Relationships of Growth Rate and Mechanical Properties in Sweetgum, *Liquidambar styraciflua*

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Abstract

Sweetgum, *Liquidambar styraciflua*, is a diffuse-porous hardwood occurring in the southeastern United States. In this observational study, trees from two plantations of sweetgum were evaluated for mechanical properties. The two plantations were similar in age, soil type, competition control, and water availability, but differed in nutrient availability, growing season, and growth rate. Three trees representing different crown classes were removed from both plantations. Each tree was sampled for compression strength parallel to grain along the height of the merchantable stem. Oven-dry specific gravity was then calculated for each sample. The results indicate that young sweetgum trees grow weaker wood than mature trees. It was observed that dominant trees were stronger and denser than other trees. Denser wood was formed in the plantation with the shortest growing season and smallest growth rate. Three of six trees showed significant correlations of strength and stiffness with height in the tree.

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Chapter 1: Introduction

Wood is important to the world for many reasons. Wood is a fuel, a material, and the backbone of the forest ecosystem. Demand for wood is also demand for forests and the quality of the wood is related to the qualities of the forest. The effect of forest growth rate on wood quality is of interest to suppliers, processors, and consumers of wood.

Forests that can supply large uniform pieces of wood have declined throughout recorded history (Perlin 1989). We are without the time or land necessary to allow similar forests to develop. Today, forests grow faster and wood from younger and smaller trees is engineered into acceptable products.

This study is an observation of wood quality in nine year old sweetgum, *Liquidambar styraciflua*. Trees from two different plantations of sweetgum are observed and compared. The plantations were similar in water availability and competition but also differed; one plantation had a longer growing season and was regularly fertilized with nitrogen. Consequently, the fertilized plantation grew faster.

The main objective of this research project is to describe the influence of growth rate on sweetgum wood. The similarities between the plantations make it possible to compare their growth rates and wood quality. Studying dominant, codominant, and suppressed trees is another way to compare growth rates and wood quality. Studying wood quality throughout the stem was necessary to characterize the effects of growth rate, but also provides information about sweetgum wood quality in different parts of the tree.

Wood quality is a subjective term because wood is put to such a wide variety of uses. A practical measurement of wood quality is mechanical performance. The

American Society for Testing and Materials (ASTM) has developed standards for many materials and specific stresses. Many types of wood have been tested with these standards; and great variation within and between trees exists.

In this study, wood quality is measured as compression strength parallel to grain, modulus of elasticity, and specific gravity. Compression testing was chosen because of its tolerance of defects that are to be expected in young trees. Specific gravity was chosen because of the importance of wood density to processing and utilization.

Another definition of wood quality is uniformity. Uniformity is desirable to most processors and users of wood (Youngs and Hammett 2001). Wood quality varies significantly within a single tree (Groom et al. 2002). The lack of uniformity is one of the greatest challenges to the use of wood.

Smaller and younger trees produce wood that is less uniform for a variety of reasons. Changes in meristematic cells during the first few decades of growth will influence the properties of the resulting wood cells. Young organisms often grow rapidly and growth rate influences wood properties. There is a significant difference in wood formed above or below the photosynthetic crown and a young tree often has a high proportion of crown.

Uniform wood products are possible by the recombination of pieces of wood into a larger piece. The differences between the pieces of wood still exist but as a gradient within the product. The limitation of a tree’s physical size is also overcome allowing for a wooden product to exceed the size of a single tree. Composite products made of hardwood are comparable to those made of softwood. (Biblis and Lee 1984, Wang and Winistorfer 2000).

In this study, samples were taken at regular intervals (15 cm) along the stem of the sweetgum trees. The samples were tested for strength, stiffness, and specific gravity. Each sample's failure mode was also recorded. The data were analyzed for relationships of wood quality (strength, stiffness, and specific gravity) with sample location and growth rate.

Six individual trees are observed, three trees from two different plantations. The three trees grew in different canopy positions; dominant, codominant, and suppressed. These different trees were chosen in order to observe the uniformity of wood within the plantation as well as within the trees.

Rapid growth has long been associated with a lower quality of wood in softwoods (Mohr 1896). Diffuse porous species show less correlation between growth rate and mechanical properties (Lauridsen and Kjaer 2002, Zhang 1995). Differences between juvenile and mature wood quality in hardwood species are small relative to softwoods (Bao et al. 2001, Bendtsen and Senft 1986, Jett and Zobel 1975).

Diffuse porous hardwoods, such as sweetgum, show very little difference in wood properties throughout the year (Browne 1958). Other tree types produce two distinct kinds of wood in a single year. In other tree types, a porous wood is grown in order to transport water early in the growing season, and later in a year a denser wood is formed for mechanical strength. In diffuse porous wood, the pores (vessels) are distributed evenly throughout a year regardless of when growth occurs. Figure 1.1 illustrates the cross-sectional diffuse porous anatomy of sweetgum.

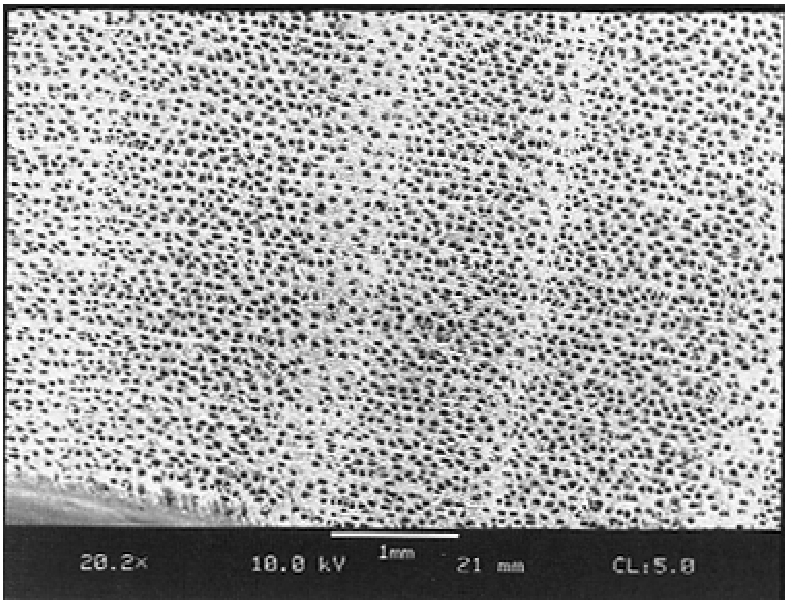

Figure 1.1. Scanning electron micrograph of cross-section of sweetgum. Magnification is 20X. Quantitative Wood Anatomy Laboratory, Virginia Tech.

Vigorously growing trees often have a large photosynthetic crown. In the past, crown wood was normally left in the forest, but today it is considered valuable as a source of pulp and wood particles. Unlike softwoods that hold their needles year-round, temperate hardwoods, such as sweetgum, drop their leaves annually. Harvesting wood after the leaves drop will leave nutrients in place for forest regeneration.

Many sites that are normally forested with hardwoods or a mix of hard and softwoods are now softwood monocultures (Kellison et al. 1988). Reintroducing hardwood species into our working forests will diversify plantation forestry and may benefit many users at once. Hardwood silviculture may lessen the impact of intensive management on forests and on forest products.

Chapter 2: Literature Review

2.1 Sweetgum

American sweetgum, *Liquidambar styraciflua*, is a common deciduous tree occurring in North and Central America. The genus *Liquidambar* was globally widespread during the Tertiary period and sweetgum first appeared during the Miocene period (Berry 1920). The genus *Liquidambar* was recently moved from the *Hamamelidaceae* family to the *Altingiaceae* family.

Sweetgum bark and resin have been used throughout recorded history. The bible mentions sweetgum resin in a perfume recipe (Moses ~1500 BC). More recently sweetgum resin was the inspiration for polystyrene. Although disregarded in the past, today sweetgum wood is utilized for veneer, pallets, composites, and wood pulp.

The uniformity of sweetgum and other diffuse porous woods is ideal for engineering wood composites from small pieces of wood. Each small piece of sweetgum wood should perform very similarly to other pieces of similar dimensions. The low density of sweetgum is favorable when heat and pressure are used to recombine smaller pieces of wood into a larger wood composite.

As illustrated in Figure 1.1, the wood of sweetgum is diffuse-porous, and only the last few rows of cells in a growth ring are significantly different from those formed previously that year. This consistency in wood cells throughout the year suggests that an increase in growth rate should not significantly change wood properties. Previous studies have observed that intensive management has little impact on the mechanical properties of diffuse porous wood (Bendtsen and Senft 1986, Jett and Zobel 1975).

Sweetgum occurs in bottomlands along the Atlantic coast from Connecticut to Florida. In the southeast, the species also grows in the uplands and extends its range west of the Mississippi River. In Central America, sweetgum grows at higher elevations in the cloud forests. The best growth of sweetgum occurs on moist alluvial clay and loamy river bottoms, but the tree has growth potential on drier upland sites (Kormanik 1990).

When growing in drier soil types, sweetgum exhibits a different physiology. Sweetgum normally exhibits strong apical dominance that declines with age, and this decline occurs faster on drier soils (Kormanik 1990). Sweetgum has a higher likelihood of top breakage than other hardwood species when growing in sandy soil (Gresham et al. 1991).

Sweetgum trees in drier soils often grow faster presumably because of greater ease in penetrating soil, but growth rates decline earlier than those of trees in wetter soils (Ferguson and Cooper 1977). When pioneering on abandoned agricultural land, sweetgum grew largest in drier soil types, but survival was best in moist soils (Wenger 1952, Bowman 1953, Ferrel 1953). This increased growth rate at early ages in drier soils was also noted in a provenance study (Wells et al. 1991) and multi-species trial in Tennessee (Buckner and Maki 1977).

Researchers have also found ecotypic variation in sweetgum along a latitudinal gradient. Northern provenances of sweetgum showed the best potential on upland sites (Prowant et al. 1982). Sweetgum from areas having longer growing seasons and more summer rainfall had longer fiber cells (Hunter and Goggans 1969). A sweetgum provenance test in Mississippi showed a trend of increased tree height and better form at more southern latitudes (Wells et al. 1991). Sweetgum wood from six different locations in the southeast had significantly different specific gravities; however there was no clear pattern of variation (Taylor 1977).

Temperature has also been shown to affect the physiology of sweetgum wood. Sweetgum seedlings grown at colder temperatures had denser stems than those grown at warmer temperatures (Lam and Brown 1974). Seedlings grown at cool temperatures and with short photoperiods had smaller fiber diameters but there was no reduction in cell wall thickness. The increase in density was likely a result of more cell wall area (Randel and Winstead 1976).

Light availability has an affect on sweetgum growth independent of temperature or latitude. Sweetgum growth increased with intensity of sunlight, but sweetgum showed adaptability to lower light levels (Guo et al. 2002). Potted sweetgum seedlings grew faster and had wider internodes when grown at a longer photoperiod. The additional length between nodes was because of a greater number of wood cells and not longer wood cells (Lam and Brown 1974). Internodes, which are the stem between two branches, produce the highest quality wood that is clear of knots and grain deviations.

2.2 Sweetgum Forests

Sweetgum is a pioneer species and may form monocultures on abandoned agricultural areas (Kormanik 1990). Plantations resemble these natural monocultures and may fulfill some of their environmental services. Several studies have showed that bird populations benefit from short rotation poplar plantations in contrast to grassland or row crop landscapes (Tolbert and Wright 1998). Over time these pioneer forests gain diversity and other tree species share the canopy.

Natural monocultures usually occur on bare or deforested soil and are maintained by shade, competition, and allelopathy. Intensively managed plantations are somewhat similar in that site preparation creates bare soil conditions, herbicides are used to control competing vegetation, and crown closure of the monoculture signals victory over the weeds. In both situations, a monoculture is more susceptible to outbreaks of pests than a mixed stand would be (Braganca et al. 1998, Ewell 1999)

The major difference between natural forests and plantations is stand density. Young natural stands in the south-eastern U.S. often have 20,000 or more stems per acre (Schuler and Robison 2006). Plantations often have 2,000 or less stems per acre. Decreasing stem density will leave more bare soil exposed to erosion. Fewer stems may also detract from other forest ecosystem services such as carbon sequestration, wildlife habitat, and oxygen production.

In terms of carbon or biomass, monocultures do not outperform mixed stands (Burkhart and Tham 1992, Ewell 1999). The greatest benefit of a monoculture is that the majority of the wood produced is a uniform material. Unlike natural forests which contain dozens of different tree species of various ages, plantation monocultures consist of one species of tree and one age. Researchers have discussed the gains possible to wood processors by increasing the uniformity of the raw material (Youngs and Hammett 2001).

Competition from other species can stimulate the growth of crop trees. Shading the stem of a sweetgum was shown to increase height growth and decrease the portion of live crown without affecting mechanical properties (Holbrook and Putz 1989). Artificial lateral shading increased the height, diameter, and biomass of one year old sweetgum planted in a field near Salem, South Carolina (Mou 1997). No difference was found between the total biomass of crowded and open grown sweetgum but there were large shifts in allocation to the stem in crowded sweetgum (Holbrook and Putz 1989).

Separating vine competition into purely aboveground and belowground activity showed that aboveground competition stimulated stem elongation and that belowground competition stimulated diameter growth of sweetgum (Dillenburg et al. 1995). Competition control via mulches and/or amazine herbicides improved the height and diameter of plantation sweetgum trees for four consecutive years (Kaszkurewicz and Keister 1975).

Sweetgum is increasingly intolerant of shade or suppression as the trees age (Kormanik 1990). Thinning to reduce competition within mature stands of sweetgum has been shown to increase volumes but at the expense of log quality (Howell and Lawrence 2002, Meadows et al. 2006). Other studies have shown that thinning does not degrade sweetgum log quality (Meadows and Sklojac 2006). Vine competition was shown to be reduced by thinning (Howell and Lawrence 2002).

Intensive management of sweetgum grown with other crop plants has shown mixed results. Five year old sweetgum grew vigorously in a mixed species plantation (Kormanik et al. 1999). Sweetgum and cherrybark oak, *Quercus pagoda*, grew together in a plantation without significant mortality (Lockhart et al. 2006). Competition by sweetgum reduced the volume of loblolly pine, *Pinus taeda*, by nineteen percent in controlled conditions (Ludovici and Morris 1996). Fescue cover crops reduced the height but not survival of sweetgum growing on coal spoil banks (Plass 1968). Cover crops of annuals and low growing perennials significantly reduced sweetgum biomass (Malik et al. 2001).

2.3 Water Availability

Sweetgum is not drought tolerant and the best observed growth of sweetgum is in moist soils. In drier soils, sweetgum is more short-lived and prone to damage. Water availability has been shown to change the xylem anatomy of diffuse porous species (Liphschitz and Waisel 1970, Bissing 1982, Schume et al. 2004, Naidoo et al. 2006).

In the Pacific northwest irrigation increased the size of red alder, *Alnus rubra*, by allowing growth to continue longer into the season (Harrington and DeBell 1995). Irrigation does not always increase growth and has been shown to be ineffective in the humid southeast (Steinbeck 1999). Irrigation does increase growth in the drier soil types of the southeast. Irrigation significantly increased the aboveground biomass of sweetgum growing in dry upland sites (Allen et al. 2005a, Coleman et al. 2004).

Porosity and vessel grouping of *Populus* were correlated to water availability (Liphschitz and Waisel 1970, Schume et al. 2004). Mature poplars reacted to a decrease in water availability by forming vessels with smaller diameters and increasing vessel density (Schume et al. 2004). Rose-gum, e*ucalyptus grandis,* grown in South Africa showed a trend of increasing vessel area with increasing precipitation (Naidoo et al. 2006). These traits, porosity and vessel grouping, will affect the density and uniformity of the wood.

Irrigation decreased the density of radiata pine, *Pinus radiata*, but increased the uniformity of density throughout the stem (Wielinga et al. 2007). Irrigation increased the density of poplar hybrids on two different sites, while fertilization and combinations of irrigation decreased density (Blankenhorn et al. 1988). Increased water availability decreased the density of rose-gum (Naidoo et al. 2006).

Irrigation increased the length of internodes in young peach trees, *Prunus persica*, but not the number of nodes (Hipps et al. 1995). Sweetgum exposed to intermittent drought had shorter internodes because of reduced cell division (Sommer et al. 1999). Internode length is desirable and internodes produce the highest quality wood.

Drip irrigation was shown to increase the ratio of above-ground to below-ground biomass in diffuse porous species. Higher shoot-to-root ratios were observed in eastern cottonwood, *Populus deltoides*, and American sycamore, *Platanus occidentalis*, because of advanced physiological development (Coyle and Coleman 2005). Water stress increased below ground biomass and decreased above ground biomass in young sweetgum (Ehlert and Cunningham 1989).

Increased water availability has important effects on tree crowns. Irrigation increased the leaf surface area of sweetgum crowns (Allen et al. 2005b). Drought was shown to decrease the surface area of sweetgum seedlings (Tschaplinski et al. 1995). Irrigated sweetgum trees keep stomata open longer than unirrigated trees when exposed to drought stress. Drought and heat stress have been shown to affect plant metabolism individually and in concert (Rhizsky et al. 2004).

2.4 Nitrogen Availability

Nitrogen is an integral element within amino acids. Plants can assimilate nitrogen when they have access to adequate light (Stitt et al. 2002). When nitrogen is readily available to a plant carbon sequestration increases (Lawlor 2002). Low nitrogen availability increases the proportions of carbohydrates within cell walls, while high nitrogen increases the proportion of protein (Taiz and Zeiger 1998).

Fertilization increased the aboveground biomass of sweetgum in multiple studies (Allen 2005a, Cox and Leach 1999, Devine et al. 2000, Nelson and Switzer 1992, Coleman et al. 2004). Fertigation, the combination of fertilizer with irrigation water is considered the most efficient way to apply nitrogen to tree crops (Quinones et al. 2003). Fertilization and irrigation are additive in sweetgum (Coleman et al. 2004, Williams and Gresham 2006).

Nitrogen availability regulates the production of protein in plants (Lawlor 2002). Deficiencies of nitrogen were shown to decrease the number of rays and the diameter of vessels within sweetgum seedlings (Murphey et al. 1962). The strength and stiffness of diffuse porous species is affected by ray morphology, especially when wood is loaded radially (Kennedy 1968).

A general opinion among foresters is that nitrogen fertilization of diffuse porous species may lead to broken tree tops and poor stem form (Dunham 2006, Garcia 2006 personal communication). A study of ice storm damage to a fertilized sweetgum plantation found that larger trees were more prone to damage (Guo 1999).

Nitrogen fertilization was correlated with increased growth rate, higher specific gravity, and longer fibers in the seven year old American sycamore (Saucier and Ike 1969). Fertilization and irrigation increased fiber lengths in young quaking aspen, *Populus tremuloides*, although fertilizer alone had little effect (Einspahr et al. 1971). Nitrogen deficiency reduced fiber dimensions and vessel width in cottonwood (Foulger 1968). Increased nitrogen availability in hybrid poplar seedlings, *Populus trichocarpa x P. deltoides*, resulted in shorter and wider fibers with thicker cell walls (Pitre et al. 2007).

Fertilization has also been shown to negatively affect the growth of the crop plants. Weeds have gained an advantage from nitrogen application that boosted their growth and subsequently depressed that of crop plants (Davis and Liebman 2001). Vigorously growing leaves are more appealing to herbivores. Nitrogen fertilization increased defoliation of sweetgum seedlings by the yellow-striped army worm, *Spodoptora ornithogalli* (Ward and Sayer 2004).

2.5 Variation within a Tree Stem

It has long been appreciated that wood quality changes throughout a tree. In a mature tree, the wood of the stem and crown were often put to different uses. Today the entire biomass of much younger trees are used for composite and fiber products. Some researchers have suggested separating portions of plantation trees to minimize the variation in those trees (Herajarvi 2004, Xu and Walker 2004).

The variation in properties within a single tree is of interest to wood processors. Variation within one tree is often greater than that between trees. Within an individual tree variation is often predictable and follows a trend with age, height, or distance from the pith. Variation between trees is less predictable, although geographical trends exist due to soil type or photoperiod.

Most research on gymnosperms finds that wood is denser at the base of the tree. Density slightly decreased with height in black spruce, *Picea mariana*, and this trend was greater in older trees (Alteyrac et al. 2006). The differences between juvenile wood and mature wood also decreased at greater heights (Alteyrac et al. 2006). Density also decreased with height in black pine, *Pinus nigra* (Oliva et al. 2006). Density decreased at greater heights in the stems of radiata pine (Wielinga et al. 2007). The density of nine year old pyinkado, *Xylia xylocarpa,* decreased with height and increased form pith to bark (Josue 2004). Specific gravity decreased with height in white fir, *Abies glauca* (Gerhards 1964).

Other researchers have found different trends of height and density in gymnosperms. Specific gravity decreases from the base to half the height of gamhar, *Gmelina arborea*, then specific gravity increases towards the top of the tree (Espinoza 2003). Density increased from stump to breast height (4.5ft), and then decreased slightly at greater heights in Douglas-fir, *Pseudotsuga menziensii* (Gartner et al. 2002).

Research on the relationship of height and density in ring porous species has been less conclusive. Density was higher at lower heights in California white oak, *Quercus lobata*, but was lower at lower heights in Oregon white oak, *Quercus garryana,* (Benson et al. 1958). Specific gravity decreases with greater heights in yellow-poplar trees, *Liriodendron tulipifera*, (Erickson 1949, Thorbjornsen 1961, Barefoot 1963). Large yellow-poplar trees show a trend of decreasing specific gravity with greater heights, but the trend eventually reverses itself with specific gravity then increasing at even greater heights in the tree (Taylor 1968, Schroeder and Phillips 1972, Koch and Stenglein 1986).

