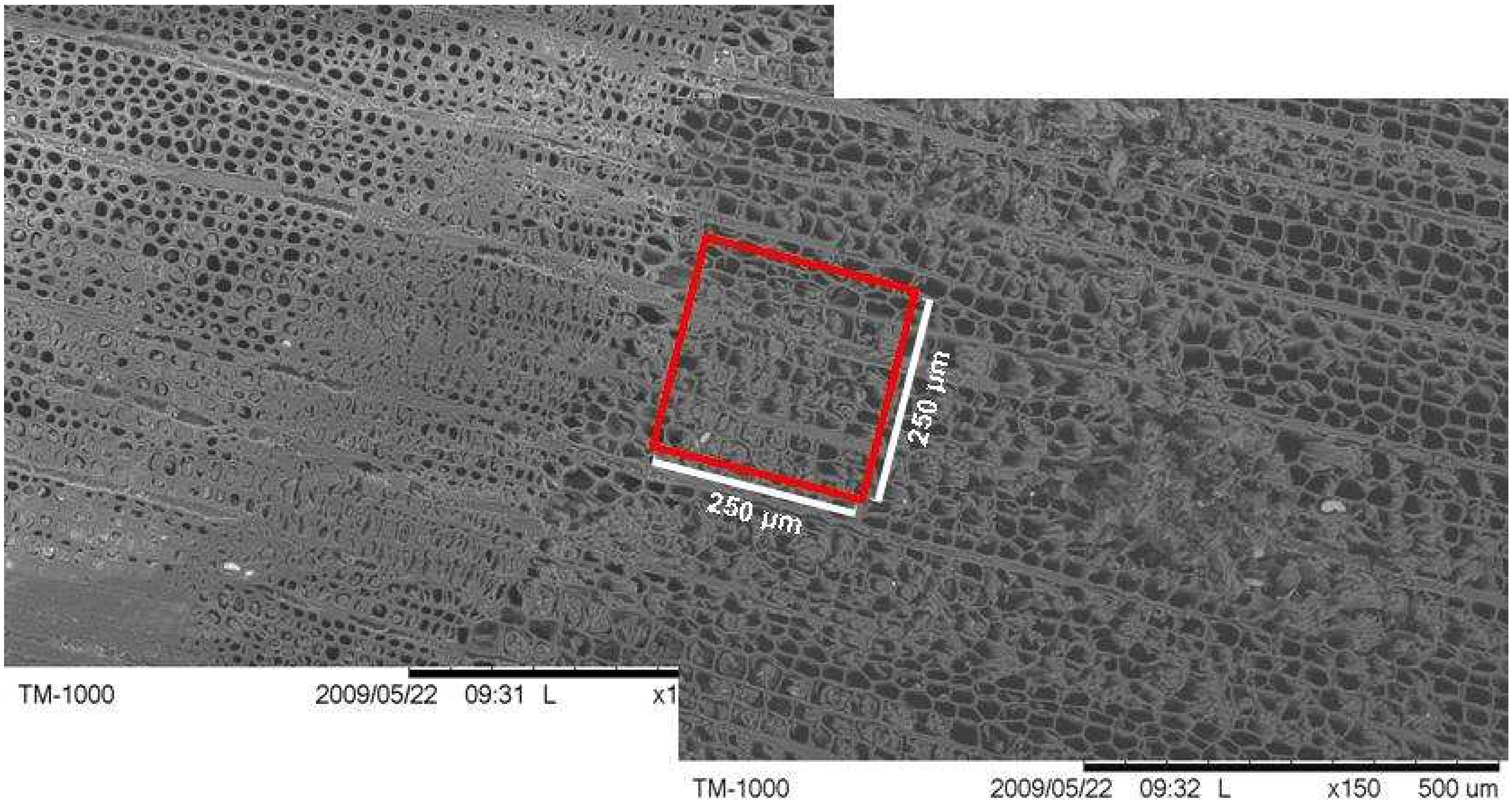

Figure 3.16. Image of earlywood tracheids in treatment TTTTT sampled from tree 33, plot 1, block 3, having approximately 72 cells per 62,500 µm2 area.