Diffuse porous species have not shown strong trends between density and height. Mature specimens of alder, *Alnus glutinosa*, American sycamore, and birch, *Betula pubescens and B. alba*, showed no clear pattern of specific gravity and height, although wood from the center of birch and sycamore trees showed trends of decreasing specific gravity at greater heights in the stem (Desch 1932). Specific gravity decreased in the first sixteen feet of mature sugar maple trees, *Acer saccharum* (Lamb and Marden 1970). The specific gravity of hybrid poplars was found to decrease with height (Benson 1956). The specific gravity of wood from guere or soap tree, *Petersianthus macrocarpus,* was found to increase with height (Poku et al. 2001).

Height and density in sweetgum have been studied multiple times but no consistent relationship has been found. Webb found no significant difference in specific gravity relative to height in sweetgum (1964). Ezzel and Schilling found that specific gravity varied vertically and diametrically but that the patterns were not consistent within or among trees (1980).

Mechanical properties of gymnosperms are generally observed to decrease at greater heights in the tree. Compression strength and stiffness parallel to grain decreased with height in the stem of maritime pine (*Pinus pinaster*) and increased with distance from pith (Machado and Cruz 2005). Compression strength parallel to grain decreased with height in white fir, but stiffness was unaffected (Gerhards 1964). Bending strength decreased with height in the stem of maritime pine, and increased with distance from pith (Machado and Cruz 2005). The lowest bending stiffness values of fast grown radiata pine were found in the butt log, the researchers suggested sorting fast grown butt logs from other logs because of large cones of juvenile wood (Xu and Walker 2004).

Angiosperms do not show a general trend of mechanical properties and height. The compression strength and specific gravity of wood from guere or soap tree was found to increase with height (Poku et al. 2001). Compression strength parallel to grain decreased significantly with height in the stems of nine year old *Xylia xylocarpa* (Josue 2004). Bending strength was higher at lower heights in California white oak but was lower at lower heights in Oregon white oak (Benson et al. 1958). Herajarvi found that birch, *Betula spp.*, has slightly decreasing bending strength and stiffness with greater heights in the tree, and sorting wood by its location in the stem was suggested (Herajarvi 2004).

Fiber length can be correlated with mechanical properties and density. Webb measured sweetgum fibers along the height of a sweetgum tree and found that fiber length decreased at greater heights in the stem (Webb 1964). A study on plantation grown black wattle, *Acacia mangium*, a diffuse porous species, also shows a trend of fiber length decreasing at greater heights and increasing with distance from the pith (Sahri et al. 1993). Sweetgum from natural stands in Louisiana contained more fibers and fewer vessels at greater heights in the tree (Ezell 1979). A study of fibers along a single sweetgum stem showed insignificant variation with height (Chow 1971).

2.6 Growth Rate

The term growth rate means the amount of diametric, vertical, or volumetric growth over a period of time. A tree's growth rate is measured by individual growth rings; it is common to measure a tree's diameter at one and a half meters from the ground. Rings per inch (rpi or rings per 2.54 cm) is a common metric used on lumber, it is measured by taking a cross section of wood and counting the growth rings within a one inch linear distance across the radius.

Aside from stem width, stem height is another useful measurement of growth. Height and width can be combined to calculate volumetric growth. A more subjective way to measure growth rate is by canopy class, meaning how the tree is growing relative to its neighbors. In an even aged stand, the dominant trees can be assumed to have the highest growth rate and the suppressed trees the lowest. The effects of growth rate are misleading because the causes of a change in growth rate are so varied and are more likely the driving force behind any effects.

It is generally accepted that increases in growth rate decrease the density of gymnosperm wood. Greater ring widths resulted in lower density in hybrid larch wood, *Larix gmelinii var. japonica x Larix kaempferi*, this trend was more severe at early ages (Fujimoto et al. 2006). The density of Japanese cedar was found to decrease with greater growth rates because of a lower percentage of latewood (Chuang and Wang 2001). Increases in growth rate due to fertilization decreased the density of Norway spruce, *Picea abies*, because of a larger number of cells with thinner walls (Makinen et al. 2002, Lundgren 2004). Density of black spruce was more related to cambial age than to ring width and therefore maturity had more impact than growth rate (Zhang and Jiang 1998).

Among angiosperms, many studies have shown that density is negatively correlated with growth rate. Accelerated growth in quaking aspen slightly reduced specific gravity (Einspahr 1971). Red alder density was unaffected by growth in seven year old trees (Lei et al. 1997). Fast grown silver birch, *Betula pendula*, was found to have slightly lower density than slow grown birch (Dunham 1999). Faster growth rates in gamhar have been correlated with lower wood density (Lauridsen and Kjaer 2002). White ash, *Fraxinus pennsylvanica*, was denser when grown slowly (Blankenhorn et al. 2005). Specific gravity of gamhar, has a strong negative correlation to diametric growth rate (Espinoza 2003). Young *Populus* showed no relation between growth rate and wood density (DeBell et al. 2002). Teak, *Tectona grandis*, that grew slower had higher density (Bhat and Priya 2004).

There is also evidence that growth rate does not negatively affect density in angiosperms. Specific gravity of red maple is higher in canopy trees than in subcanopy trees (Woodcock and Shier 2003). Density was independent of growth rate in rauli, *Nothofagus nervosa*, (Denne et al. 1999). Increased growth rates could both increase or decrease the specific gravity of eucalyptus species (Goncalves et al. 2004).

Gymnosperms have shown decreased mechanical properties with faster growth rates in multiple studies. Chuang and Wang used stress wave and ultra sonic wave methods to calculate that compression parallel to grain should decrease with greater growth rates in Japanese cedar (2001). Compression strength parallel to grain was found to decrease with ring width in taiwania, *Taiwania cryptomerioides* (Lin and Chiu 2007).

Ring width was not correlated to the bending strength and stiffness of Laricio pine, *Pinus nigra v. saltzmannii*, (Seco et al. 2004).

The bending strength of angiosperms has been negatively correlated with growth rate. Growth rate was unrelated to bending properties in seven year old red alder (Lei et al. 1997). Fast grown silver birch was found to have significantly lower bending stiffness than slow grown birch (Dunham 1999). Teak was weaker in bending when grown faster in two studies (Bhat et al. 2001, Bhat and Priya 2004). White ash had greater bending strength when grown slow (Blankenhorn et al. 2005).

The compression strength of angiosperms has also been negatively correlated with rate of growth. Increasing the growth rate of teak wood was found to have no effect on compression strength parallel to grain (Bhat et al. 2001). In another study, teak that grew slower had lower compression strength, and this difference was attributed to a greater proportion of parenchyma and less fiber within the wood (Bhat and Priya 2004). Velami, *Sclerolobium paniculatum Vogel*, has shown a trend of decreasing compression strength parallel to grain when growth was accelerated with nitrogen (Oliviera et al. 2006). The compression strength parallel to grain of guere, was found to decrease with growth rate (Poku et al. 2001).

2.7 Utilization of Sweetgum

Sweetgum and other diffuse porous woods are used for a variety of purposes such as furniture, composites, pallets, and paper products. Hardwoods such as sweetgum have a tremendously more diverse market than softwoods. Subsequently, the value of roundwood from hardwood trees is both higher and lower than that of softwood roundwood (Luppold and Bumgardner 2004). Most hardwood plantations supply wood for low value markets such as fuel or pulp.

The domestic manufacture of wood products that sweetgum is suitable for generates over 130 billion dollars in revenue and over 575 thousand jobs nationwide. In Virginia alone, these products generate over 3.3 billion dollars of revenue and over 24 thousand jobs (US Economic Census 2002). The demand for sweetgum and similar wood is obvious.

Shortages of sweetgum are a reality for southern pulp mills during winter months (Gallagher and Shaffer 2002). Periods of wet and cold weather make many hardwood stands inaccessible in the southern United States. Researchers have examined the possibility of irrigated dryland hardwood plantations to supplement bottomland forests in wet winters. Research has shown that the value of the wood harvested would not equal the costs of intensive management unless prices increased by thirty percent or more (Bar 1999, Gallagher and Shaffer 2002).

A small-scale drip irrigated wood plantation in Florida had establishment costs of \$4,178/ha and maintenance costs of \$135/ha while nearby citrus groves commonly use drip irrigation with establishment costs of \$1,475-\$2,458/ha and maintenance costs of \$61-\$123/ha (Cox and Leach 1999). Citrus orchards commonly have around 369/ha, while hardwood plantations have as many as 5,000 trees/ha. A 1.9 ha drip irrigated hardwood plantation in Texas was expected to cost \$6,250 to install and \$1,000 a year to maintain (Rock 2003). A 1,628 ha wood plantation in California was estimated to cost \$300/ha to run and maintain (Hartsough and Richter 1994).

In 2002, domestic production of nitrogen fertilizers consumed 10.2 billion cubic meters of natural gas worth over one billion dollars (US Economic Census 2002). The price of domestic natural gas has risen one hundred and seventy-five percent in the last ten years (Energy Information Administration 2008). Water scarcities commonly occur in the southeastern United States. Although the value of wood has increased, it is not increasing at the same pace as nitrogen or water.

Upland sweetgum plantations are accessible in wet weather when shortages can increase the price of sweetgum stumpage. The real value of sweetgum wood does not justify the effort needed to cultivate it on upland sites. Water contaminated with nitrogen can be used as irrigant, but this is problematic in other ways (Guo and Sims 2002, Hooda et al. 2003). Although disregarded in the past, today, sweetgum and other diffuse porous species are increasingly in demand. Knowledge of sweetgum wood quality within a tree or a monoculture will be useful in many forests.

2.8 Forest Experimentation

The specific effects of intensive management on wood quality are of interest to wood producers and processors. Regardless of its economic value, an intensively managed plantation is an opportunity to simplify forests in order to study specific cause and effects. In a review of hardwood silviculture, intensively managed plantations and agroforestsry systems have been increasingly useful to researchers (Cutter et al. 2004).

Studying the effect of growth rate on a specific wood quality is difficult. Experiments involving young trees in containers are useful for examining specific relationships between a growth stimulant and a wood quality; however the results may not apply to a real forest. Intensive management is useful to researchers because it simplifies the forest to the point where specific growth stimulants can be linked to specific wood qualities in a commercial setting.

Competition control is the most common form of forest management. Methods to control competing vegetation include soil disturbance, herbicide application, and manual removal. Lack of competition removes an important variable between different plantations if other differences between those plantations are intended for study. Without the influence of competition fertigation, thinning, or other activities have a more or less constant effect on every tree in the plantation.

2.9 Summary

Sweetgum is a common tree with a wide range in the south-eastern United States. On drier upland sites sweetgum matures faster. At higher latitudes with colder temperatures and more pronounced photoperiods sweetgum wood is denser. In regions of high summer rainfall and longer growing seasons sweetgum fibers are longer.

Sweetgum grows well in monocultures and mixed stands. Competition control increases growth and crown vigor. Irrigation increases growth on dry upland sites. Water stress may decrease vessel diameters and internode length. Nitrogen fertilization increases the growth rate and fiber length of diffuse porous wood.

Growth rate can be increased by climate, canopy position, or silviculture. Wood density normally decreases with growth rate in gymnosperms but not angiosperms. The density of diffuse porous trees is increased when growing in colder climates or in dominant canopy positions. Mechanical properties are negatively correlated with growth rate in angiosperms and gymnosperms.

Wood quality often varies more within a tree than between trees. Many trees show a pattern of variation in wood quality within a single tree. The study of wood quality is difficult in a commercial setting because of stress from competition for water and nutrients. Intensive plantations create opportunities to examine specific causes of growth rate and effects on wood quality.

Chapter 3: Materials and Methods

3.1 Materials

Six sweetgum trees from intensively managed plantations were sampled in this study. Three sweetgum trees near Pensacola, Florida and three more trees near Summerville, South Carolina were used to produce compression samples.

The Pensacola trees were planted in the winter of 1995 and harvested in the fall of 2004. Sample trees were felled by chain saw and bucked into 2 m logs from the butt to an approximately 5 cm top. Within the canopy of the plantation one tree was dominant, one was codominant, and one was suppressed. Each log was end-coated to prevent splitting.

Plantation topography was very level at approximately 72 m above sea level. A sandy Troup topsoil varied from 25 cm to 150 cm deep across the site, the subsoil varied from coarse loamy to fine loamy. Lime was broadcast to adjust soil pH to 6. Micronutrients (calcium, magnesium, zinc, copper, and manganese) were applied before planting. Dolomitic lime was reapplied during the third growing season (1998).

The sweetgum seedlings were planted at a spacing of 3.6 m by 2.3 m resulting in 229 trees per hectare. Complete competition control was accomplished by herbicides, mowing, and manual pulling. Initial growth of the sweetgum trees was impacted by disease in the seedlings; many seedlings planted in the fall died back to the soil line and resprouted the following spring.

The Pensacola trees were fertigated for the first seven growing seasons with groundwater and soluble fertilizer. An 8-2-8 analysis fertilizer was used the first year and a 12-2-8 analysis fertilizer was used thereafter. The suppressed tree received 37 kg

N/ha/yr. The dominant and codominant trees received 9 kg N/ha/yr. Drip irrigation was used to apply the water by emitters spaced at and between every tree.

Three sweetgum trees grown in another plantation near Summerville, South Carolina were compared with the first study group. The trees were planted in the spring of 1997 and harvested in the spring of 2006. Each tree was felled by chainsaw and bucked into 2.5 m logs from the butt to an approximately 5 cm top. One dominant, one co-dominant, and one suppressed tree were selected. Each log was end-coated to prevent splitting.

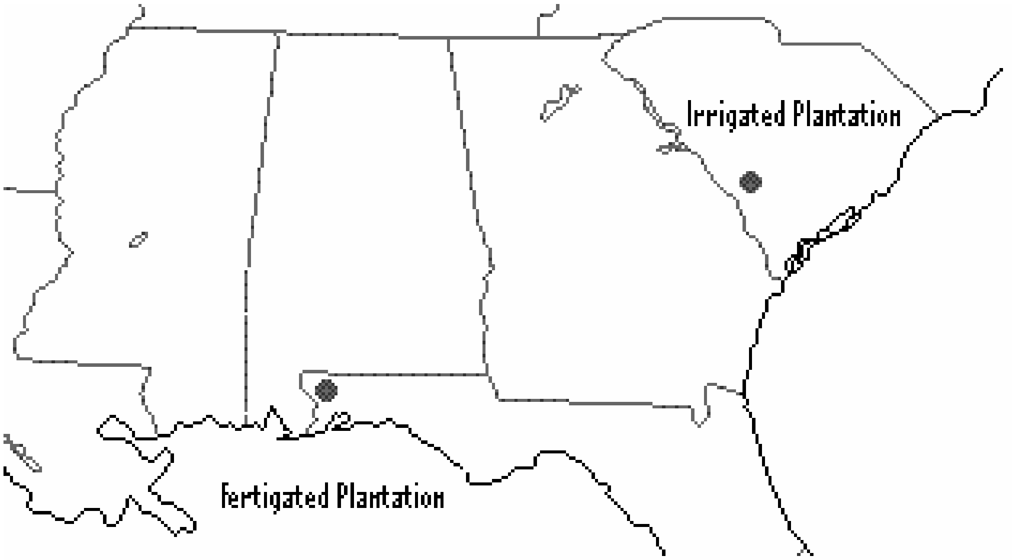

Figure 3.1. Map of the south-eastern United States showing locations of the plantations.

Plantation topography was level at approximately 56m above sea level. Soil series was Alpin and Troup, the soil texture was sandy. Alpin is similar to Troup in that both are well drained soils with low water-holding potential. Figure 3.1 shows the location of each plantation, they are approximately 725 km apart.

The Summerville trees were spaced 3.3m by 2.6m for a total of 221 trees per hectare. Complete competition control was accomplished with herbicides and manual pulling. The trees were irrigated with groundwater for the first seven growing seasons.

Irrigation lines were initially placed close to each tree and were gradually moved further in between rows as the trees grew, this was in an effort to encourage root growth. Table 3.1 summarizes useful information about the two plantations.

Table 3.1. Comparison of study groups, see references for sources.

Parameter	**Summerville, SC**	**Pensacola, FL**	**Source**
Age	9 years	9 years	Dunham 2006, Cox and Leach 1999
Spacing	3.3 m x 2.6 m	3.6 m x 2.3 m	
Trees per Hectare	221	229	
Fertilization	None	9 kg or 37 kg N/ha/year	
Irrigation	Approx. 2.5cm/week	Approx. 5cm/week	
Prior Land Use	Agricultural	Agricultural	
Water Source	Groundwater	Groundwater	
Avg. Diameter at 1.5m	12.2 cm	14.7 cm	Cruise Data Spinney 2003
Avg. Height to Crown	4.1 m	5.5 m	
Avg. Total Height	12.5	14.4	
Avg. % live crown	66.8%	62.1%	
Avg. Volume per tree	0.09 m^3	0.14 m^3	
Latitude and Longitude	33, 17N 81, 2W	30, 47N 87, 8W	
Mean Annual Increment	1.35 cm/year	1.63 cm/year	
Soil Series	Alpin and Troup	Troup	USDA NRCS Soil Survey
Soil pH	4.5-6.5	4.5-5.5	
Soil Organic Matter	low	low	
Site Index (Loblolly)	83.5	80	
Water Capacity	0.33 cm	.08-.25 cm	
Water Permeability	15-50 cm/hour	15-50 cm/hour	
Depth of Solum	200-300 cm	200+ cm	
Average Annual Rainfall	120cm	171cm	NCDC NOAA
Growing Season	228 days	300 days	
Ozone	.0976ppm 2nd max/1hr	.0956 2nd max/1hr	USEPA
Clear Days	115.5	104.9	
Cloudy Days	147.1	137	

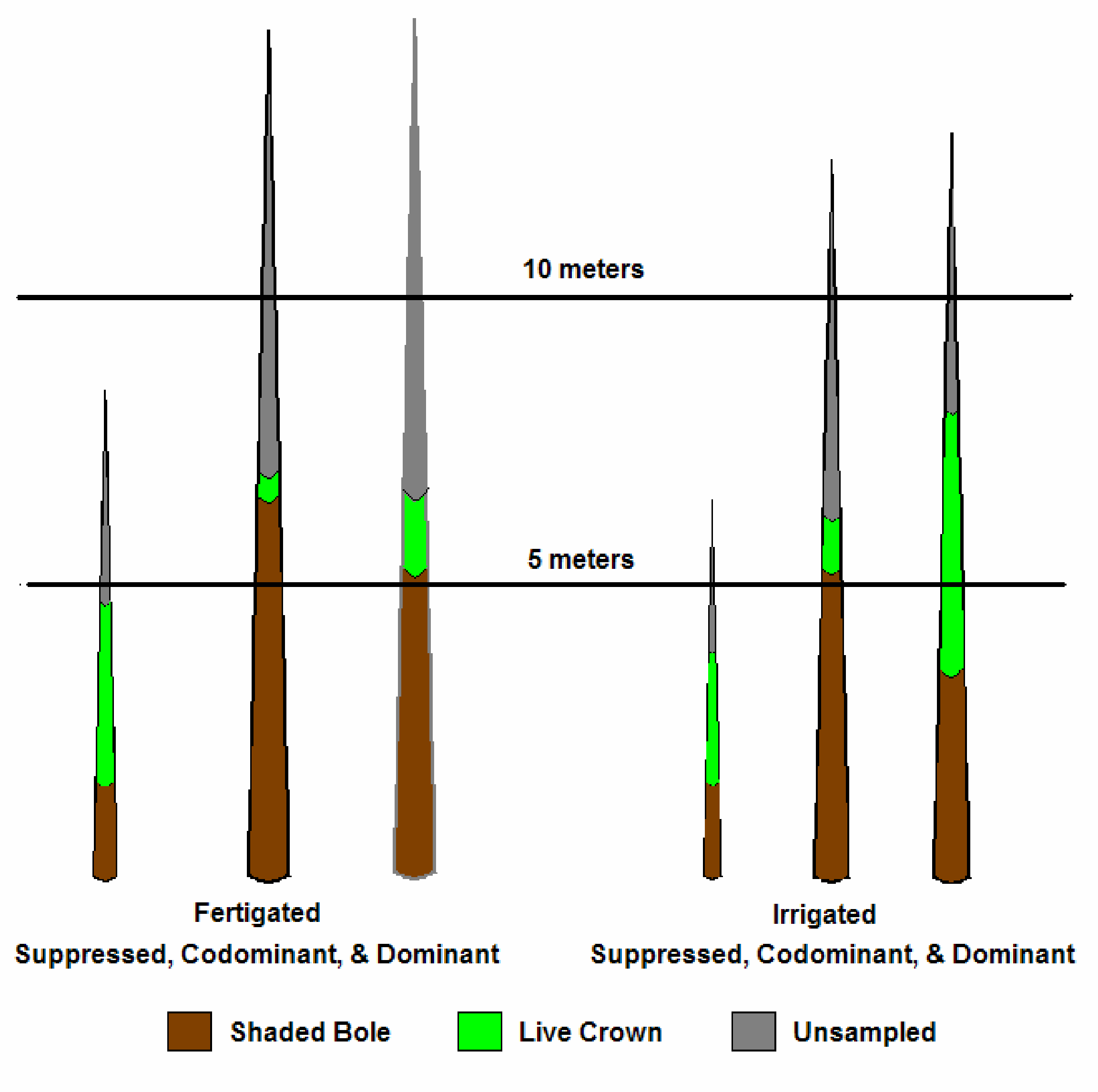

Figure 3.2. Sampling along the height of a tree.

Figure 3.2 demonstrates what portion of the stem was sampled and what amount of sampled stem was within the photosynthetically active crown. Interestingly, both suppressed and dominant trees had larger proportions of crown than codominant trees. Table 3.2 lists the number of samples taken at different heights within each tree The majority of samples were taken near the bottom of the trees where wood volume and variation were greatest.

No preference was given to sample material based on distance from the pith. Each sample was conditioned to 12% moisture content to enable comparisons with each other and with previous data. The wood from the irrigated plantation was conditioned in a shorter amount of time than that of the fertigated plantation. Consequently, the samples were prepared differently and more sample material was discarded because of splitting.

The logs from Pensacola were air dried outdoors for 6 months. Larger logs were then milled into 25mm thick boards on a Woodmizer LT40 saw mill and smaller logs were milled on an electric band mill. Milled boards were then allowed to air dry for 3 months. Each board was then debarked and milled into 25mm x 25mm x 100mm samples that represented a 150mm portion of the height of the tree. All samples were then stored in a conditioning chamber at 20.8C and 46% relative humidity to condition the wood to 12% moisture content.

Table 3.2. Number of samples taken along the height of each tree.
F = Fertigated, I = Irrigated, S = Suppressed, C = Codominant, D = Dominant.

Height	FS	FC	FD	IS	IC	ID	All Trees
8-9			3			8	11
7-8		1	9			7	17
6-7		5	12		6	2	25
5-6	1	10	18		8	3	40
4-5	2	10	8		4	6	30
3-4	4	12	13		8	11	48
2-3	4	10	11	2	9	11	47
1-2	5	22	16	4	17	10	74
0-1	9	23	16	14	23	35	120
Total	25	93	106	20	75	93	412

The logs from Summerville were air dried outdoors for one week. The largest log was milled into 25mm thick boards on a Woodmizer LT40 saw mill. All other logs were canted on an electric band mill. After milling, the boards and cants were debarked, end-coated, and stored for two months inside a conditioning chamber at 20°C and 64%RH. Both boards and cants were milled into 25mm x 25mm x 100mm samples that represented a 150mm section of the tree. The samples were conditioned to 12% moisture content by storing them in a different conditioning chamber at 20.8°C and 46% relative humidity. Figure 3.3 illustrates the cutting scheme used to segment the tree stem.

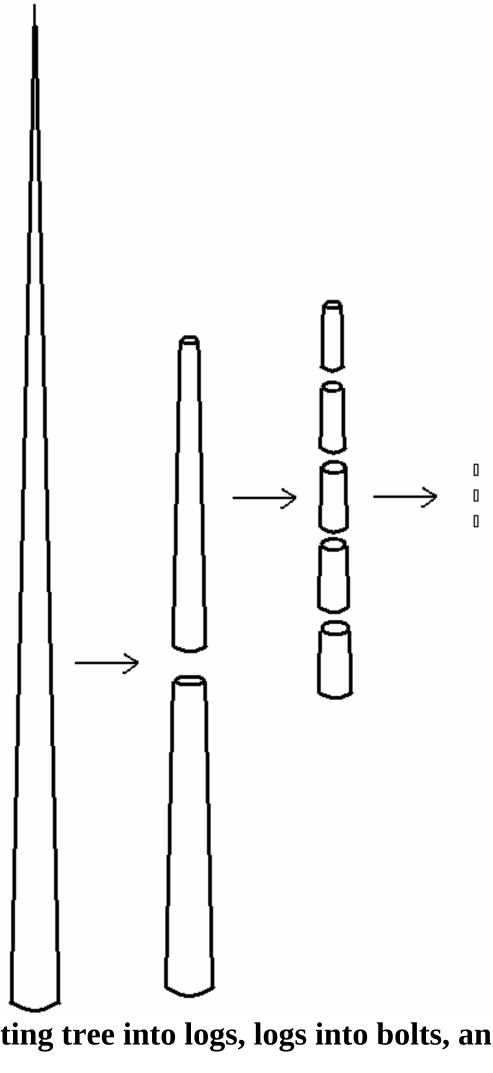

Figure 3.3. Diagram of cutting tree into logs, logs into bolts, and bolts into samples.

3.2 Methods

Prior to testing each sample end was recut on a miter saw. The samples were then measured for their dimensions, rings per inch, ring curvature, grain deviations, pith, and observed for any defects. Dimensions were measured to three decimal places with an electronic micrometer. Ring curvature, grain deviations, and pith were observed visually. Defects included splitting, large and/or unsound knots, void space, and improper machining.

Rings per inch were observed on both ends of the samples and then the values were average. Observing the rings proved to be the most difficult part of sample preparation. Average ring width was determined by measuring the entire trees diameter at 1.5m from the ground. The diameter was divided by the trees age, nine, and then again by two. The average ring width that is calculated represents the entire tree, not an individual sample.

Each sample was then tested in compression parallel to grain. The compression testing followed ASTM Standard D143-83 using the secondary method sample size of 25mm x 25mm x 100mm. A United SFM-100KN testing machine equipped with a 20,000 pound load cell was used. Load was applied at a rate of 0.075mm/minute from above, and a spherical bearing was present below the sample.

Compression parallel to grain was chosen because the test is tolerant of defects in the sample relative to tension and bending testing. Many of the samples tested contained sound knots or abnormal grain patterns but did not fail as a result of those minor defects.

A 100 mm long sample was chosen to represent each 150 mm section of tree stem in an effort to avoid defects.

Displacement was measured at the cross-head of the testing machine for simplicity. Roller-type compressometers were not available and automatic type compressometers would likely have not accurately measured the displacement of a sample that experienced a buckling failure.

A stress-strain curve was plotted on an MS Excel spreadsheet and two points were chosen within the linear region of the curve. The linear region of the curve is where there is a one for one relationship between units of stress and displacement. The equation (stress @ time 2 – stress @ time 1) / (strain @ time 2 – strain @ time 1) was then used to calculate stiffness.

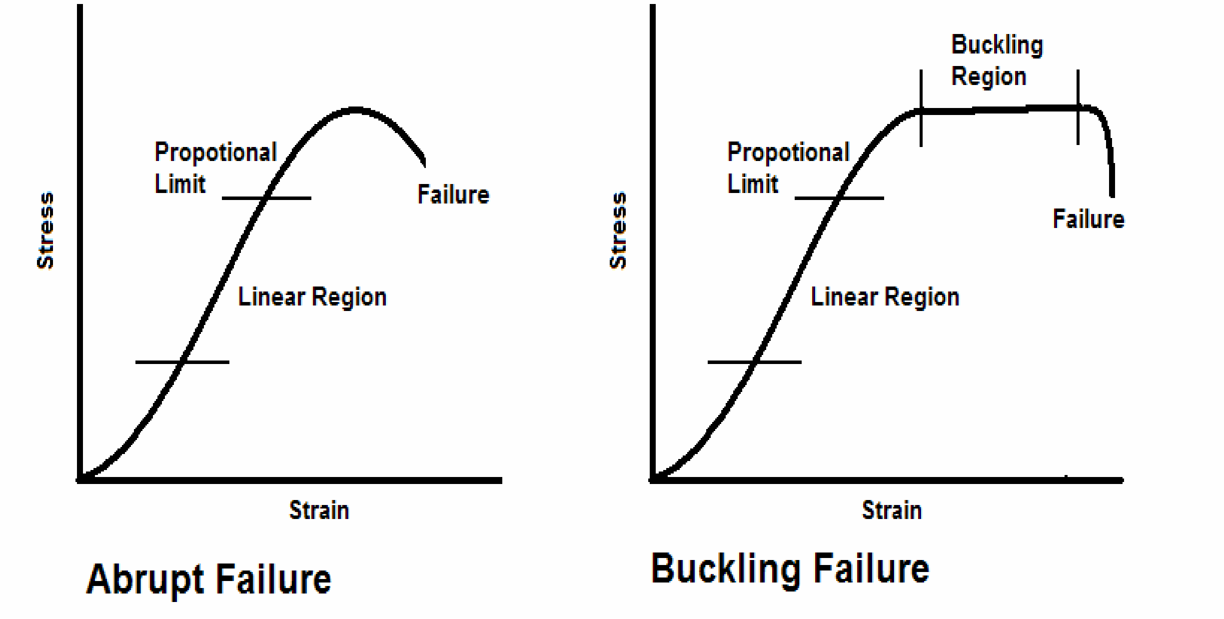

Figure 3.4. Stress-strain curves for abrupt failures (broom, shear, crush, or split) and buckling failures.

Failure mode was recorded while the specimen was under compression. Certain samples withstood their peak stress for longer time periods. These same samples were observed to buckle along the entire 100mm length of the sample. Eventually these samples failed most often by shearing. These samples were recorded as failing by buckling if the buckling region of the stress strain curve was longer than the linear region (see Figure 3.4).

Moisture content and oven-dry specific gravity were then measured. Moisture content was calculated as the difference of the initial sample weight and the weight of the sample in the oven-dry condition; divided by the weight of the sample in the oven-dry condition. Initial weight was determined by weighing the sample immediately prior to and after testing and then averaging those values. Oven-dry weight was determined by weighing the sample after drying at 100° C for 24 hours or until the oven-dry weight of the sample did not vary more than 0.01 g.

Specific gravity was determined by immersing the oven-dry sample in hot wax and then displacing water with the sample. Specific gravity was calculated as the weight of the sample in the oven-dry condition divided by the volume of the sample in the oven-dry condition. Metric units were used and it was not necessary to multiply the quotient by the density of water. Oven-dry volume was chosen because of the difficulty in bringing samples to a standard (12%) moisture content. Immersion in water would likely have further complicated the conditioning of the samples.

3.3 Data Analysis

An original pool of 733 samples was refined to 412 samples. Samples were removed because they had developed stress fractures during drying, they failed at a defect, or the sample moisture content was below 11% or above 13%. Figure 3.5

demonstrates the effect of moisture content on the strength of the samples. Drier samples tested higher and wetter samples tested lower in compression parallel to grain.

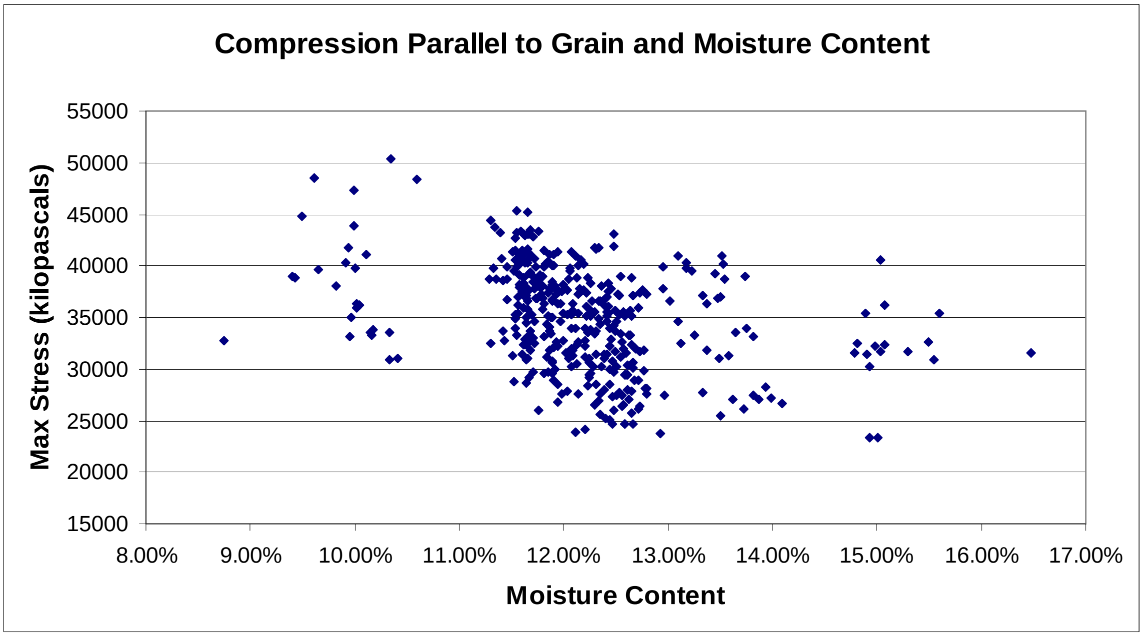

Figure 3.5. Comparison of maximum stress and moisture content of fertigated samples.

All six trees were considered a single population for statistical tests. T-tests compared the average strength and density of each tree against established data. A SAS general linear model was used to observe the influence of crown class, silviculture or average ring width on strength, stiffness, and density. The average value of all the samples within a tree was used to represent strength, stiffness, and density. Average ring width was determined at 1.5m and used to represent growth rate.

Each tree was also treated as a different population for correlations of wood quality and stem location. A correlation procedure was used to determine any relationships between height, stress, stiffness, and specific gravity within each tree. There were more samples representing the bottom portion of the tree than the top. There was more variation in the strength and stiffness of samples from the bottom than in the top of a given tree.

The correlation procedure was accomplished using SAS version 8.1. Microsoft Excel was used to create the scatter-plots found in the results; r^2 values were calculated by Excel and p values were calculated by SAS. The comparisons between trees were made with general linear models using SAS version 8.1.

All of the samples were pooled together and then divided into two groups for the final statistical test. The samples were divided into those taken below and above the live crown of the tree. A SAS t-test was used to compare wood from the shaded bole with wood from the photosynthetic crown. The SAS code and output are available in Appendix 2.

Chapter 4: Results and Discussion

The average values of the sweetgum wood samples were significantly lower than the values of previous researchers. Three of the six tree showed strong correlations of strength, stiffness, and specific gravity with height. Compression strength and stiffness increased at greater heights in the trees. Strength and stiffness are higher in the live crown ($p<0.001$). Stiffness and density are significantly higher in the live crown ($p<0.001$)

No significant relationship was found between average ring width and specific gravity or compression strength and stiffness within a tree. Dominant trees were slightly superior to codominant and suppressed trees in compression strength, stiffness, and specific gravity. There was little difference in compression strength and stiffness between irrigated and fertigated trees. The specific gravity of irrigated trees was significantly higher than that of fertigated trees ($p=0.0101$). Table 4.1 lists the summary values of the wood samples grouped by crown class and treatment.

Table 4.1. Average values for samples grouped in different categories.

Tree	Average Height of sample (m)	Average Rings per Inch of Samples	Average Ring Width (cm taken@1.5m)	Average Strength (kPa)	COV Strength (kPa)	Average Stiffness (kPa)	COV Stiffness (kPa)	Average Specific Gravity	COV Specific Gravity
Irrigated Dominant	2.90	2.8	0.80	36,686	8.6%	20,982,049	11.2%	0.62	8.3%
Irrigated Codominant	2.47	2.8	0.70	33,108	9.6%	19,114,128	15.9%	0.59	9.0%
Irrigated Suppressed	0.81	2.6	0.60	33,289	6.2%	18,343,431	17.9%	0.61	9.0%
Fertigated Dominant	3.86	2.6	1.30	38,956	7.5%	20,668,467	12.1%	0.54	4.8%
Fertigated Codominant	2.64	2.9	0.85	31,179	13.5%	16,624,654	22%	0.50	6.7%
Fertigated Suppressed	1.99	3.7	0.45	33,459	9.0%	19,118,745	10.9%	0.49	4.6%
All Irrigated	2.51	2.8	0.70	34,897		19,950,678		0.61	
All Fertigated	3.14	2.9	0.85	35,114		18,838,075		0.52	
All Dominant	3.41	2.7	1.05	37,895		20,814,911		0.58	
All Codominant	2.56	2.9	0.75	32,040		17,756,233		0.54	
All Suppressed	1.47	3.2	0.50	33,383		18,774,161		0.54	
All Trees	2.85	2.8	0.75	35,015		19,349,271		0.56	

4.1 Growth Rate

The two plantations have many similarities. Both were 9 years of age, grew in dry soils, were drip-irrigated, and grew completely free of competition. There are also important differences in the climate and silviculture between the stands resulting in different growth rates.

Growth rate was measured as the average ring width at 1.5 meters above the ground. Average ring width was calculated by measuring the circumference of the tree, determining its diameter, and then dividing the diameter by nine. Figures 4.1 and 4.2 illustrate the relationships between ring width and strength (4.1) and stiffness (4.2). Figure 4.3 shows the average specific gravity of the six trees. The variation in specific gravity is much lower in the irrigated trees and the average values are higher.

Mechanical properties increased when average ring width increased, however the trends are not significant. Specific gravity also increased with growth rate but the trend was even less significant. The average values of the irrigated trees showed less variation in average ring width and in strength, stiffness, and density. The dominant trees were stronger, stiffer, and denser than the other trees in their respective plantations.

In figures 4.1 and 4. 2 there is an outlier with wide rings and low mechanical properties. The outlying data point represents the fertigated codominant tree. Another way to measure growth rate is by canopy class. The fertigated codominant tree had similar diametric growth as the irrigated codominant tree; however the irrigated dominant tree had a much higher growth rate within its plantation. The proportion of live crown is much higher in the irrigated dominant tree (71%) is higher than that of the fertigated codominant (55%). The amount of live crown may have more impact than growth rate on compression strength and stiffness parallel to grain than average ring width.

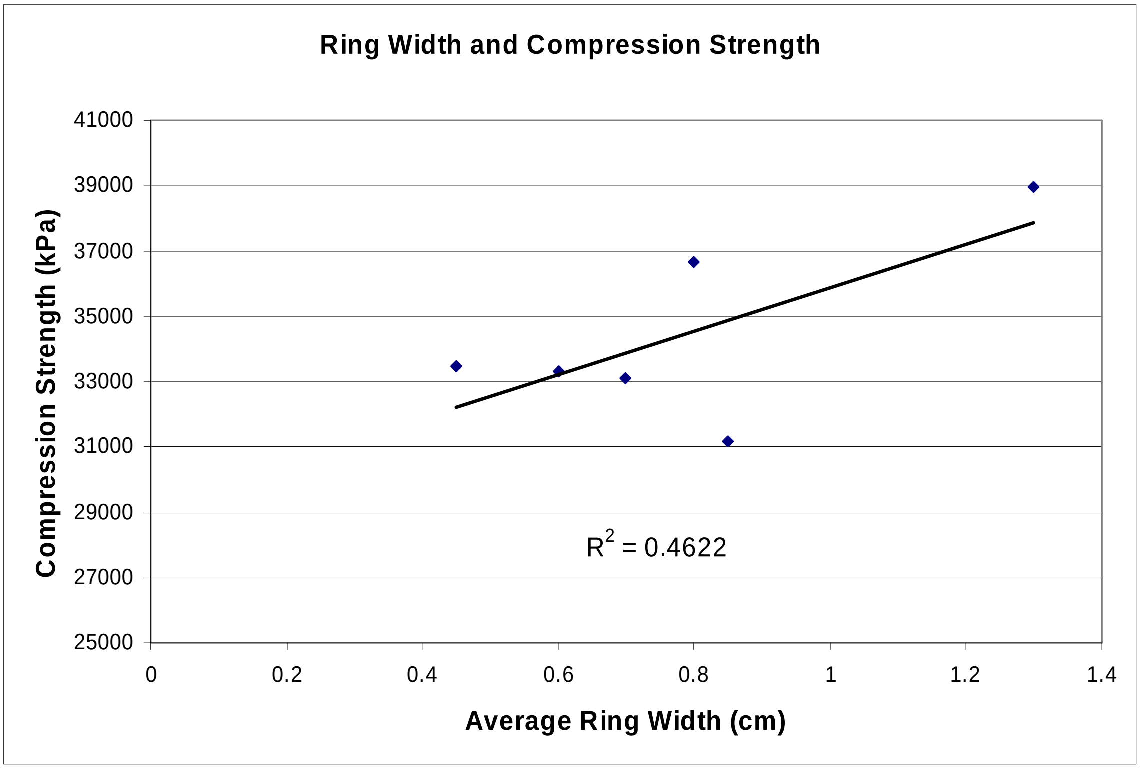

Figure 4.1. Average compression strength parallel to grain of sweetgum trees with different average ring widths.