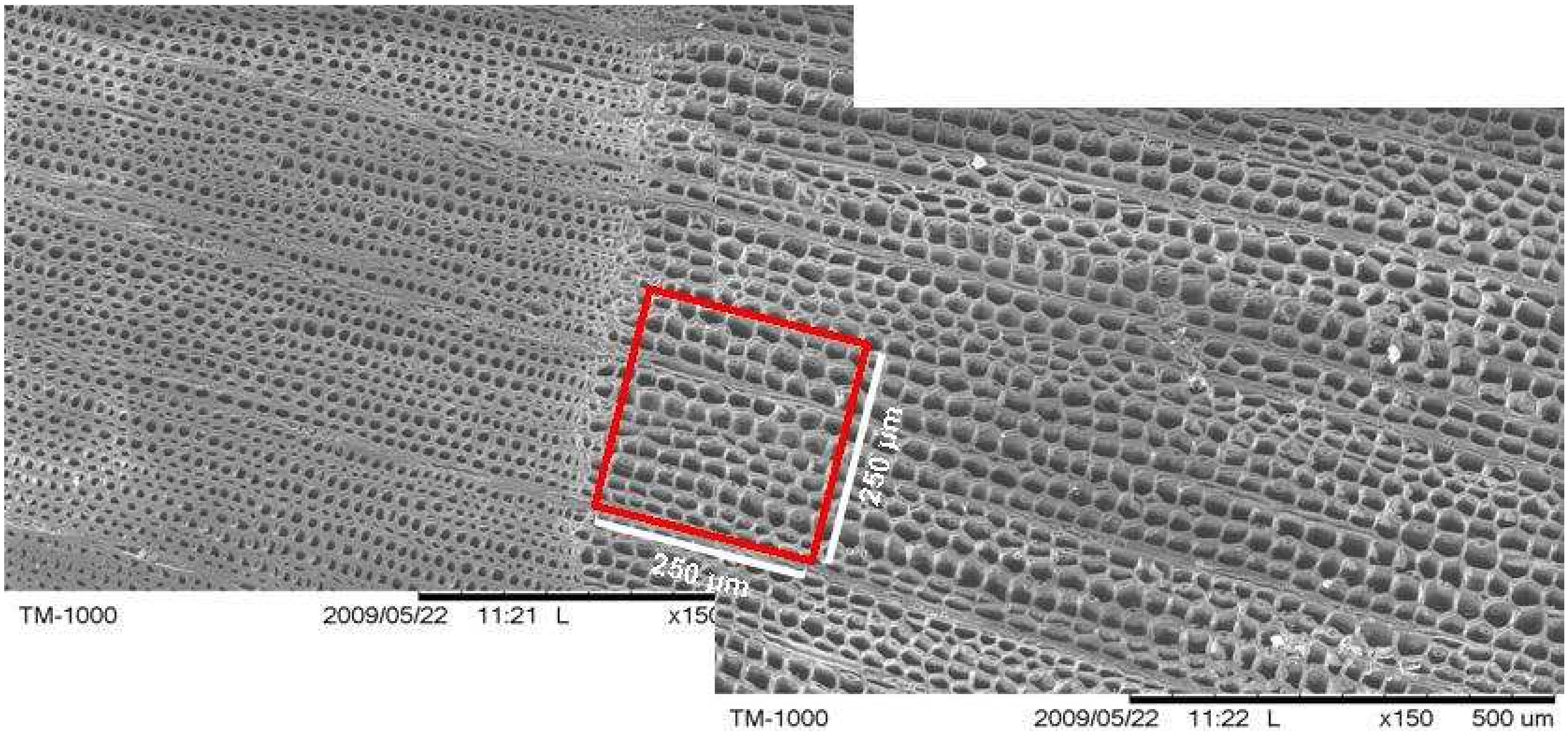

Figure 3.17. Image of earlywood tracheids in treatment OOOOO sampled from tree 32, plot 8, block 3, having approximately 90 cells per 62,500 µm2 area.

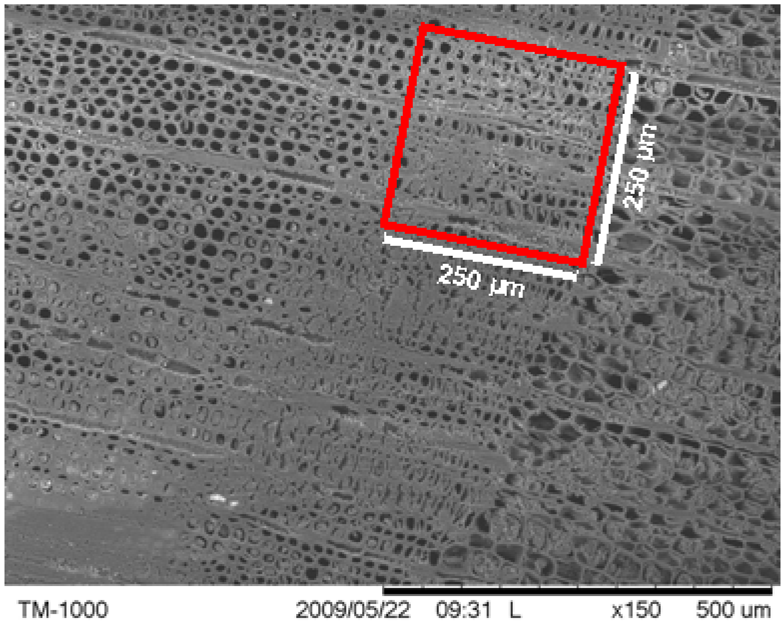

Figure 3.18. Image of latewood tracheids in treatment TTTTT sampled from tree 33, plot 1, block 3, having approximately 156 cells per 62,500 µm2 area.