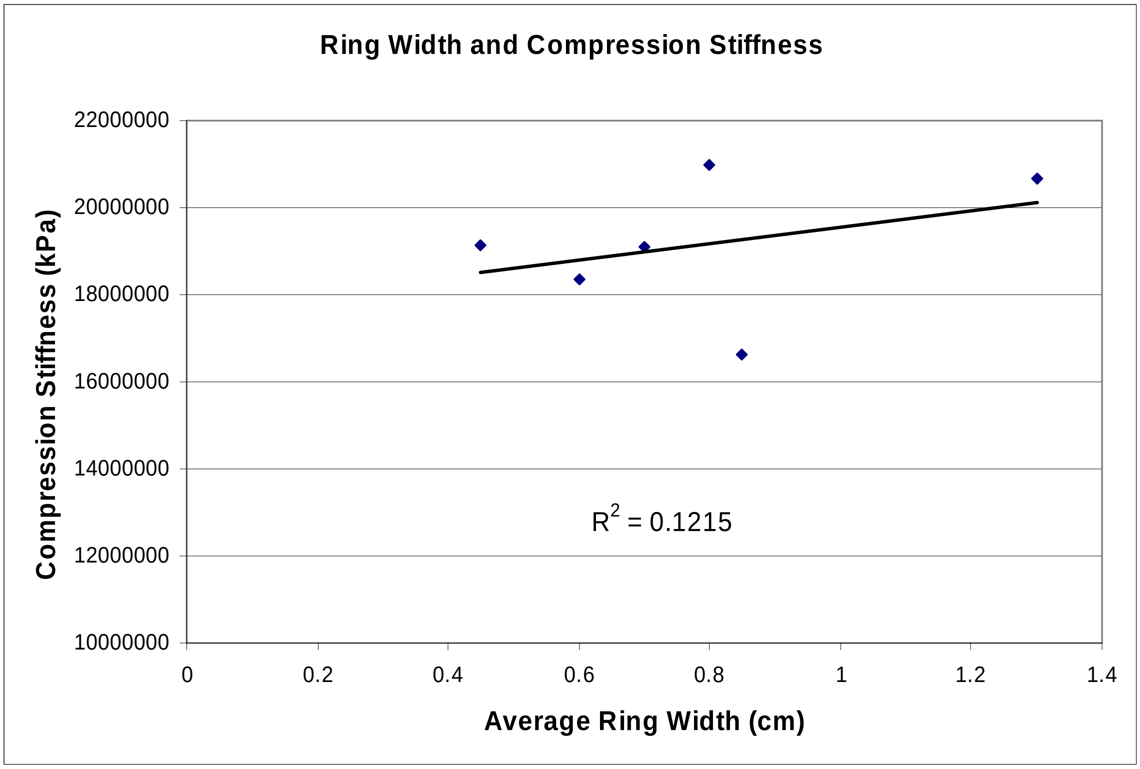

Figure 4.2. Average compression stiffness parallel to grain of sweetgum trees with different average ring widths.

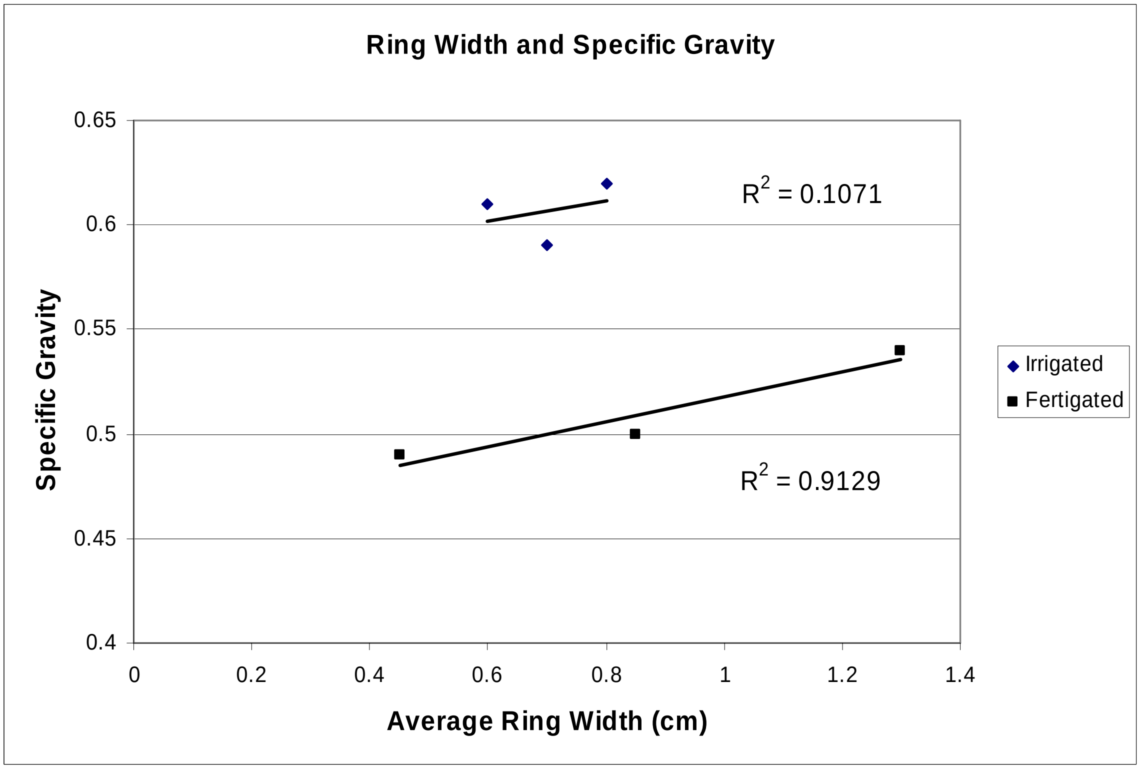

Figure 4.3. Average specific gravity of sweetgum trees with different average ring widths.

4.2 Compression Parallel to Grain and Height

Previous research has shown sweetgum has an average strength of 45,000 kilopascals (kPa) in compression parallel to grain (Wood Handbook 1999). The average compression strength of the samples from this study was almost 35,000 kPa, this is significantly lower (p=0.0004) than the wood handbook values. There is a trend of increasing strength with height in the tree that is observable in Figures 4.4 – 4.9. The two dominant trees (Fig. 4.4 and 4.5) were slightly stronger than codominant (Fig. 4.6 and 4.7) or suppressed trees (Fig. 4.8 and 4.9).

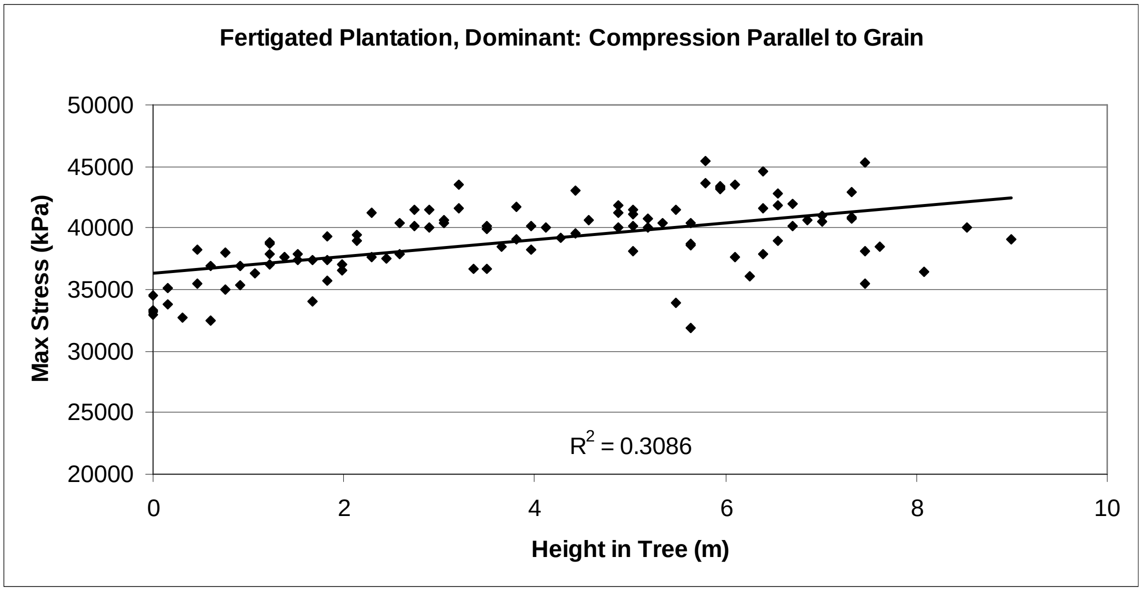

Figure 4.4. Strength of dominant fertigated sweetgum wood tested in compression parallel to grain at different heights in the tree (p<0.0001).

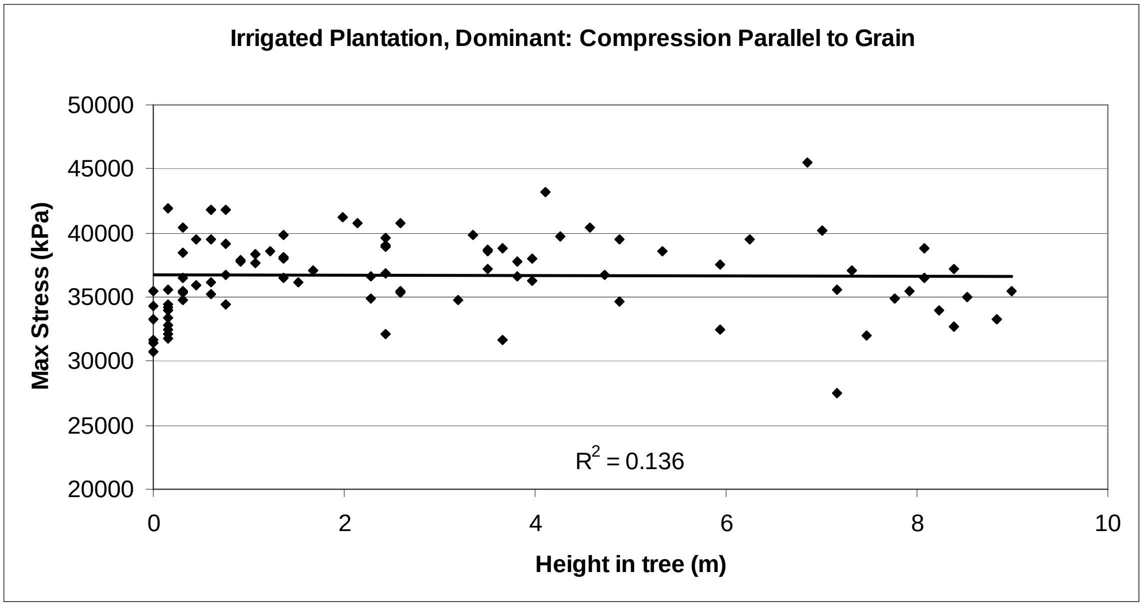

Figure 4.5. Strength of dominant irrigated sweetgum wood tested in compression parallel to grain at different heights in the tree (p<0.0001).

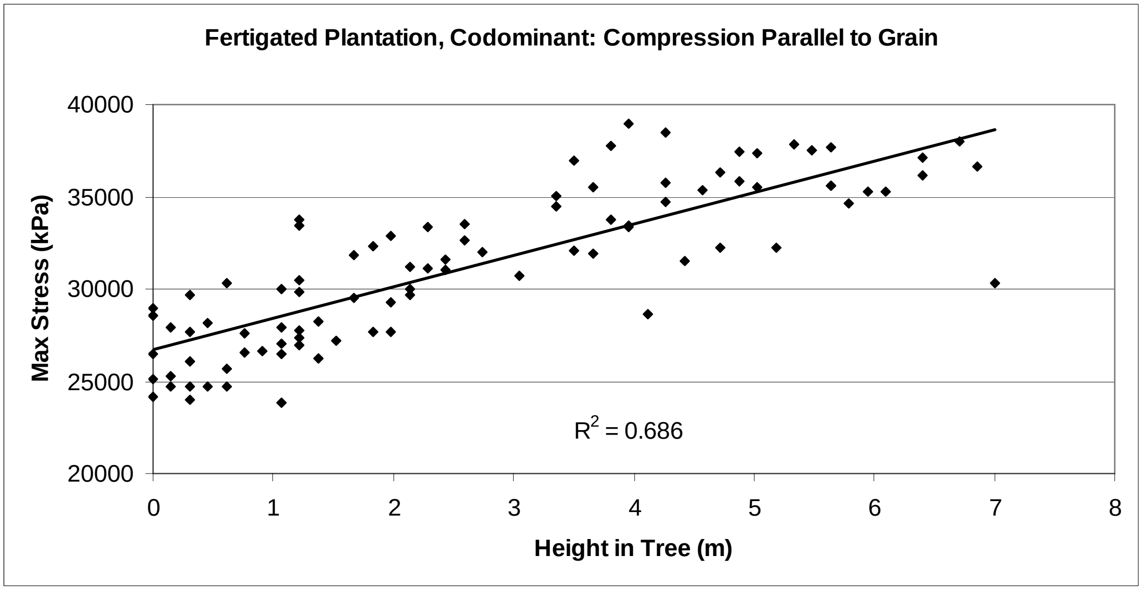

Figure 4.6. Strength of codominant fertigated sweetgum wood tested in compression parallel to grain at different heights in the tree (p<0.0001).

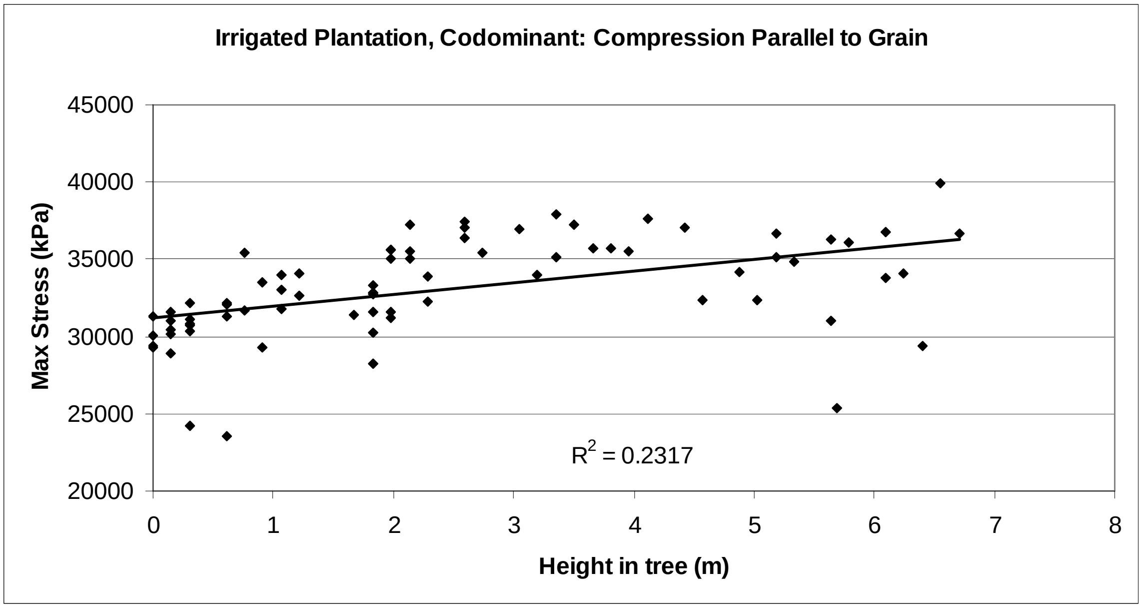

Figure 4.7. Strength of codominant irrigated sweetgum wood tested in compression parallel to grain at different heights in the tree (p<0.0001).

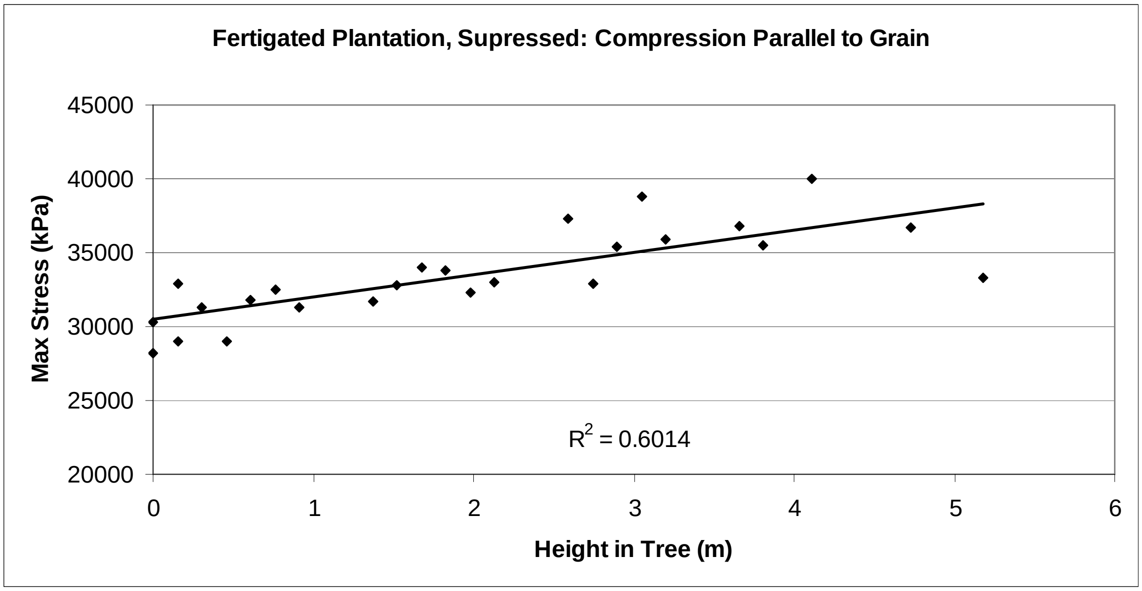

Figure 4.8. Strength of suppressed fertigated sweetgum wood tested in compression parallel to grain at different heights in the tree (p<0.0001).

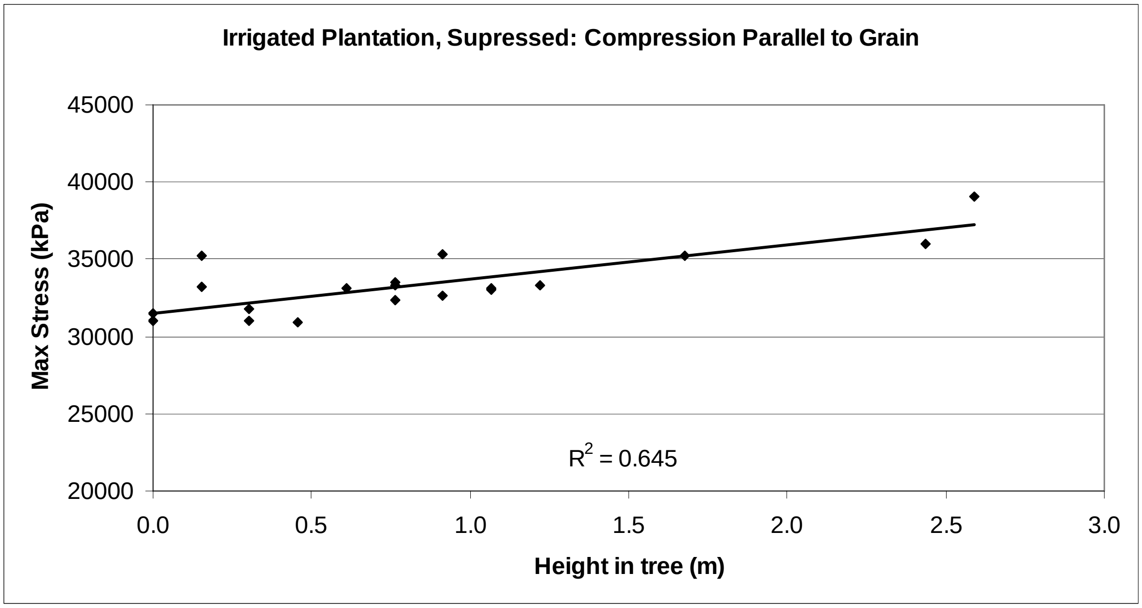

Figure 4.9. Strength of suppressed irrigated sweetgum wood tested in compression parallel to grain at different heights in the tree ($p<0.0001$).

4.3 Modulus of Elasticity (Stiffness) and Height

Previous research has shown sweetgum to have an elastic modulus of over 1.13×10^7 kilopascals in bending strength (Wood Handbook 1999). Samples in this study had higher stiffness values averaging over 1.91×10^7 kilopascals, the higher values are because the wood was tested in compression parallel to grain. The stiffness of the wood increased with a pattern similar to the compression strength as seen in figures 4.10 – 4.15. Stiffness was higher in dominant trees (fig. 4.10 and 4.11) than in codominant (fig. 4.12 and 4.13) or suppressed trees (fig. 4.14 and 4.15).

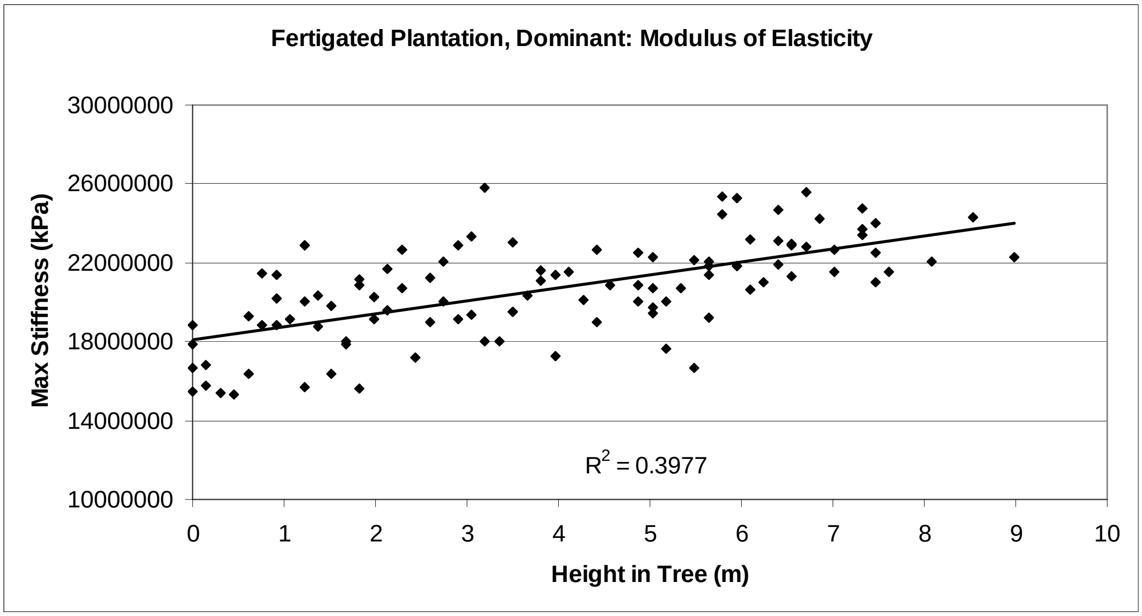

Figure 4.10. Stiffness of dominant fertigated sweetgum wood tested in compression parallel to grain at different heights in the tree ($p<0.0001$).

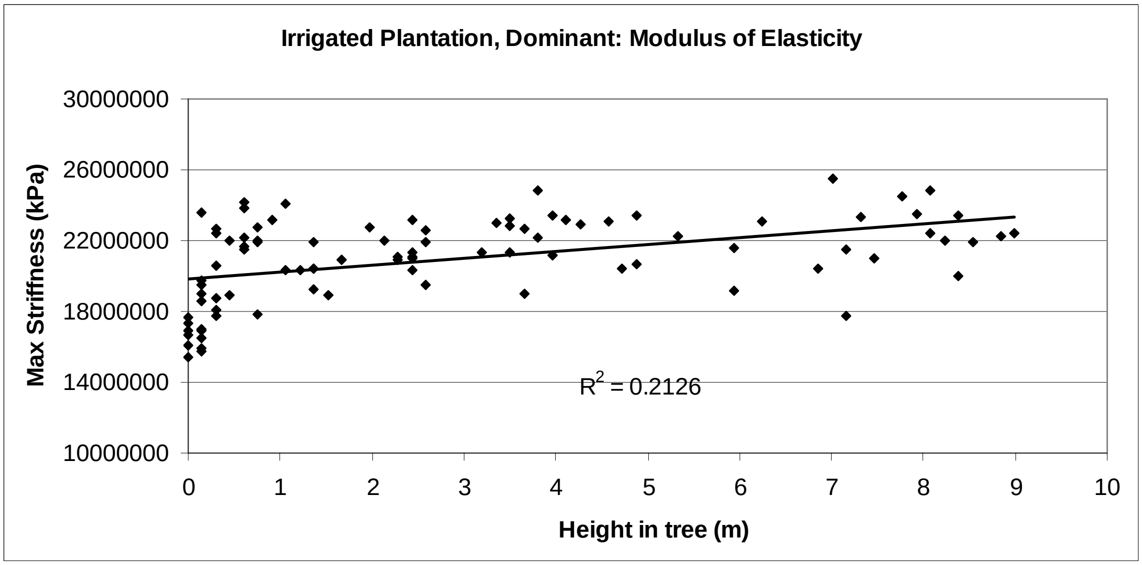

Figure 4.11. Stiffness of dominant irrigated sweetgum wood tested in compression parallel to grain at different heights in the tree ($p<0.0001$).

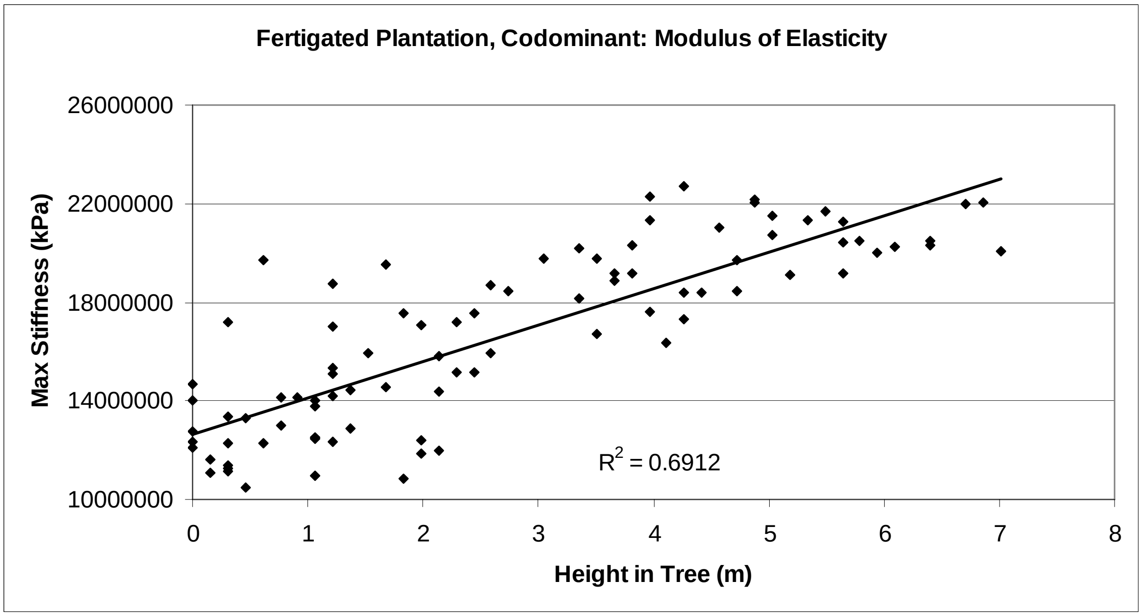

Figure 4.12. Stiffness of codominant fertigated sweetgum wood tested in compression parallel to grain at different heights in the tree (p<0.0001).

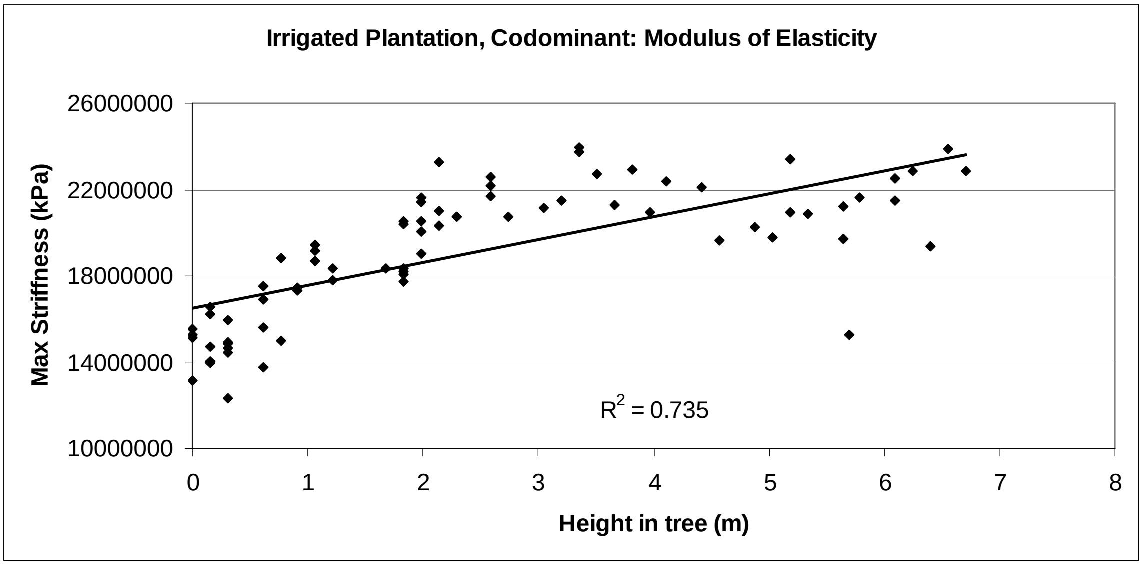

Figure 4.13. Stiffness of codominant irrigated sweetgum wood tested in compression parallel to grain at different heights in the tree (p<0.0001).

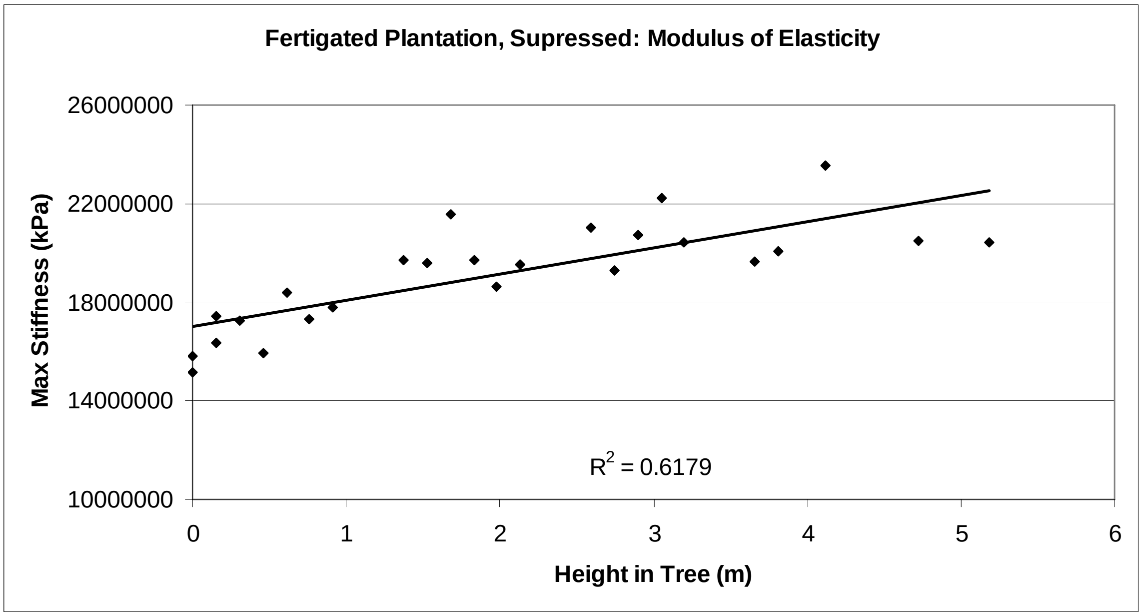

Figure 4.14. Stiffness of suppressed fertigated sweetgum wood tested in compression parallel to grain at different heights in the tree (p<0.0001).

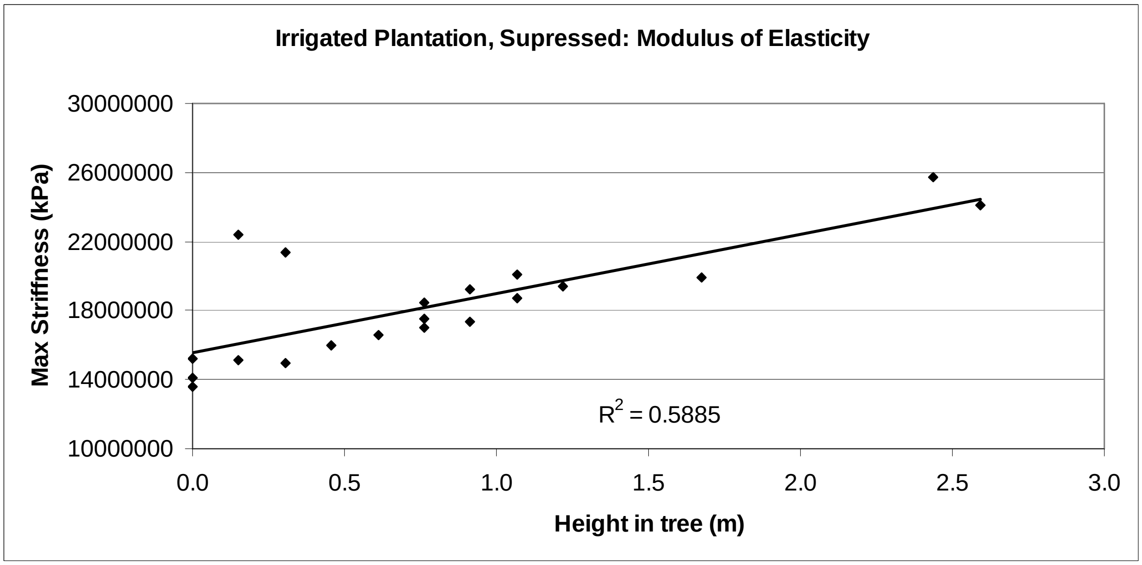

Figure 4.15. Stiffness of suppressed irrigated sweetgum wood tested in compression parallel to grain at different heights in the tree (p<0.0001).

4.4 Specific Gravity and Height

Average oven-dry specific gravity of sweetgum has been found to be 0.53 (Forest Products Laboratory 1964). The average oven-dry specific gravity of the fertigated samples from this study (0.52) is comparable to these results. The average oven-dry specific gravity of the irrigated samples (0.61) is 15% greater than previous research. A scatterwaithe t-test showed that the specific gravity of the irrigated trees was significantly higher (p=0.0101) than the fertigated trees. There is a slight pattern of decreasing specific gravity with height in the irrigated dominant tree (figure 4.17) and both suppressed trees (figures 4.20 – 4.21). The other trees do not show any correlation of specific gravity with height (figure 4.16-4.21). A general linear model showed an observable but insignificant effect of plantation location on specific gravity (p=0.021).

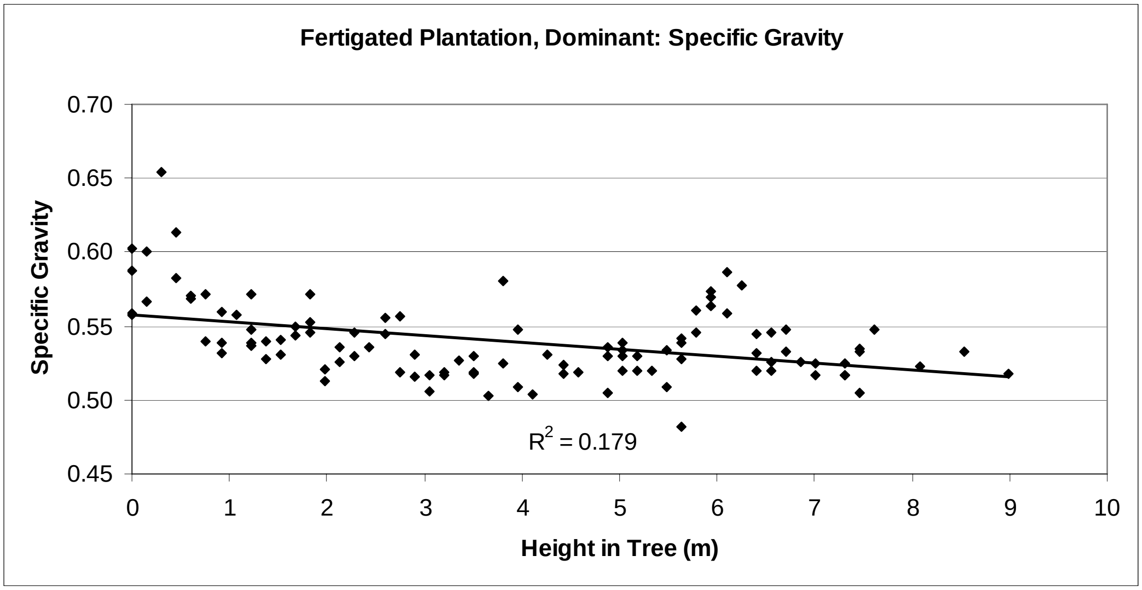

Figure 4.16. Oven-dry specific gravity of dominant fertigated sweetgum at different heights in the tree (p=0.1322).

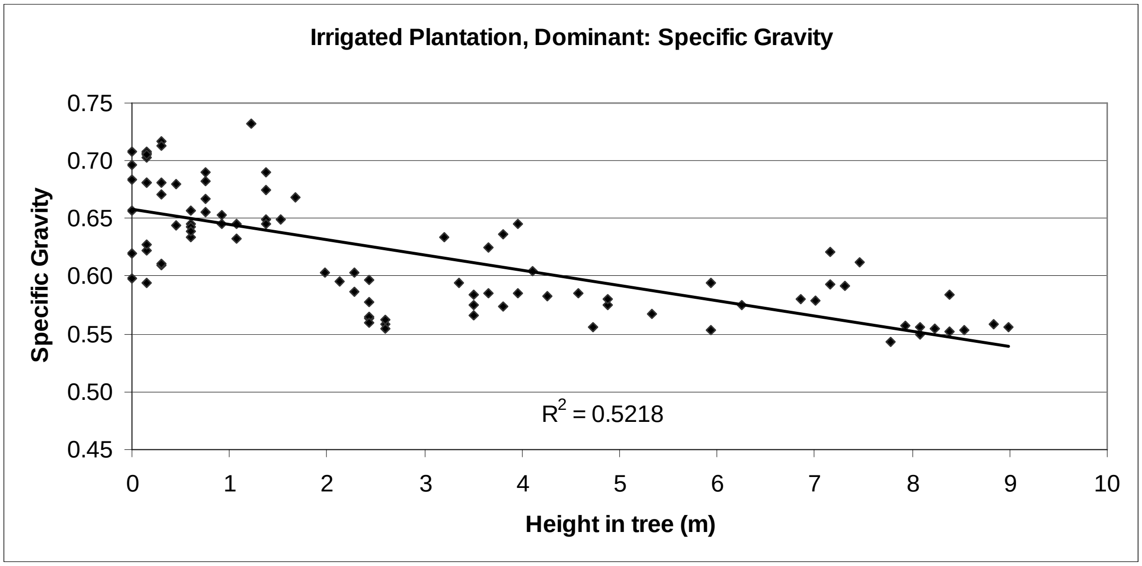

Figure 4.17. Oven-dry specific gravity of dominant irrigated sweetgum at different heights in the tree (p<0.2233).

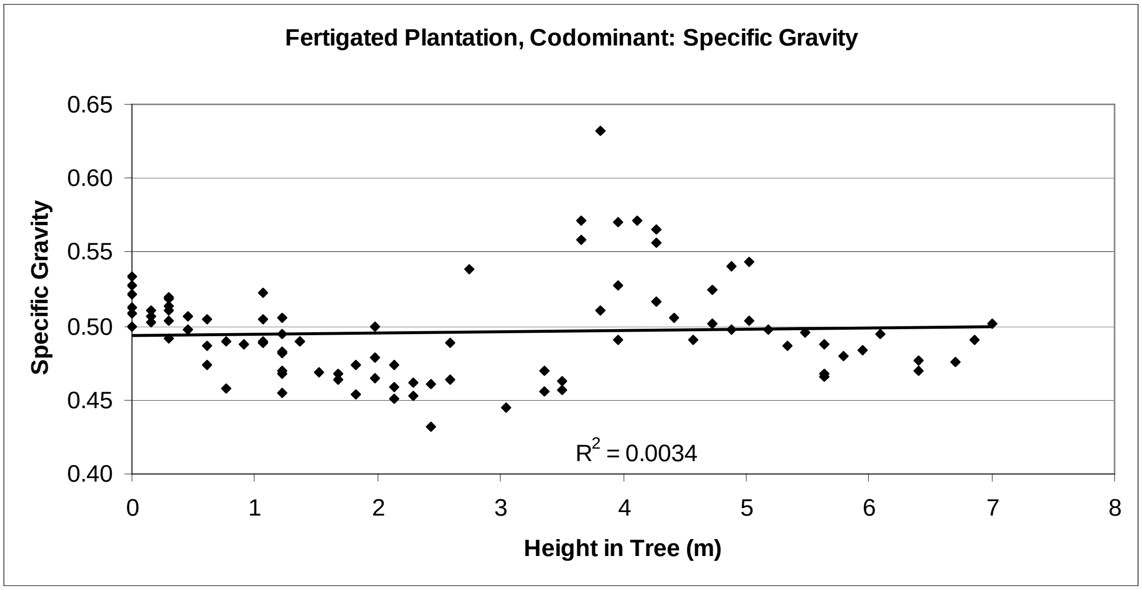

Figure 4.18. Oven-dry specific gravity of codominant fertigated sweetgum at different heights in the tree (p=0.104).

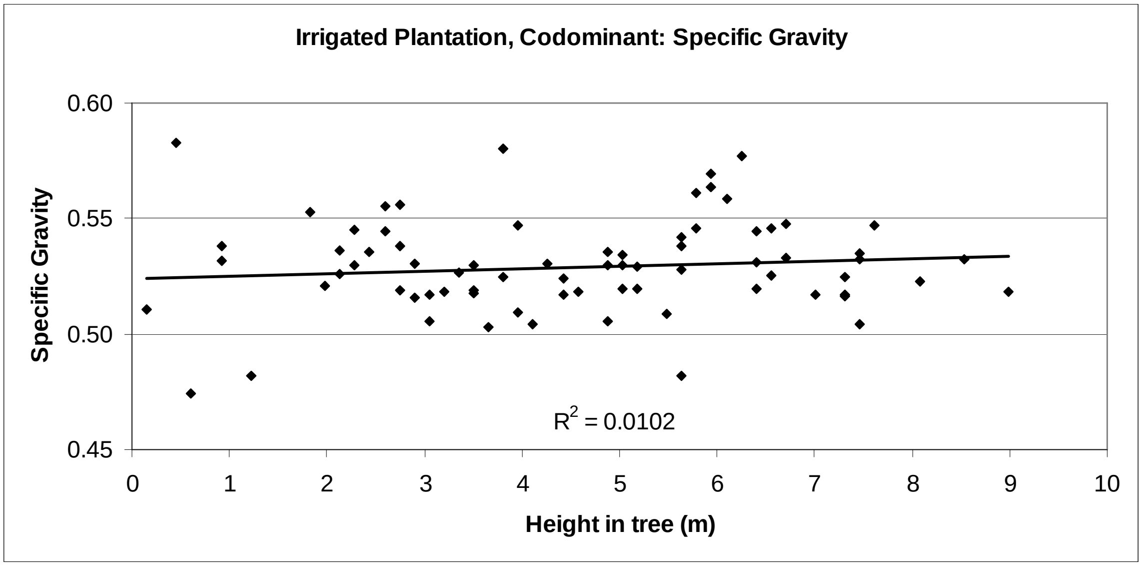

Figure 4.19. Oven-dry specific gravity of codominant irrigated sweetgum at different heights in the tree (p<0.0001).