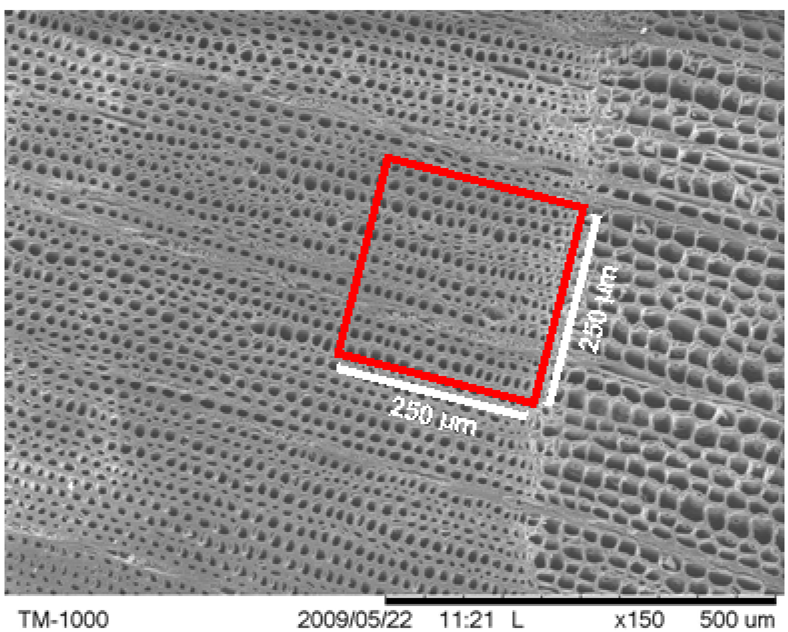

Figure 3.19. Image of latewood tracheids in treatment OOOOO sampled from tree 32, plot 8, block 3, having approximately 224 cells per 62,500 µm2 area.

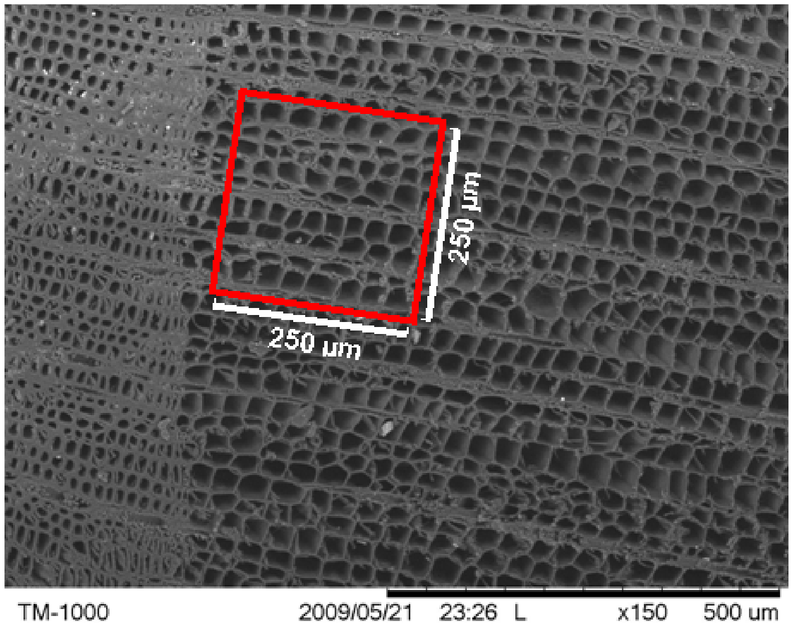

Figure 3.20. Image of earlywood tracheids in treatment TTTTT sampled from tree 31, plot 6, block 8, having approximately 72 cells per 62,500 µm2 area.

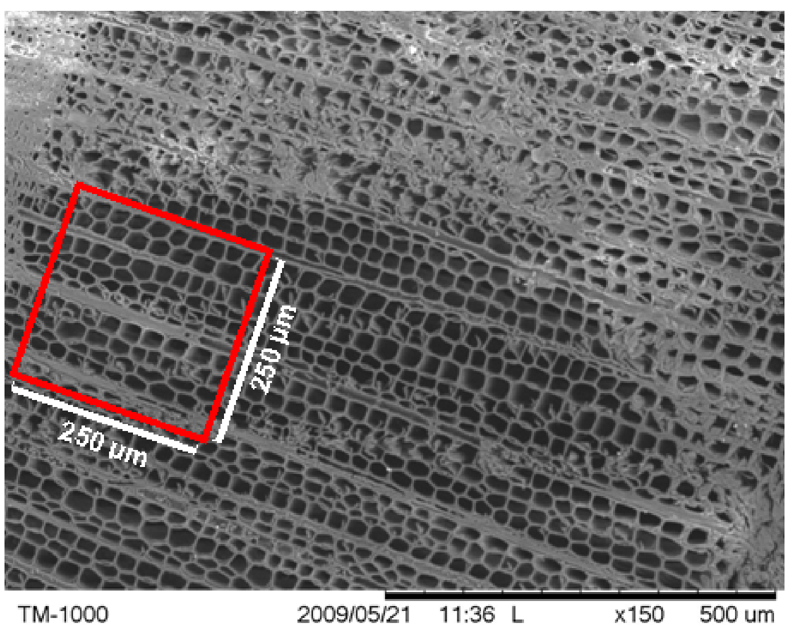

Figure 3.21. Image of earlywood tracheids in treatment OOOOO sampled from tree 15, plot 5, block 8, having approximately 126 cells per 62,500 µm2 area.