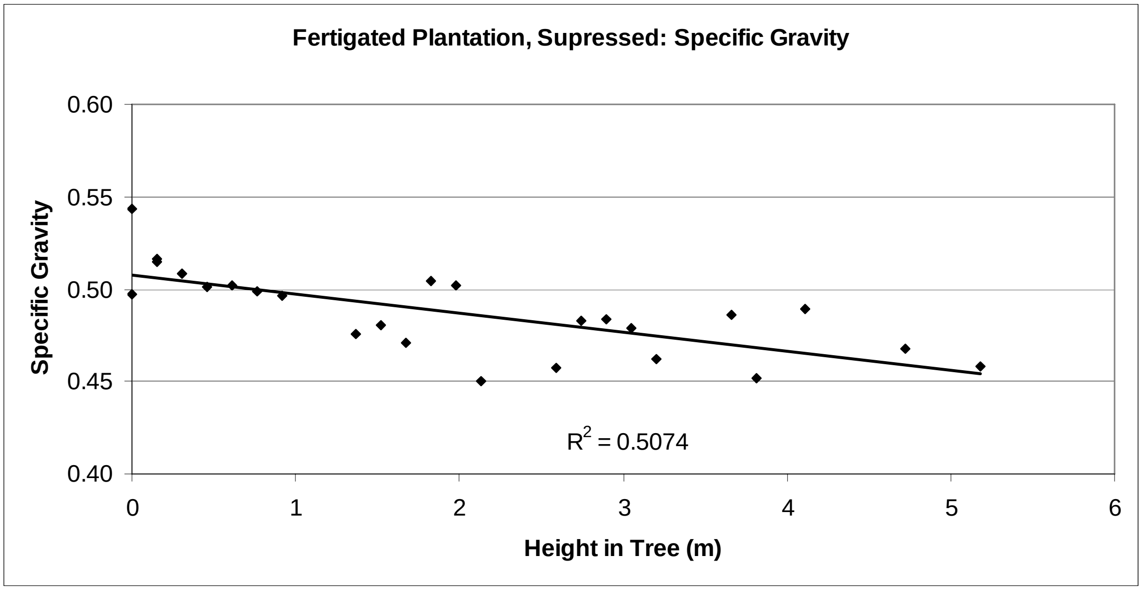

Figure 4.20. Oven-dry specific gravity of suppressed fertigated sweetgum at different heights in the tree (p<0.0001).

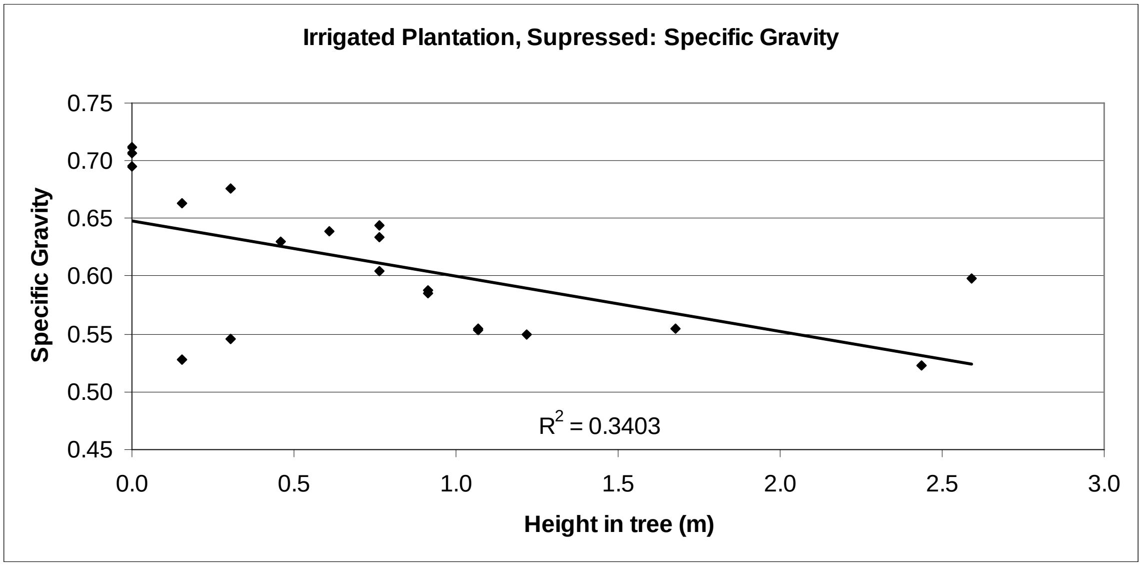

Figure 4.21. Oven-dry specific gravity of suppressed irrigated sweetgum at different heights in the tree (p=0.0068).

4.5 Failure Modes

When stressed in compression parallel to grain wood normally exhibits four failure patterns; brooming, shearing, crushing, and splitting. Wood is also known to fail by buckling, especially when the sample has a high aspect ratio. Figures 4.22 -4.26 demonstrate the differences between the different failure types. Figure 4.22 shows the S shaped displacement that buckling samples retain even after the load has been removed, this displacement was observed to occur in the buckling region of strain. Figures 4.23 – 4.26 show the physical effects of brooming, shearing, crushing, and splitting failures.

Buckling Failure

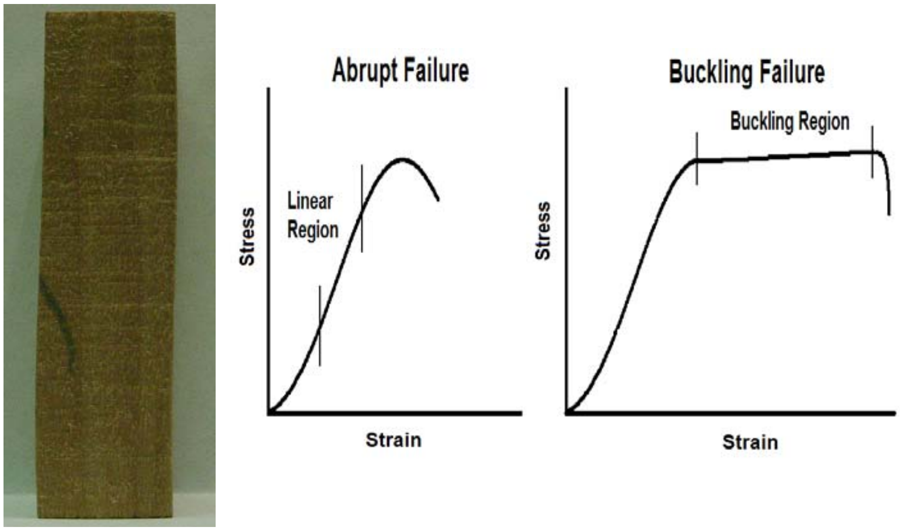

Figure 4.22. Example of a Buckling Failure.

Brooming Failure

Figure 4.23. Example of a Brooming Failure.

Shearing Failure

Figure 4.24. Example of a Shearing Failure.

Crushing Failure

Figure 4.25. Example of a Crushing Failure.

Figure 4.26. Example of a Splitting Failure.

Figures 4.27 – 4.32 demonstrate the proportions of different failure modes within the samples grouped by treatment, canopy class, and stem position. Buckling was the most common failure in all samples. Different crown classes experienced different proportions of failure types. Dominant and codominant trees experienced shearing and brooming failures while suppressed trees experienced more crushing failures. Fertigated samples experienced more brooming failures than irrigated samples. Table 4.2 lists the average sample values for the different failure modes. The average height of a buckling failures was lower than any other failure type.

Table 4.2. Average values of samples with different failure types.

Failure Mode	Average Height (m)	Average MCS (kPa)	Average MOE (kPa)	Average SpGr
Buckle	1.78	34,140	18,080,423	0.57
Broom	4.14	36,438	20,238,624	0.52
Shear	3.02	36,072	19,961,767	0.57
Crush	3.78	33,920	20,053,121	0.57
Split	3.54	35,706	20,657,024	0.55

Previous researchers have found that an aspect ration of four-to-one should prevent buckling of wood samples in compression parallel to grain (Bodig and Jayne 1993, Niklas 1994). Previous research has shown that sweetgum fibers are shorter at greater heights in the tree (Hunter and Goggans 1969, Webb 1964). Longer fibers might buckle more than shorter fibers because of a greater aspect ratio. The greater proportion of buckling in lower samples is likely due to higher aspect ratios of fibers in the lower stem. The lack of shear failures and excess of crushing failures for the suppressed samples is not easily explained.

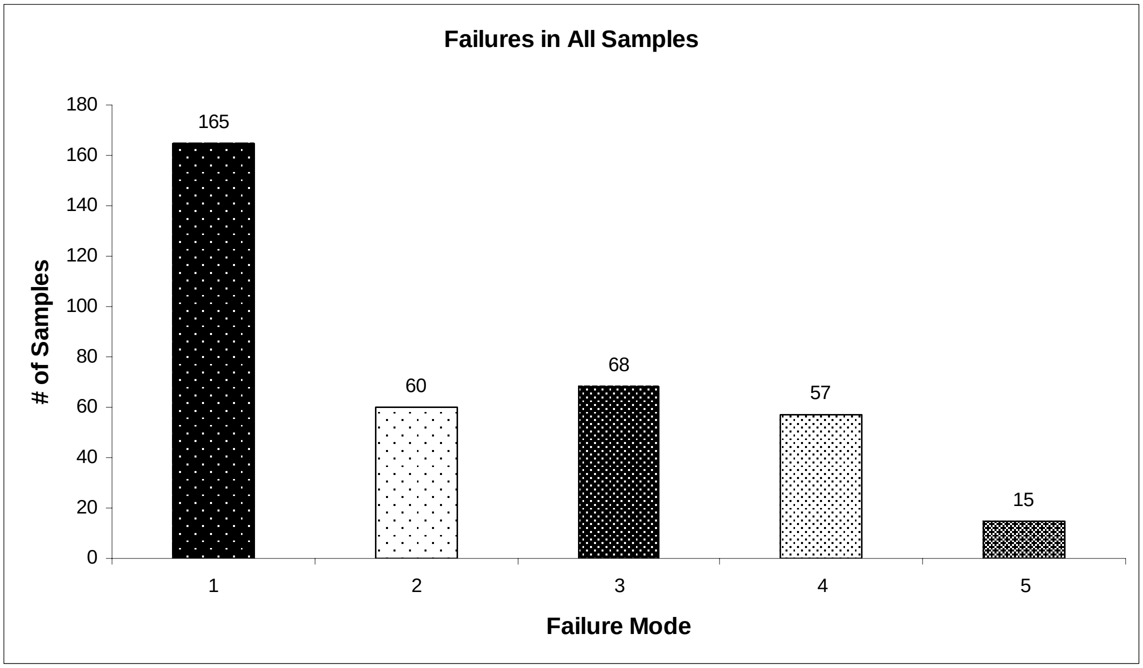

Figure 4.27. Failure Types for All Samples.
1= Buckle, 2= Broom, 3= Shear, 4= Crush, 5= Split.

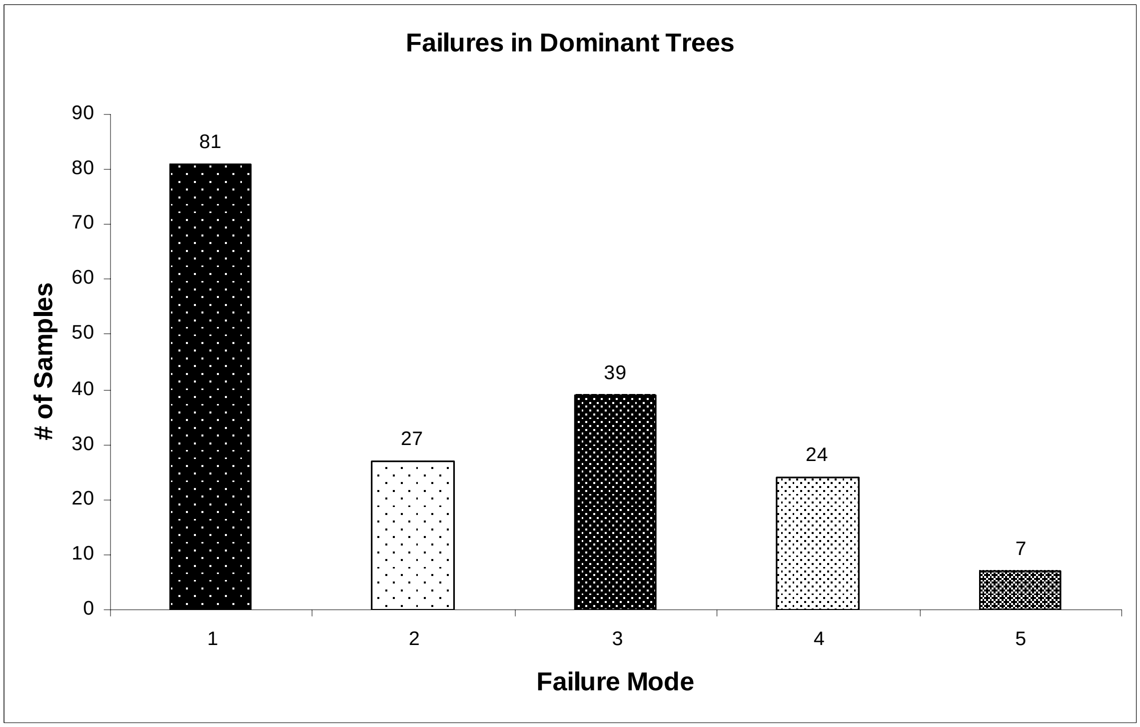

Figure 4.28. Failure types for dominant samples.
1= Buckle, 2= Broom, 3= Shear, 4= Crush, 5= Split.

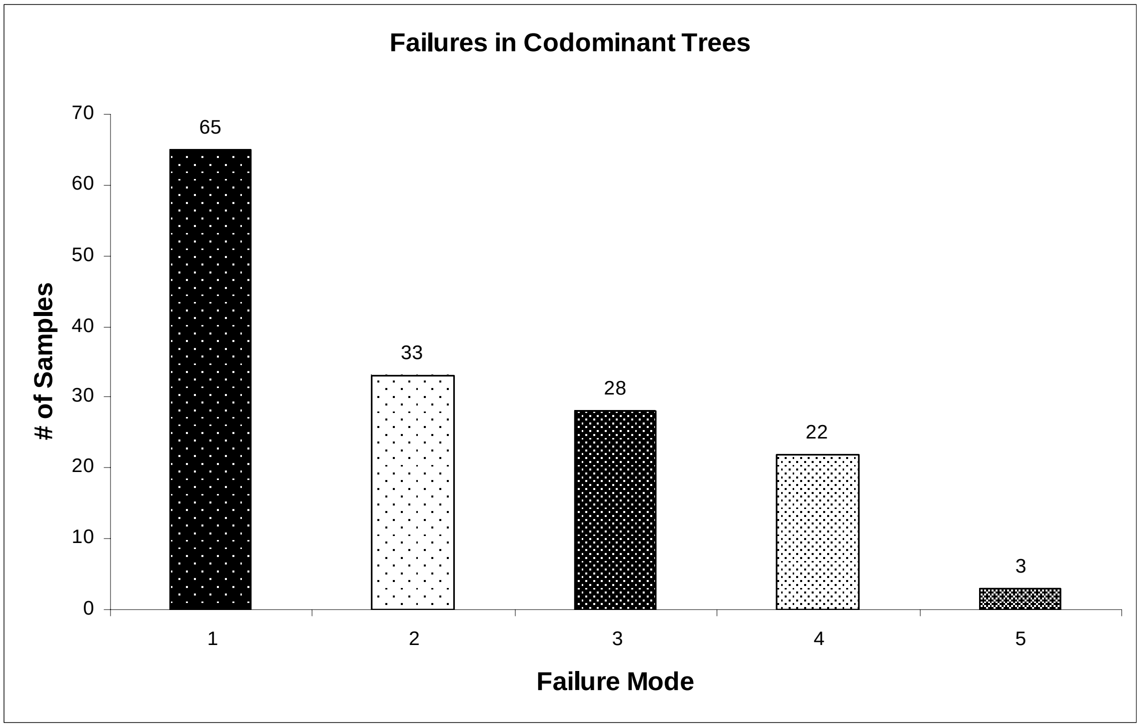

Figure 4.29. Failure types for codominant samples.
1= Buckle, 2= Broom, 3= Shear, 4= Crush, 5= Split.

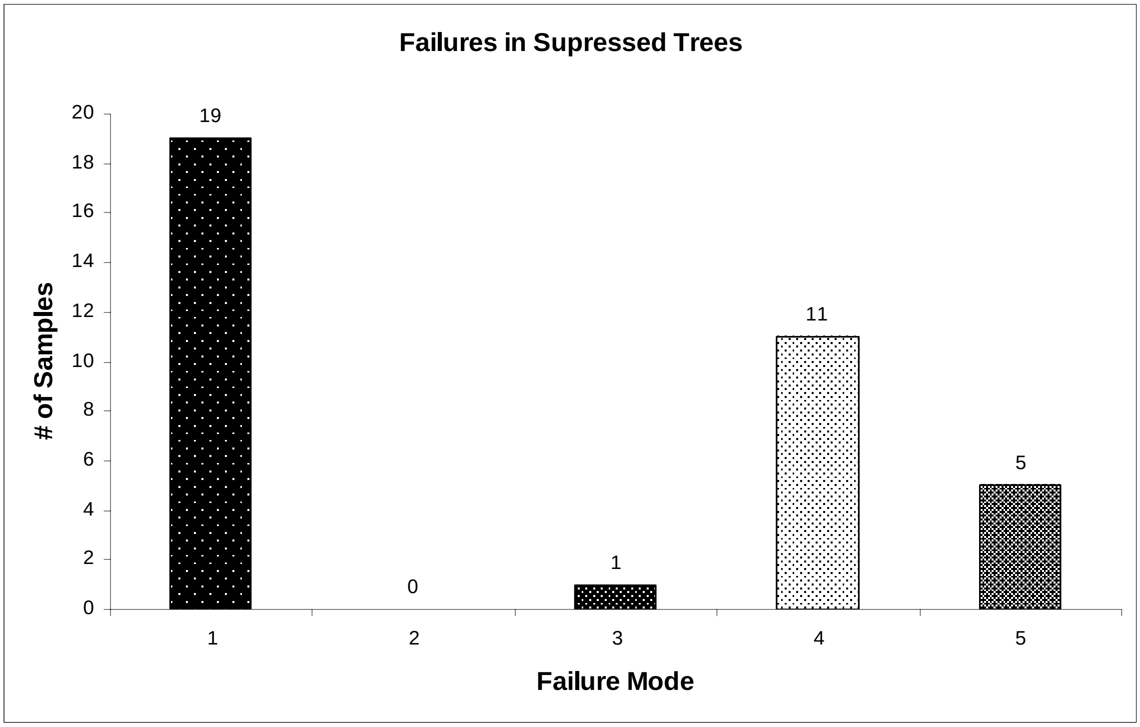

Figure 4.30. Failure types for suppressed samples.
1= Buckle, 2= Broom, 3= Shear, 4= Crush, 5= Split.

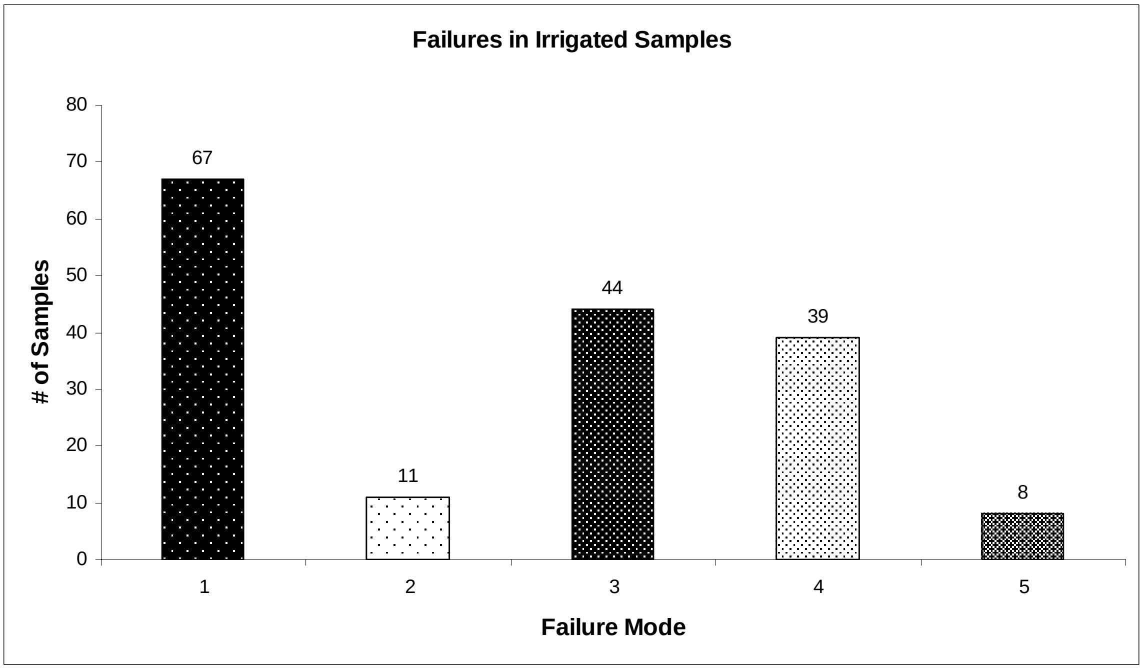

Figure 4.31. Failure types for irrigated samples.
1= Buckle, 2= Broom, 3= Shear, 4= Crush, 5= Split.

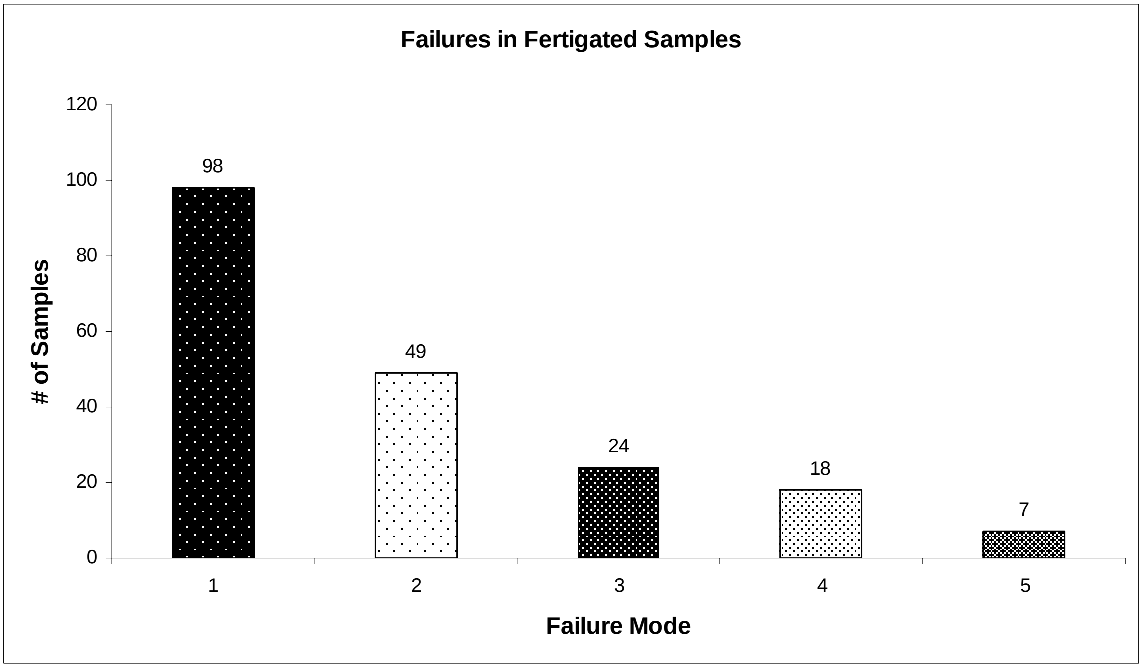

Figure 4.32. Failure types for fertigated samples.
1= Buckle, 2= Broom, 3= Shear, 4= Crush, 5= Split.

4.6 Specific gravity and mechanical properties

The specific gravity of wood from the Summerville, SC plantation (0.61) is twenty percent higher than in the Pensacola, FL plantation (0.51) and also higher than that of previous studies (0.40-0.57) (Forest Products Laboratory 1964, Carpenter and Hopkins 1966, Winstead 1972). Specific gravity of sweetgum increases with increasing latitude, longer photoperiods, and colder temperatures. (Randal and Winstead 1976). Bamberg is near the middle of the contiguous range of sweetgum. Winter temperatures and summer rainfall for the fertigated plantation were 6.6° C and 5.33 cm higher than the irrigated plantation.

Wood density or specific gravity is easily measured and can be related to mechanical properties. In softwoods, higher specific gravity is correlated with higher strength and stiffness. Only weak correlations have been found between specific gravity and mechanical properties in the diffuse porous genera such as maple (*Acer*) and eucalyptus (Walton and Armstrong 1986). Research of young red alder showed no relationship with specific gravity or bending strength (Hua et al. 1997).

Zhang found that growth rate had an additional influence on mechanical properties beyond that of specific gravity in diffuse porous species (Zhang 1997). Specific gravity showed no relationship with strength or stiffness in compression parallel to grain as seen in figures 4.33 and 4.34. Low correlations between strength and stiffness were found in sweetgum wood tested in compression parallel to grain (Faust et al. 1990).

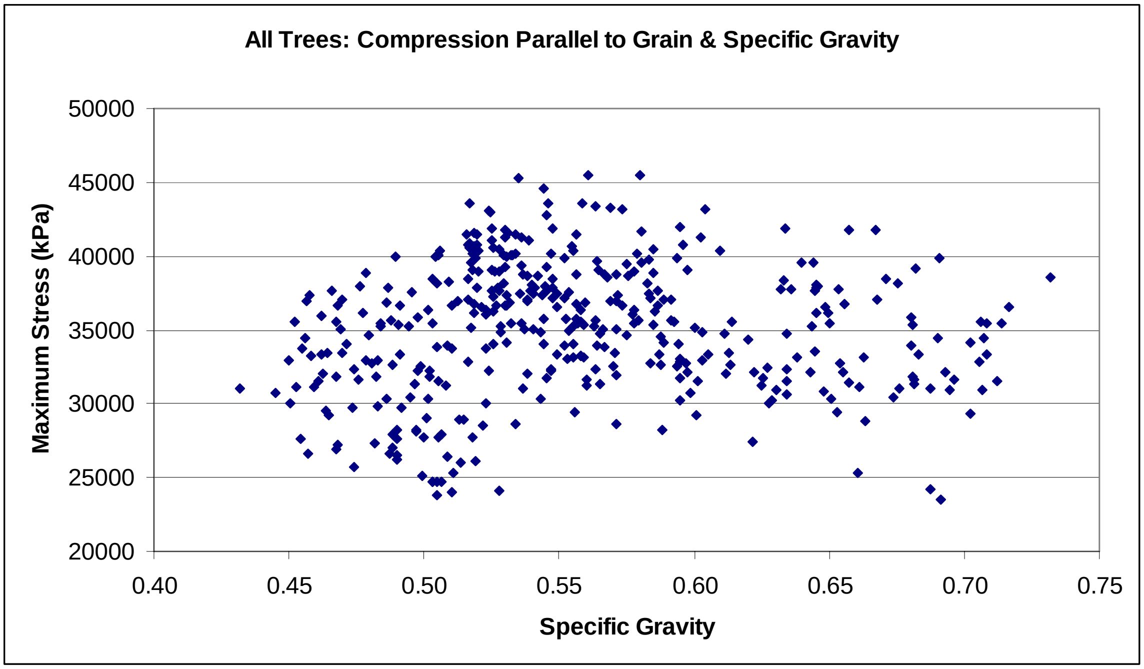

Figure 4.33. Compression Strength Parallel to Grain and Specific Gravity.

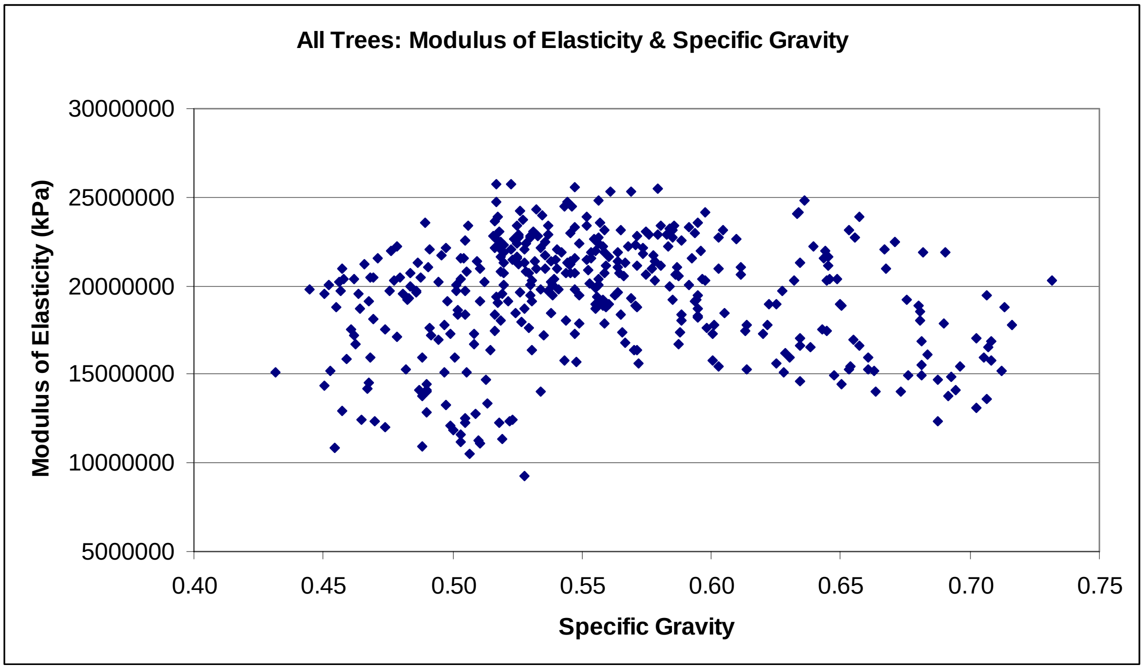

Figure 4.34. Modulus of Elasticity and Specific Gravity.

4.7 Sample size

Sample size also has an effect on the mechanical performance of wood. Samples from within individual tree rings of three diffuse porous species (red maple or *Acer rubrum*, yellow-poplar, and sweetgum) showed no correlation between growth rate and specific gravity or compression strength parallel to grain (Zink-Sharp and Price 2006). Major differences were found between fast and slow grown silver birch but very little difference was found when comparing small pieces containing only clear wood (Dunham 1999). Small pieces of wood from pine, beech, and oak were compressed radially and tangentially and showed that density had more of an effect on mechanical properties than specific anatomy (Walther 1993). The samples used in this study were likely small enough to make the amount of growth rings per inch irrelevant.

The high proportion of buckling failures may be in part explained by sample size. Nine inch long compression samples of sweetgum were not observed buckle when tested in compression parallel to grain (Faust et al. 1990). Smaller spruce samples were found to buckle when tested in compression parallel to grain (Reiterer and Stanzl-Tschegg 2001). Japanese beech, *Fagus crenata*, buckled when loads were applied eccentrically (Yoshihara and Yamamoto 2004). 1x1x4mm specimens of white oak, *Quercus alba*, tested for compression strength parallel to grain had two distinct failure modes: the early wood failed by buckling and the latewood failed by crushing (Zink-Sharp et al. 1999). 1x1x4mm samples of sugar maple failed consistently by crushing and is attributed to its diffuse porous anatomy (Zink-Sharp et al. 1999).

Chapter 5. Conclusions

Each nine-year-old sweetgum observed in this study was significantly weaker in compression parallel to grain than previous data from mature trees. No significant effect of growth rate on wood quality was detected, however a few interesting trends emerged. Correlations of wood properties with stem location were significant.

Trees that grew in dominant canopy positions were stronger and stiffer in compression parallel to grain. Dominant trees were denser than other trees. Codominant trees had the lowest proportion of live crown and also the lowest compression strength values.

The irrigated plantation growing near Summerville, SC grew denser wood than the fertigated plantation growing near Pensacola, FL. The denser wood was likely a result of lower temperatures and more pronounced photoperiod.

Wood failure modes were different between the two plantations, fertigated trees had more brooming failures than the irrigated samples. Wood from trees that are suppressed beneath the canopy failed more by crushing and wood from dominant trees failed more by shearing. Buckling failures were more common in wood from the bottom of the tree.

The most remarkable trends were related to stem location. Three of six trees showed a significant correlation of greater strength with increasing height in the tree. When every sample is considered, compression strength and stiffness were significantly higher in samples taken above the crown than samples taken beneath the crown. Stiffness and density were significantly more uniform in samples taken above the live crown.

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Appendix 1. Metadata for samples tested in compression parallel to grain.

Treatment	Crown	Bole	Postion (m)	Stress (kPa)	MOE (kPa)	SpGr	ARO (cm)	Failure
0	1	1	0.00	30771	17642774	0.60	10.2	0
0	1	1	0.00	34322	17307371	0.62	10.2	1
0	1	1	0.00	35418	16903304	0.71	12.7	1
0	1	1	0.00	33309	16109063	0.68	12.7	1
0	1	1	0.00	31619	15418746	0.70	10.2	3
0	1	1	0.00	31406	16625059	0.66	12.7	3
0	1	1	0.15	32136	18986300	0.62	8.5	0
0	1	1	0.15	34150	17019357	0.70	12.7	1
0	1	1	0.15	34426	16518053	0.71	10.2	1
0	1	1	0.15	35598	19483529	0.71	12.7	1
0	1	1	0.15	32467	19752507	0.63	8.5	1
0	1	1	0.15	41975	23573375	0.59	10.2	3
0	1	1	0.15	33984	18556915	0.68	8.5	3
0	1	1	0.15	33350	15774336	0.71	12.7	3
0	1	1	0.15	31792	16906048	0.68	12.7	3
0	1	1	0.15	32812	15931509	0.71	12.7	3
0	1	1	0.30	36528	17769320	0.72	10.2	0
0	1	1	0.30	40410	22678387	0.61	8.5	1
0	1	1	0.30	34756	20608871	0.61	8.5	1
0	1	1	0.30	35363	18066719	0.68	12.7	1
0	1	1	0.30	38424	22457610	0.67	10.2	3
0	1	1	0.30	35474	18773383	0.71	12.7	4
0	1	1	0.46	39528	21959692	0.64	10.2	1
0	1	1	0.46	35894	18883072	0.68	8.5	1
0	1	1	0.61	41858	24167703	0.63	12.7	1
0	1	1	0.61	36149	21657281	0.64	7.3	1
0	1	1	0.61	35232	21537994	0.64	10.2	1
0	1	1	0.61	41810	23855695	0.66	10.2	3
0	1	1	0.61	39521	22196154	0.64	8.5	3
0	1	1	0.76	41755	22016084	0.67	6.4	2
0	1	1	0.76	36777	22747728	0.66	6.4	2
0	1	1	0.76	39210	21888014	0.68	12.7	3
0	1	1	0.76	34412	17840750	0.69	12.7	4
0	1	1	0.91	37728	23169397	0.65	8.5	1
0	1	1	0.91	37887		0.65	7.3	4
0	1	1	1.07	38397	24092833	0.63	12.7	1
0	1	1	1.07	37611	20306267	0.64	10.2	3
0	1	1	1.22	38549	20292360	0.73	6.4	1
0	1	1	1.37	36542	20380413	0.65	7.3	1
0	1	1	1.37	38149	19255382	0.68	10.2	1
0	1	1	1.37	39838	21917034	0.69	10.2	1
0	1	1	1.37	37963	20378524	0.65	10.2	3

0	1	1	1.52	36170	18951626	0.65	8.5	1
0	1	1	1.68	37032	20944142	0.67	7.3	1
0	1	1	1.98	41272	22712130	0.60	8.5	5
0	1	1	2.13	40734	21973529	0.60	7.3	3
0	1	1	2.29	36666	21075963	0.59	7.3	1
0	1	1	2.29	34867	20955084	0.60	12.7	4
0	1	1	2.44	39659	21024528	0.56	8.5	0
0	1	1	2.44	38948	21365708	0.58	10.2	3
0	1	1	2.44	39024	23136647	0.56	10.2	3
0	1	1	2.44	36852	21103115	0.56	8.5	3
0	1	1	2.44	32136	20306805	0.60	8.5	4
0	1	1	2.59	35501	21875320	0.56	8.5	1
0	1	1	2.59	40714	22617072	0.55	10.2	3
0	1	1	2.59	35294	19489631	0.56	8.5	3
0	1	0	3.20	34715	21342907	0.63	8.5	5
0	1	0	3.35	39865	23013011	0.59	8.5	3
0	1	0	3.51	38728	21328359	0.57	8.5	3
0	1	0	3.51	37142	23260139	0.58	8.5	4
0	1	0	3.51	38624	22874605	0.58	8.5	5
0	1	0	3.66	38817	22690329	0.59	8.5	1
0	1	0	3.66	31709	18976964	0.63	6.4	4
0	1	0	3.81	36666	22151676	0.57	8.5	2
0	1	0	3.81	37714	24826614	0.64	8.5	5
0	1	0	3.96	38038	21141904	0.64	5.1	1
0	1	0	3.96	36260	23425165	0.59	8.5	5
0	1	0	4.11	43196	23175382	0.60	8.5	0
0	1	0	4.27	39748	22884030	0.58	10.2	3
0	1	0	4.57	40479	23114329	0.59	10.2	0
0	1	0	4.72	36721	20410805	0.56	8.5	2
0	1	0	4.88	34639	20629362	0.57	8.5	2
0	1	0	4.88	39541	23414499	0.58	12.7	3
0	1	0	5.33	38555	22244190	0.57	12.7	3
0	1	0	5.94	37542	21595779	0.55	8.5	3
0	1	0	5.94	32502	19155552	0.59	8.5	4
0	1	0	6.25	39472	23067500	0.57	7.3	0
0	1	0	6.86	45512	20170564	0.58	8.5	4
0	1	0	7.01	40141	25461808	0.58	10.2	0
0	1	0	7.16	35577	21515662	0.59	7.3	3
0	1	0	7.16	27469	17758688	0.62	12.7	4
0	1	0	7.32	37032	23306796	0.59	8.5	3
0	1	0	7.47	31999	21039379	0.61	12.7	4
0	1	0	7.77	34846	24496838	0.54	8.5	4
0	1	0	7.92	35405	23522230	0.56	7.3	4
0	1	0	8.08	38790	24828510	0.56	6.4	3
0	1	0	8.08	36556	22428618	0.55	7.3	3
0	1	0	8.23	34005	21966786	0.56	5.6	4
0	1	0	8.38	32723	19996251	0.58	8.5	4
0	1	0	8.38	37190	23400234	0.55	6.4	4
0	1	0	8.53	34956	21876106	0.55	8.5	0
0	1	0	8.84	33253	22256587	0.56	7.3	2

0	1	0	8.99	35460	22391690	0.56	10.2	1
0	2	1	0.00	31309	15526138	0.68	10.2	1
0	2	1	0.00	30075	15102773	0.63	12.7	1
0	2	1	0.00	29282	13117483	0.70	8.5	1
0	2	1	0.00	29434	15249790	0.65	8.5	1
0	2	1	0.15	31578	16587648	0.63	8.5	1
0	2	1	0.15	28868	13999384	0.66	10.2	1
0	2	1	0.15	30454	14067718	0.67	10.2	1
0	2	1	0.15	31006	14722203	0.69	8.5	1
0	2	1	0.15	30192	16232224	0.63	8.5	1
0	2	1	0.30	30806	14923357	0.65	10.2	1
0	2	1	0.30	31116	15966817	0.66	7.3	1
0	2	1	0.30	30316	14419806	0.65	12.7	1
0	2	1	0.30	30682	14656716	0.63	8.5	1
0	2	1	0.30	32178	14879927	0.69	10.2	3
0	2	1	0.30	24194	12358432	0.69	8.5	4
0	2	1	0.61	32185	16926946	0.66	12.7	1
0	2	1	0.61	32109	17525135	0.64	10.2	1
0	2	1	0.61	31275	15620052	0.62	8.5	4
0	2	1	0.61	23539	13756378	0.69	8.5	4
0	2	1	0.76	35460	18843792	0.65	8.5	1
0	2	1	0.76	31675	14961106	0.68	10.2	1
0	2	1	0.91	33481	17483077	0.61	12.7	1
0	2	1	0.91	29268	17326670	0.60	8.5	4
0	2	1	1.07	33998	19172465	0.59	10.2	1
0	2	1	1.07	33033	18712902	0.59	12.7	1
0	2	1	1.07	31743	19443243	0.59	10.2	1
0	2	1	1.22	34122	18366103	0.59	12.7	1
0	2	1	1.22	32667	17768838	0.61	12.7	1
0	2	1	1.68	31357	18343178	0.56	12.7	0
0	2	1	1.83	32881	18237433	0.59	12.7	1
0	2	1	1.83	32729	20364617	0.60	12.7	1
0	2	1	1.83	31585	17756889	0.60	10.2	1
0	2	1	1.83	28200	18084728	0.59	7.3	4
0	2	1	1.83	30227	18334421	0.59	12.7	4
0	2	1	1.83	33302	20512910	0.59	10.2	4
0	2	1	1.98	35611	21421452	0.56	12.7	0
0	2	1	1.98	31226	18998897	0.56	8.5	0
0	2	1	1.98	31599	21630060	0.56	12.7	1
0	2	1	1.98	35605	20047396	0.59	12.7	3
0	2	1	1.98	35067	20563041	0.57	12.7	4
0	2	1	2.13	35025	21000155	0.54	7.3	1
0	2	1	2.13	35487	20327061	0.58	12.7	2
0	2	1	2.13	37204	23288766	0.55	10.2	3
0	2	1	2.29	33936	20733438	0.56	10.2	0
0	2	1	2.29	32274	20717622	0.55	8.5	4
0	2	1	2.59	36349	21713121	0.58	8.5	1
0	2	1	2.59	37418	22189315	0.58	10.2	3
0	2	1	2.59	37046	22579903	0.59	8.5	4
0	2	1	2.74	35418	20730880	0.56	8.5	3