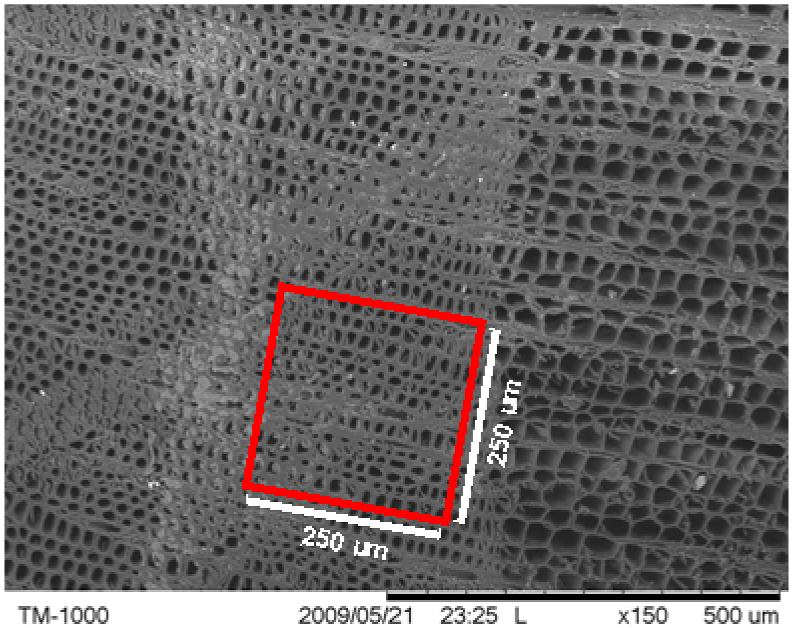

Figure 3.22. Image of latewood tracheids in treatment TTTTT sampled from tree 31, plot 6, block 8, having approximately 180 cells per 62,500 µm2 area.

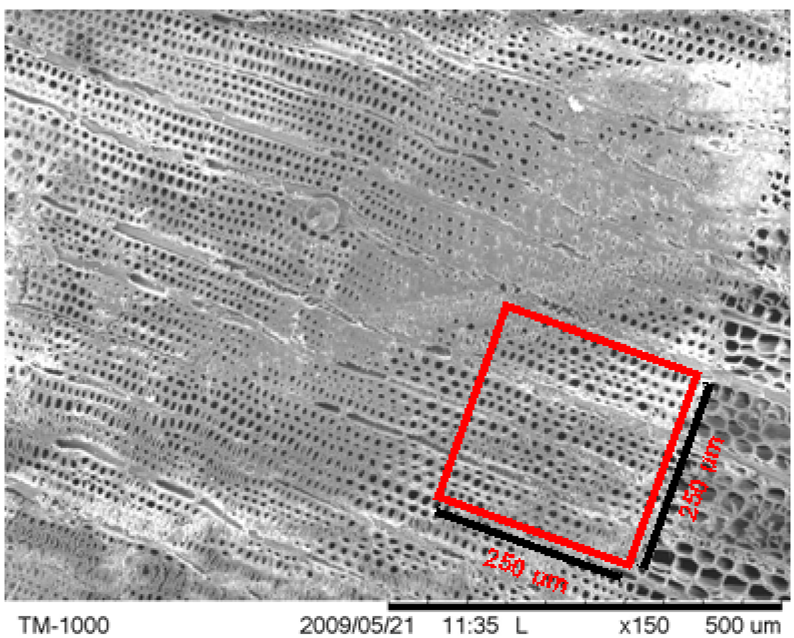

Figure 3.23. Image of latewood tracheids in treatment OOOOO sampled from tree 15, plot 5, block 8, having approximately 270 cells per 62,500 µm2 area.

3.5 Discussion

3.5.1 Vegetation Control Regime Effect on Wood Quality Properties

Silvicultural practices such as thinning, pruning, and fertilization, interact with environmental conditions and genetics to affect wood quality through growth rate and percent latewood, in part by influencing the timing of transition to latewood (Megraw 1986; Jozsa and Brix 1989; and Jozsa and Middleton 1994). Results of this study demonstrate that controlling competing vegetation increases ring width and growth rate at a young age, while at the same time, having no significant effect on specific gravity. Only one study was found that investigated the effect of continuous vegetation control on wood quality. In an attempt to evaluate productivity of loblolly pine resulting from 10 years of continuous weed control and fertilization in a 2 × 2 factorial, Martin and Jokela (2004) reported specific gravity and earlywood/latewood ratio trends from ring four to ring ten from 18 year-old trees. They found that specific gravity was increased and earlywood/latewood ratio was decreased with continuous vegetation control. Significant differences, however, were only reported for ring age six. Specific gravity in the weed control only treatment ranged from about 0.39 at ring age four to 0.54 at ring age ten. Indirect methods were used to linearly derive specific gravity from the earlywood/latewood ratio, which may have some effect on their results. Contradictory findings were reported in a study by Smith and Anderson (1977), who investigated various site preparation treatments in order to determine the economically optimum method for use in slash pine. Methods for measuring specific gravity were not reported in detail, but they observed only the most intensive site preparation treatment to have a significantly lower specific gravity than the others; i.e. 0.487 compared to 0.492 for the mean of the three other treatments. The authors state that this significant difference is of little consequence considering that the 1.2% reduction in specific gravity was associated with a 60% increase in volume over the control treatment.

Early vegetation control sets these trees on a trajectory to achieve maximum stem volume at a younger age. Results from the CPT study suggest that increasing the growth rate of young stands does not necessarily mean wood produced will be of poor quality. Clark and Saucier (1989) found that increases in early growth rate from increased spacing in southern pines resulted in an increased growth rate for the life of the tree. At harvest age, this increase can ultimately result in a decreased proportion of juvenile wood and overall increase in wood quality and volume. Juvenile wood has always been present in solid wood products (Cown 1992); however the demand for wood has changed, compelling growers to produce the same volumes in shorter rotations. Results reported in the literature suggest that growth rate and specific gravity are not directly related to each other, and that age or distance from pith and vertical location within the tree have a stronger influence on wood quality than rate of growth (Megraw 1985; Megraw 1986; Zobel and van Buijtenen 1989). Jozsa and Middleton (1994) found that when rings of the same age were compared for Douglas-fir and three other conifer species, the relationship between annual ring width and wood density was very weak, indicating that age rather than growth rate controls density. This trend strongly implies that a longer rotation age will ensure that a greater proportion of harvested wood will have mature qualities. Young, fast-grown trees may be the same size as older trees but will contain a high proportion of juvenile wood; hence, there is great value in allowing young trees to grow for a longer period of time. Nevertheless, the objective of many plantation growers is to increase growth early during stand development in order to decrease rotation age.

This study affirms that the juvenile wood zone of Douglas-fir can be characterized by a pattern of decreasing specific gravity from the pith to at least year eight. Specific gravity patterns within the present study fell within the expected range (0.36-0.54) presented by Haygreen and Bowyer (1996) for Douglas-fir and were not significantly altered by increasing duration of competing vegetation control. Ring width (segment length) was significantly increased by two to three or more years of competing vegetation control, and was maintained by these treatments through year eight. Percent latewood was significantly reduced by increased duration of competing vegetation control for only the pre-segment, but effects on percent latewood disappeared during the three years after treatment was terminated. For both segments, changes in latewood were not significant enough to cause significant changes in specific gravity. Although increased growth at this stage can be equated with an increased proportion of juvenile wood, future wood quality cannot be predicted from wood quality at year eight because future stand development and silvicultural practices employed will influence the proportion of juvenile wood and the quality of mature wood. The power of this study design may not have been suitable for detecting differences in specific gravity across the treatments; i.e. a larger sample size may have revealed significant differences among treatments. However, results suggest any differences are probably not of practical significance, also, sampling only trees having the largest basal diameters may have influenced the outcome of the statistical tests because trees having similar basal diameter are most likely to have similar values for specific gravity. The study design itself may have contributed to the lack of significant treatment effect as well. The comparison of treatments by pre- and post-segments created a comparison of treatments that were essentially the same. Assuming there was little memory of the first two years of treatment, pre-segment periods of growth in treatments TOOOO and TTOOO were essentially the same. A revised study design that considers this similarity may be able to detect significant treatment effects.

3.5.2 Specific Gravity in the Juvenile Zone

Juvenile wood is often characterized by its high variability within and among individuals (Paul 1957; Zobel et al. 1959; Megraw 1986; Jozsa et al. 1989; Zobel and Sprague 1998; Abdel-Gadir et al. 1993). Generally, juvenile wood is known for its lower mean specific gravity, wide growth rings, reduced proportion of latewood, short fibers and increased micro-fibril angle. Chemical composition is also known to be different from mature wood, having lower cellulose and higher lignin content closer to the pith, with a gradual reversal toward the bark. Albeit several of these traits can be used to delineate juvenile from mature wood, specific gravity is often used because of its relationship with the strength properties of wood and its correlation with more difficult to measure attributes. Depending on which trait is used, the timing of transition can vary widely (Bendtsen and Senft 1986; Zobel and Sprague 1998).

The juvenile wood pattern of specific gravity has been observed to steadily increase from pith to bark in some species, causing researchers to report this as the typical trend for radial wood formation in all conifers (Bendtsen 1978). However, specific gravity of the juvenile wood zone of Douglas-fir is known to be quite complex and somewhat unpredictable compared to other species like loblolly pine (*Pinus taeda* L.) (Megraw 1986; Abdel-Gadir et al. 1993; Zobel and Sprague 1998). Consistent with numerous studies on a variety of species, specific gravity in the present study was observed to be high closer to the pith (rings 3-5) and gradually decrease toward the bark between rings 6 and 8. An early study of specific gravity variation in 20-year old Douglas-fir stems demonstrated similar results (Chalk 1953). The mean specific gravity of each of three rings up to ring 19 was reported, ranging from 0.33 to 0.49. A general decrease from the pith to about ring 8-10 was observed, after which a gradual increase was reported. Similarly, in their study of genetic variation, Koch and Fins (2000) observed a decrease in mean green specific gravity from the pith (0.34) to ring 21 (0.46) in 21-year old ponderosa pine (*Pinus ponderosa* Laws.). Abdel-Gadir et al. (1993) observed higher average specific gravity in rings 5-10 (~0.50) than rings 6-11 (~0.45) of Douglas-fir cores, with the explanation that rings closest to the pith have a higher proportion of latewood and a generally higher earlywood density. Megraw (1986) also thought that higher earlywood density near the pith in Douglas-fir could explain this radial trend in specific gravity. In a study on genetic variation of specific gravity and tracheid length, specific gravity of 27-year old Taiwan incense cedar (*Calocedrus formosano*) was observed to decrease by 1cm segments beginning with a specific gravity of 0.58 at the pith and steadily decreasing to about 0.45 at 6 cm from the pith (Yang and Chiu 2006). This same pattern was observed in blue pine (*Pinus wallichiana* A.B. Jackson) (Seth 1984), black spruce (*Picea mariana*) (Zhang 1998), western hemlock (*Tsuga heterophylla*) (DeBell et al. 2004), and again in Douglas-fir (Jozsa et al. 1989).

The studies reporting contradictory patterns for juvenile wood specific gravity have generalized the pattern across several species or for all ages of growth rings. Bendsten's (1978) review of the properties of wood from intensively managed stands displayed a schematic of the general trend of wood properties in conifers. This trend showed an increase in specific gravity from the pith outward, but did not specify values for specific gravity. Megraw (1985) reported this pattern in loblolly pine with specific gravity taken at the base ranging from 0.39 at the pith and gradually increasing to about 0.50 near the bark. This pattern is most often reported for pines such as slash pine and loblolly and it is recommended that this trend not be mistaken for a general trend across all conifer species (Zobel et al. 1959). A report on specific gravity variation in Douglas-fir by McKimmy (1959) reported specific gravity to increase with age from pith to bark as well, however, the procedure called for a measurement of specific gravity of 10-ring increments. The average specific gravity of five samples for rings 1-10 was 0.35 and for rings 31-40 was 0.47. Such a report cannot be compared to reports of individual ring and smaller groupings of ring specific gravity.

Post/pre specific gravity ratio was derived to investigate the trend of specific gravity over time. To validate this ratio between ring segments, a study using similar ring segments was used for comparison. Koch and Fins (2000) in their assessment of genetic variability of specific gravity separated their ponderosa pine cores into five-ring segments, rings 1-5 and rings 6-11. Green specific gravity ranged from 0.34 to 0.46 for cores from Montana and Idaho, averaging 0.39, which was similar to the average of 0.38 reported by the Forest Products Lab Wood Handbook (FPL 1987) and similar to the range of mean specific gravity values found in the present study (0.37-0.45). Specific gravity of rings 6-11 were divided by specific gravity of rings 1-5 and a ratio close to one (0.97-0.99) was observed at each site. Even though our cores were separated into three-ring segments, the outcomes of the ratio were similar, ranging from 0.91 to 0.96 with no significant treatment effect. This confirmed the result of the post/pre specific gravity ratio found in the present study.

The fact that treatment TTTTT was closest to 1 could suggest that more continuous years of treatment could promote more uniform specific gravity across ring segments in the juvenile wood zone. The benefit of this type of uniformity may be marginal compared to the benefit of uniformity between juvenile and mature wood. Zobel and Sprague (1998) report several studies attempting to promote this kind of uniformity through genetic selection and vegetative propagation. Results varied, but it was determined that selection for fast growing trees plus higher specific gravity can return moderate levels of wood quality. In terms of the present study, it is clear that juvenile wood is still being formed and there is inherent variation in the pattern by which wood properties express themselves in this area of complex growth, depending on environmental conditions. However, more research and larger sample sizes could reveal some benefits to carrying out several years of vegetation control during the period of juvenile wood formation in terms of promoting homogeneity among ring specific gravity.

3.5.3 Segment Length

Segment length or ring width is related to volume growth rate and proportion of latewood and has been used as a surrogate for ring specific gravity. Oelsen (1976) developed a model to describe the relationship between basic density and ring width, implying a causal relationship between the two variables in mature Norway spruce (*Picea abies*), and confirming a strong negative correlation (r = -0.738) between ring width and basic density. The consistent reduction in percent latewood was causally attributed to increased ring width. Results from another study on Norway spruce (Dutilleul et al. 1998) revealed moderate negative among-tree correlations between ring width and density (r = -0.42) studied by Oelsen (1976) relative to slower grown spruces. The correlations were determined to be dependent on the rate of growth and year of growth assessed. Conversely, no significant correlations were observed between specific gravity and ring width (segment length) for Douglas-fir in the present study. A review of several species, by Zobel and van Buijtenen (1989) revealed a wide range of results, but concluded that for Douglas-fir and southern pines, neither ring width or growth rate were related to specific gravity; rather, the determinant of specific gravity was latewood proportion, genetics, ring number from pith, and environmental influences. Megraw (1986) stated the same conclusions for Douglas-fir, extending them to hemlock and southern pines as well. The presence of a strong relationship between ring width and basic density in studies of Norway spruce may be an indication of differences among species or age (distance from the pith) of the rings examined, or may have resulted from confounding effects from the correlation between ring width and distance from pith.

The significant treatment effect observed in segment length for both pre- and post-segments is indicative of an increase in cambial growth with increasing duration of vegetation control. This result agrees with the eighth year growth results for the experiment; i.e., as interspecific competition decreases, overall tree growth increases. The trees in the TTTOO-TTTTT have larger crowns, and thus greater leaf area compared to plots having fewer years of treatment, as explained in the results for the growth of the trees selected for wood quality assessment (Figure 3.1-3.6). The advantage of a larger photosynthetic factory combined with a greater proportion of available soil moisture created by controlling competing vegetation resulted in the production of wide growth rings in these plots. As intraspecific competition begins and crowns begin to lift, the distance between the lower stem and the influence of the active live crown grows, causing ring widths lower in the stem to exhibit more uniformity as a result of the increase in percentage of latewood (Larson 1969). This response, however, is not immune from the effects of climate on radial growth patterns (Jozsa and Brix 1989).

The juvenile wood zone is known to be highly variable in Douglas-fir (Megraw 1986); however the pre- and post-segment lengths were both shorter (15 mm and 24 mm, respectively) under two or fewer years of vegetation control, and the pre-segment was consistently shorter than the post-segment (Figure 3.9). After three years of continuous vegetation control, however, both segments are observed to converge at about the same high values of segment length (~30 mm). This result is consistent with the pattern observed by DeBell et al. (2004) for western hemlock. They reported ring widths to increase from 35 mm at the pith to 59 mm at the end of the first decade, reaching a peak at age seven that remained somewhat constant through the end of the second decade. Perhaps the plateau observed in our study indicates an increase in uniformity, because the last six years of growth (pre- and post-treatment) demonstrated relatively even ring widths when vegetation was controlled for three or more years. This ring-to-ring uniformity could be a desirable feature for clear wood end-use, yielding higher quality and efficiency during the manufacturing process (Zobel and van Buijtenen 1989).

3.5.4 Percent Latewood

Percent latewood is a potential indicator of wood quality because latewood specific gravity is normally higher than that of earlywood. A larger proportion of latewood generally translates to a higher whole-ring specific gravity (Warren 1979; Jozsa et al. 1989; Jozsa and Middleton 1994). Jozsa et al. (1989) reported a four-fold increase in specific gravity for conifers, from ~0.25 in the latewood to ~1.0 in the earlywood. Results from the present study showed that the pre-segment percent latewood was affected by treatment but the post-segment percent latewood was not affected, indicating that perhaps as tree leaf area increases, stabilization of the latewood production occurs. Three or more years of vegetation control did, however, produce a higher percentage of latewood in the three years after herbicide application. When considered alongside the mean segment length (around 30 mm) observed with three or more years of control in both segments, these results suggest that the seedlings have been producing a greater volume of wood for the last six years and wood with a slightly higher percentage of latewood in the last three years. The consistency of latewood formation in the post-segment along with the consistency in radial growth suggests a pattern of uniformity between rings in the juvenile zone.

The idea that uniformity is increased with increasing duration of vegetation control is fertile ground for further investigation. According to Larson (1969), increasing uniformity is one of the best ways to improve wood quality. Within ring uniformity is achieved by an increase in the width of the latewood band. Control of this trait is not easy to obtain because it is controlled heavily by temperature, moisture stress, and photoperiod (Renninger et al. 2006). Irrigation in late summer can extend the formation of latewood (Paul and Smith 1950) but this approach has limited practical application in the Pacific Northwest. The same result has been achieved through closer spacing or more intense competition in southern pines (Clark and Saucier 1989), corresponding in this study to the higher percent latewood observed in the treatments having zero to two years of treatment for both segments. However, it is known that limited late-summer moisture can reverse this effect, resulting in lower percent latewood, further underscoring the fact that latewood formation is highly influenced by environmental conditions (Larson 1969; Bendtsen 1978; Megraw 1986; Jozsa and Brix 1989; Zobel and van Buijtenen 1989). The spike in percent latewood in treatment TTTTO in the pre-segment could be explained by the wide tree-to-tree variation that exists or by the relative difficulty in visually demarcating the transition between earlywood and latewood of green wood samples. Nonetheless, more research is needed on the potential influence of vegetation control on ring uniformity.

3.5.5 Biomass Increment

The relatively static pattern of specific gravity suggests that volume increment, which is produced from height and basal area increment, has a more influence on biomass increment than does specific gravity. This is confirmed by the non-significant treatment effect on specific gravity coupled with the significant treatment effect on Douglas-fir volume growth. Biomass increment is an indicator of the amount of wood substance that is produced in a given time period (Zobel and van Buijtenen 1989). For the purpose of this study, the biomass increment (Figure 3.13) reflects the simultaneous influence of volume increment (Figure 3.1 (Selected wood quality tree means, 2008)) and specific gravity (Figure 3.9). This assessment provides a rough estimate of the potential for biomass and carbon accumulation in Douglas-fir plantations.

The accumulation of biomass at the Sweet Home site gives rise to implications for carbon sequestration benefits associated with vegetation control treatments and plantation forests. For the pre-segment, biomass increment showed an increase with increasing duration of vegetation control, reaching a 374% increase from the OOOOO to the TTTTT treatment. In the post-segment, the size of the biomass increment varied less by number of years of treatment, but still had a 113% gain in biomass increment and carbon accumulation between the treatments having the lowest and highest values. In the post-segment, there was no significant gain in biomass increment under more than three years of vegetation control, suggesting that at least three years of initial or delayed vegetation control is necessary and sufficient for achieving maximum biomass increment. The amount of stored carbon and the CO_2 absorption equivalent in these stands observed in the pre- and post-increments represents the potential for young, vigorous plantations to sequester large amounts of carbon (Bettinger et al. 2009). There is, however, a tradeoff associated with eliminating competing vegetation. Consideration should be made for the relative carbon turnover rates for both competing vegetation and young plantation trees as there is carbon storage and sequestration benefit associated with the presence of all vegetation.

3.5.6 Scanning Electron Microscopy

Rings with more tracheids per unit area indicate that tracheids were smaller in the OOOOO for both earlywood and latewood than in the TTTTT in the pre-segment.

This result is certainly reasonable because increase in moisture availability results in the production of larger diameter cells per unit area. Investigation of the earlywood and latewood band widths taken from the pre-segment in the TTTTT and the OOOOO revealed that the width of the earlywood band of growth in the TTTTT was 98% greater than the width of the earlywood band in the OOOOO. Latewood band widths were relatively similar for both trees. Given that volume growth was 239% greater in the TTTTT than in the OOOOO, the conclusion can be reached that larger live crowns combined with decreased moisture stress due to lack of interspecific competition in the TTTTT promotes the production of larger cells. Based on these observations of cells per unit area in the two treatments it can be speculated that fewer, but larger cells per unit area are produced in the TTTTT. Differences in wood quality based on the SEM images cannot be evaluated without further investigation of lumen diameter and cell wall width; however there is potential for this procedure to provide supplementary data for assessment of wood quality.

The accessibility and ease of use of the Hitachi TM-1000 Table-top SEM could be beneficial for future assessment of wood quality properties. With the use of this machine there is potential for a large volume of samples to be evaluated very quickly, without the cost and intensity of sample preparation required by the traditional method of SEM. However, the procedures explored in this study did not turn out to be the most efficient. The surface of the samples was not prepared consistently at a sufficiently high level of quality that would be helpful in more extensive evaluation of wood samples. It is suggested that the surface of the sample be prepared using a sliding microtome in the green state prior to ring width and specific gravity measurement to avoid damage to the radial surface of the cell walls.

3.6 Conclusions and recommendations

The effects of silvicultural practices on wood quality properties of a variety of conifer species has been researched extensively; however, there is a lack of long-term research that provides detailed information about the effect of vegetation control regimes on wood quality of Douglas-fir. The results of this study provide evidence that wood quality is not strongly influenced by the reduction of competing vegetation during plantation establishment. Nevertheless, volume growth was significantly increased, greatly affecting the size and proportion of the juvenile core. This is a marginal concern, however, given that these trees are far from crown closure. Silvicultural regimes applied in the years to come will have ample opportunity to alter the size and proportion of the juvenile wood core. Not considered in this study was the seasonal effect of temperature and precipitation on the production of earlywood and latewood during and after treatment regimes were applied. The influence of climatic effects cannot be ignored, as it is often the major determinant of wood quality in an individual from year to year as described by Lassen and Okkonen (1969).

The lack of significant differences in specific gravity among treatments in this study and in thinning studies across a wide range of species is particularly perplexing (Megraw 1985; Watson et al. 2003; Debell et al. 2004; Jaakola et al. 2005) is particularly perplexing. Perhaps some explanation lies in the fact that the anatomy of the wood substance is not influenced as much by external factors; i.e. climatic conditions and stand density, but rather, it is the arrangement and dimensions of the cells and cell walls that are influenced externally. For example, a comparison of rings of the same age and height resulted in two rings with very different widths. Earlywood and latewood in the wider ring is made up of generally larger diameter cells with narrower walls. Earlywood and latewood in the shorter ring is made up of generally smaller diameter cells with wider walls. A similar amount of wood substance (after void space is eliminated) is probably produced in both rings, generating values for specific gravity that do not significantly differ. The results of the SEM images attempt to establish this possibility to some extent, though statistical comparisons were not made.

The gains in biomass accumulation associated with at least three years of weed control are tremendous and coupled with the relatively unaffected specific gravity and percent latewood (in the last three years of growth), seem to outweigh the concern over possible adverse wood quality implications at this stage in development. The recommendation for plantation growers is to promote the maximization of early growth through competing vegetation control for the first three or more years. Large volumes of juvenile wood can be expected, but careful planning of subsequent silvicultural treatments will contribute to increased volume of mature, high quality wood. Good silvicultural practices, such as thinning, that attempt to promote optimal yield and uniformity of growth are likely to promote wood quality as well (Larson 1969). Therefore, there is added incentive, beyond meeting the legal requirements of for rapid reforestation and stand establishment, for young plantations to reach maximum volumes earlier.

Further research is recommended on the response of tree ring components to common Douglas-fir vegetation control regimes. For example, a complete dataset for wood quality would include the response of tracheid length, micro-fibril angle, and earlywood and latewood specific gravities. Measurements could also be taken at various vertical heights within the tree bole. The inclusion of these components would provide an even more complete catalog of the effects of weed control regimes on early wood quality. Returning to these plots in the future would further add to the knowledge we have collected concerning wood quality responses to these particular vegetation control regimes. Repeating these methods in other VMRC studies would be informative as well, providing wood quality data in terms of a wide range of vegetation control regimes at sites of various stages in development. In general, continued research on genetic improvement, including the genetic control and patterns of genetic variation of chemical components in wood, as well as research related to the manufacturing and production of wood products is needed. In the meantime, early control of competing vegetation through the use of herbicides is a sound method for producing large volumes of wood from plantation forests in the PNW without adversely affecting wood quality.

3.7 Literature Cited

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