0	2	1	3.05	36949	21137340	0.57	8.5	4
0	2	1	3.20	33957	21504376	0.55	12.7	2
0	2	1	3.35	37880	23722833	0.53	10.2	0
0	2	1	3.35	35122	23933605	0.52	8.5	2
0	2	1	3.51	37252	22730787	0.53	10.2	3
0	2	1	3.66	35715	21285633	0.54	10.2	1
0	2	1	3.81	35687	22927136	0.58	8.5	0
0	2	1	3.96	35487	20932490	0.54	6.4	2
0	2	1	4.11	37638	22357788	0.52	7.3	3
0	2	1	4.42	37039	22134405	0.52	8.5	0
0	2	1	4.57	32364	19613378	0.56	8.5	3
0	2	1	4.88	34129	20278591	0.53	4.6	3
0	2	1	5.03	32378	19776736	0.55	5.6	2
0	2	1	5.18	36687	20961813	0.51	8.5	3
0	2	1	5.18	35094	23368422	0.54	4.6	4
0	2	1	5.33	34812	20839211	0.53	8.5	3
0	2	1	5.64	36280	21237555	0.53	10.2	4
0	2	1	5.64	30992	19716117	0.54	8.5	4
0	2	1	5.69	25352	15283802	0.66	8.5	4
0	2	1	5.79	36108	21637989	0.52	8.5	3
0	2	0	6.10	33757	21460263	0.52	8.5	4
0	2	0	6.10	36721	22513341	0.52	7.3	4
0	2	0	6.25	34088	22826859	0.53	7.3	4
0	2	0	6.40	29420	19386644	0.56	6.4	4
0	2	0	6.55	39900	23860059	0.55	8.5	3
0	2	0	6.71	36694	22839987	0.53	8.5	3
0	3	1	0.00	30985	13573943	0.71	12.7	1
0	3	1	0.00	30971	14099896	0.69	12.7	1
0	3	1	0.00	31495	15202368	0.71	10.2	3
0	3	1	0.15	33178	15169224	0.66	12.7	1
0	3	1	0.15	35225	22354610	0.53	6.4	4
0	3	1	0.30	31033	14979150	0.68	7.3	1
0	3	1	0.30	31778	21352002	0.55	8.5	4
0	3	1	0.46	30930	15963149	0.63	8.5	1
0	3	1	0.61	33136	16569874	0.64	12.7	1
0	3	1	0.76	33350	18477157	0.60	12.7	0
0	3	1	0.76	33515	17478665	0.64	8.5	4
0	3	1	0.76	32316	17014034	0.63	10.2	5
0	3	1	0.91	35308	19204526	0.58	12.7	0
0	3	1	0.91	32633	17392949	0.59	8.5	1
0	3	1	1.07	33164	18752650	0.56	10.2	1
0	3	1	1.07	33074	20097852	0.55	8.5	5
0	3	1	1.22	33322	19424986	0.55	10.2	1
0	3	1	1.68	35239	19891009	0.56	8.5	5
0	3	0	2.44	36025	25728793	0.52	10.2	0
0	3	0	2.59	39093	24141779	0.60	10.2	4
1	1	1	0.00	32929	15439513	0.60	8.5	1
1	1	1	0.00	34543	16678142	0.59	6.4	1
1	1	1	0.00	33260	18850418	0.56	25.4	1
1	1	1	0.00	33178	17901582	0.56	12.7	1

1	1	1	0.15	35163	15781589	0.60	8.5	1
1	1	1	0.15	33853	16783873	0.57	10.2	1
1	1	1	0.30	32764	15428412	0.65	12.7	1
1	1	1	0.46	35529	15285305	0.61	10.2	1
1	1	1	0.46	38183		0.58	12.7	3
1	1	1	0.61	32502	16380744	0.57	8.5	1
1	1	1	0.61	36977	19272977	0.57	8.5	1
1	1	1	0.76	35005	18817964	0.57	12.7	1
1	1	1	0.76	38045	21469261	0.54	10.2	1
1	1	1	0.91	35336	18828182	0.56	12.7	1
1	1	1	0.91	36901	21375802	0.53	8.5	2
1	1	1	0.91	36942	20178934	0.54	12.7	3
1	1	1	1.07	36322	19105883	0.56	7.3	1
1	1	1	1.22	38749	22850467	0.57	8.5	1
1	1	1	1.22	38783	22875109	0.54	12.7	1
1	1	1	1.22	37032	20069466	0.54	8.5	1
1	1	1	1.22	37859	15680788	0.55	8.5	1
1	1	1	1.37	37673	20355730	0.54	8.5	1
1	1	1	1.37	37652	18745149	0.53	8.5	1
1	1	1	1.52	37342	16400580	0.53	8.5	1
1	1	1	1.52	37859	19797578	0.54	8.5	1
1	1	1	1.68	37411	17899031	0.55	7.3	0
1	1	1	1.68	34005	18003363	0.54	8.5	1
1	1	1	1.83	39293	21182687	0.55	8.5	0
1	1	1	1.83	37390	15586537	0.57	8.5	1
1	1	1	1.83	35722	20875739	0.55	12.7	1
1	1	1	1.98	36983	20243587	0.51	12.7	0
1	1	1	1.98	36515	19150381	0.52	10.2	4
1	1	1	2.13	38928	19617874	0.53	8.5	1
1	1	1	2.13	39383	21686390	0.54	8.5	2
1	1	1	2.29	41279	22696534	0.53	8.5	2
1	1	1	2.29	37638	20716601	0.55	10.2	4
1	1	1	2.44	37466	17199103	0.54	8.5	1
1	1	1	2.59	40369	18971986	0.56	8.5	1
1	1	1	2.59	37935	21257771	0.54	7.3	2
1	1	1	2.74	41506	20061303	0.56	10.2	1
1	1	1	2.74	40141	22025978	0.52	8.5	3
1	1	1	2.90	40003	19108944	0.53	8.5	3
1	1	1	2.90	41451	22848198	0.52	12.7	3
1	1	1	3.05	40596	19344765	0.52	10.2	2
1	1	1	3.05	40396	23367105	0.51	12.7	3
1	1	1	3.20	43547	25769990	0.52	12.7	0
1	1	1	3.20	41617	18044180	0.52	8.5	2
1	1	1	3.35	36653	17999122	0.53	8.5	2
1	1	1	3.51	39914	19547064	0.52	6.4	1
1	1	1	3.51	36680	19505330	0.53	8.5	1
1	1	1	3.51	40196	23064494	0.52	10.2	4
1	1	1	3.66	38452	20365824	0.50	10.2	1
1	1	1	3.81	41686	21117297	0.58	10.2	1
1	1	1	3.81	39038	21605763	0.52	8.5	4

1	1	1	3.96	38287	21409076	0.51	8.5	1
1	1	1	3.96	40121	17255006	0.55	6.4	1
1	1	1	4.11	39990	21513766	0.50	12.7	4
1	1	1	4.27	39259	20088951	0.53	8.5	2
1	1	1	4.42	43085	22670672	0.52	10.2	2
1	1	1	4.42	39603	19011018	0.52	8.5	3
1	1	1	4.57	40658	20836818	0.52	10.2	1
1	1	1	4.88	41810	20074762	0.53	8.5	2
1	1	1	4.88	41286	22496014	0.54	8.5	2
1	1	1	4.88	40017	20828662	0.51	10.2	3
1	1	1	5.03	41072	19424172	0.54	12.7	0
1	1	1	5.03	41500	22277588	0.52	12.7	1
1	1	1	5.03	40141	19773385	0.53	10.2	2
1	1	1	5.03	38121	20682748	0.53	8.5	2
1	1	1	5.18	40024	17616022	0.53	12.7	1
1	1	1	5.18	40727	20028270	0.52	12.7	1
1	1	1	5.33	40355	20703377	0.52	10.2	0
1	1	1	5.49	41493	22168341	0.53	12.7	0
1	1	1	5.49	33977	16677446	0.51	12.7	3
1	1	1	5.64	31874	19246922	0.48	6.4	1
1	1	1	5.64	38624	21374465	0.54	10.2	1
1	1	1	5.64	40424	22095484	0.53	12.7	2
1	1	1	5.64	38666	21867309	0.54	12.7	4
1	1	1	5.79	43616	24490316	0.55	12.7	1
1	1	1	5.79	45485	25327036	0.56	6.4	2
1	1	0	5.94	43209	21804049	0.57	10.2	0
1	1	0	5.94	43389	21850823	0.56	12.7	1
1	1	0	5.94	43278	25318321	0.57	12.7	1
1	1	0	6.10	37625	20608712	0.59	12.7	0
1	1	0	6.10	43547	23169797	0.56	8.5	1
1	1	0	6.25	36101	20996866	0.58	10.2	1
1	1	0	6.40	41575	23098706	0.53	16.9	1
1	1	0	6.40	37873	21923549	0.52	10.2	1
1	1	0	6.40	44595	24708611	0.54	10.2	2
1	1	0	6.55	38935	21300201	0.52	12.7	0
1	1	0	6.55	41899	22859478	0.53	12.7	2
1	1	0	6.55	42796	22968891	0.55	12.7	4
1	1	0	6.71	40114	22784691	0.53	12.7	1
1	1	0	6.71	41906	25603819	0.55	8.5	2
1	1	0	6.86	40589	24244187	0.53	12.7	0
1	1	0	7.01	41051	21568318	0.52	8.5	0
1	1	0	7.01	40562	22649381	0.52	10.2	1
1	1	0	7.32	40817	23685773	0.52	12.7	2
1	1	0	7.32	42975	23420711	0.52	8.5	3
1	1	0	7.32	40831	24761893	0.52	12.7	5
1	1	0	7.47	35439	20976479	0.53	10.2	1
1	1	0	7.47	45292	23991039	0.53	10.2	1
1	1	0	7.47	38135	22546746	0.50	10.2	1
1	1	0	7.62	38487	21542014	0.55	12.7	2
1	1	0	8.08	36404	22056432	0.52	12.7	4

1	1	0	8.53	40045	24318691	0.53	16.9	2
1	1	0	8.99	39059	22276816	0.52	12.7	5
1	2	1	0.00	28972	14702456	0.51	5.6	1
1	2	1	0.00	28558	12349972	0.52	5.6	1
1	2	1	0.00	24159	9262148	0.53	12.7	1
1	2	1	0.00	28599	14004990	0.53	6.4	1
1	2	1	0.00	25145	12116185	0.50	12.7	1
1	2	1	0.00	26462	12760341	0.51	6.4	1
1	2	1	0.15	25304	11085549	0.51	12.7	0
1	2	1	0.15	24711	11630842	0.50	12.7	1
1	2	1	0.15	27910		0.51	6.4	1
1	2	1	0.30	26041	13330131	0.51	10.2	1
1	2	1	0.30	29716	17209783	0.49	8.5	1
1	2	1	0.30	23966	11278396	0.51	12.7	1
1	2	1	0.30	27696	12298944	0.52	8.5	1
1	2	1	0.30	26110	11382527	0.52	8.5	1
1	2	1	0.30	24752	11164115	0.50	10.2	3
1	2	1	0.46	24759	10506176	0.51	12.7	1
1	2	1	0.46	28124	13280192	0.50	12.7	3
1	2	1	0.61	25676		0.47	8.5	0
1	2	1	0.61	30296	19726369	0.49	6.4	1
1	2	1	0.61	24752	12299247	0.50	12.7	1
1	2	1	0.76	27600	14106749	0.49	8.5	1
1	2	1	0.76	26593	12972734	0.46	12.7	3
1	2	1	0.91	26621	14139803	0.49	12.7	3
1	2	1	1.07	27951	13789018	0.49	8.5	1
1	2	1	1.07	27062	10975833	0.49	12.7	1
1	2	1	1.07	29985	12436549	0.52	7.3	1
1	2	1	1.07	26517	14044448	0.49	12.7	4
1	2	1	1.07	23842	12527691	0.50	10.2	5
1	2	1	1.22	27372	15317372	0.48	10.2	0
1	2	1	1.22	33757	18759745	0.45	6.4	1
1	2	1	1.22	29834		0.48	8.5	1
1	2	1	1.22	33453	12325930	0.47	6.4	1
1	2	1	1.22	26931	14176338	0.47	16.9	2
1	2	1	1.22	27751	15118196	0.51	8.5	2
1	2	1	1.22	30482	16983787	0.49	6.4	2
1	2	1	1.37	26235	14441269	0.49	8.5	1
1	2	1	1.37	28275	12861577	0.49	8.5	3
1	2	1	1.52	27179	15956151	0.47	12.7	1
1	2	1	1.68	31833	14526378	0.47	5.1	2
1	2	1	1.68	29482	19532820	0.46	8.5	2
1	2	1	1.83	27669	10850018	0.45	6.4	1
1	2	1	1.83	32350	17551211	0.47	5.1	3
1	2	1	1.98	32895	17095571	0.48	6.4	1
1	2	1	1.98	27710	11861527	0.50	6.4	1
1	2	1	1.98	29254	12405564	0.46	8.5	1
1	2	1	2.13	29716	11981916	0.47	12.7	2
1	2	1	2.13	31171	15834651	0.46	6.4	2
1	2	1	2.13	30006	14362938	0.45	7.3	3

1	2	1	2.29	31109	15163840	0.45	6.4	2
1	2	1	2.29	33371	17195821	0.46	6.4	3
1	2	1	2.44	31075	15155014	0.43	8.5	2
1	2	1	2.44	31564	17541269	0.46	6.4	2
1	2	1	2.59	32619	15921374	0.49	6.4	2
1	2	1	2.59	33495	18682696	0.46	8.5	2
1	2	1	2.74	32005	18422847	0.54	7.3	0
1	2	1	3.05	30695	19786623	0.44	8.5	0
1	2	1	3.35	35012	18124352	0.47	6.4	1
1	2	1	3.35	34474	20184347	0.46	8.5	1
1	2	1	3.51	36942	19749294	0.46	12.7	3
1	2	1	3.51	32088	16727184	0.46	6.4	5
1	2	1	3.66	31943	18865200	0.57	12.7	1
1	2	1	3.66	35536	19186793	0.56	6.4	3
1	2	1	3.81	33764	19162999	0.51	6.4	1
1	2	1	3.81	37769	20307163	0.63	8.5	2
1	2	1	3.96	38962	21341046	0.53	8.5	0
1	2	1	3.96	33467	22291288	0.57	10.2	1
1	2	1	3.96	33384	17640147	0.49	8.5	2
1	2	1	4.11	28613	16360769	0.57	12.7	3
1	2	1	4.27	34756	17334799	0.57	10.2	2
1	2	1	4.27	35784	22712068	0.56	8.5	2
1	2	1	4.27	38487	18418475	0.52	10.2	3
1	2	1	4.42	31557	18398136	0.51	12.7	2
1	2	1	4.57	35398	21022529	0.49	8.5	2
1	2	1	4.72	36328	19722329	0.50	12.7	0
1	2	1	4.72	32267	18426487	0.52	10.2	4
1	2	1	4.88	35825	22147746	0.50	12.7	2
1	2	1	4.88	37411	22064988	0.54	12.7	3
1	2	1	5.03	35494	21513649	0.50	8.5	2
1	2	1	5.03	37328	20709927	0.54	10.2	2
1	2	1	5.18	32219	19091004	0.50	12.7	3
1	2	1	5.33	37825	21296257	0.49	12.7	5
1	2	1	5.49	37542	21700028	0.50	7.3	2
1	2	1	5.64	35632	20439515	0.49	8.5	1
1	2	1	5.64	37673	21240596	0.47	10.2	2
1	2	1	5.64	35591	19144962	0.47	10.2	2
1	2	1	5.79	34667	20504788	0.48	8.5	0
1	2	1	5.94	35267	19981200	0.48	8.5	0
1	2	1	6.10	35280	20256121	0.49	16.9	2
1	2	1	6.40	36163	20327158	0.48	12.7	0
1	2	1	6.40	37101	20502967	0.47	10.2	2
1	2	1	6.71	37963	21983430	0.48	10.2	2
1	2	1	6.86	36659	22066409	0.49	12.7	2
1	2	1	7.01	30330	20079091	0.50	8.5	4
1	3	1	0.00	30323	15808624	0.54	5.1	4
1	3	1	0.00	28213	15125257	0.50	8.5	4
1	3	1	0.15	32854	17445735	0.52	8.5	1
1	3	1	0.15	28972	16347470	0.51	10.2	4
1	3	1	0.30	31261	17269595	0.51	10.2	1

1	3	1	0.46	28999	15958026	0.50	10.2	1
1	3	1	0.61	31826	18406899	0.50	7.3	0
1	3	1	0.76	32495	17292348	0.50	12.7	1
1	3	1	0.91	31323	17791921	0.50	6.4	1
1	3	1	1.37	31688	19716296	0.48	6.4	0
1	3	1	1.52	32791	19588557	0.48	8.5	0
1	3	1	1.68	34026	21576660	0.47	8.5	1
1	3	0	1.83	33798	19687035	0.50	6.4	0
1	3	0	1.98	32288	18624043	0.50	10.2	1
1	3	0	2.13	32978	19536943	0.45	8.5	0
1	3	0	2.59	37314	21005347	0.46	7.3	1
1	3	0	2.74	32902	19307092	0.48	5.1	0
1	3	0	2.90	35418	20712768	0.48	4.6	1
1	3	0	3.05	38845	22216459	0.48	5.6	4
1	3	0	3.20	35915	20416748	0.46	6.4	5
1	3	0	3.66	36818	19664455	0.49	7.3	5
1	3	0	3.81	35542	20042136	0.45	4.2	4
1	3	0	4.11	39955	23529483	0.49	4.2	4
1	3	0	4.72	36653	20490715	0.47	6.4	1
1	3	0	5.18	33281	20408026	0.46	6.4	4

Treatment 0 = irrigated, 1 = fertigated
Crown 1 = dominant, 2 = codominant, 3 = suppressed
Bole 0 = shaded stem, 1 = live crown
Failure 0 = not recorded, 1 = buckle, 2 = broom, 3 = shear, 4 = crush, 5 = split

Appendix 2. SAS Code and Output

```
data average;
infile 'z:\sas\average.txt' dlm = '09'x missover;
input treat crown stress moe spgr arw;
run;
proc ttest data = average alpha = .05 h0 = 43575;
var stress;
run;
proc ttest data = average alpha = .05 h0= .53;
var spgr;
run;
proc ttest data = average;
class treat;
var stress moe spgr arw;
run;
proc reg data = average;
model stress moe spgr= treat crown arw;
run;
data IS;
infile 'z:\sas\IS.txt' dlm = '09'x missover;
input treat crown bole height stress moe spgr;
run;
proc corr data = IS;
var height stress moe spgr;
run;
data IC;
infile 'z:\sas\IC.txt' dlm = '09'x missover;
input treat crown bole height stress moe spgr;
run;
proc corr data = IC;
var height stress moe spgr;
run;
data ID;
infile 'z:\sas\ID.txt' dlm = '09'x missover;
input treat crown bole height stress moe spgr;
run;
proc corr data = ID;
var height stress moe spgr;
run;
data FS;
infile 'z:\sas\FS.txt' dlm = '09'x missover;
input treat crown bole height stress moe spgr;
run;
proc corr data = FS;
var height stress moe spgr;
run;
data FC;
infile 'z:\sas\FC.txt' dlm = '09'x missover;
input treat crown bole height stress moe spgr;
run;
```

```
proc corr data = FC;
var height stress moe spgr;
run;
data FD;
infile 'z:\sas\FD.txt' dlm = '09'x missover;
input treat crown bole height stress moe spgr;
run;
proc corr data = FD;
var height stress moe spgr;
run;
data alldata;
infile 'z:\sas\alldata.txt' dlm = '09'x missover;
input treat crown bole height stress moe spgr;
run;
proc ttest data = alldata;
class bole;
var stress moe spgr;
run;
```

All Trees (n=6)

```
                            The TTEST Procedure

                                Statistics

                   Lower CL           Upper CL  Lower CL            Upper
CL
  Variable      N      Mean     Mean      Mean   Std Dev   Std Dev   Std
Dev   Std Err

  stress        6     31532    34386     37241    1697.9    2720.1
6671.4   1110.5

                                 T-Tests

                  Variable     DF    t Value    Pr > |t|

                  stress        5      -8.27      0.0004


                            The TTEST Procedure

                                Statistics

                   Lower CL           Upper CL  Lower CL            Upper
CL
  Variable      N      Mean     Mean      Mean   Std Dev   Std Dev   Std
Dev   Std Err

  spgr          6    0.4992   0.5583    0.6175    0.0352    0.0564
0.1382    0.023

                                 T-Tests

                  Variable     DF    t Value    Pr > |t|
```

```
                    spgr           5       1.23      0.2729

                              The TTEST Procedure

                                  Statistics

                               Lower CL          Upper CL  Lower CL
Upper CL
Variable  treat             N      Mean    Mean      Mean   Std Dev  Std Dev
Std Dev  Std Err

stress               0      3     29354   34361     39368    1049.4   2015.5
12667   1163.7
stress               1      3     24974   34411     43849      1978   3799.1
23876   2193.4
stress    Diff (1-2)              -6944  -50.33    6843.5      1822     3041
8738.5     2483
moe                  0      3    1.61E7  1.95E7    2.29E7    706428   1.36E6
8.53E6   783348
moe                  1      3    1.37E7  1.88E7    2.39E7    1.06E6   2.04E6
1.28E7   1.18E6
moe       Diff (1-2)             -325E4  675914     4.6E6    1.04E6   1.73E6
4.98E6   1.41E6
spgr                 0      3    0.5687  0.6067    0.6446     0.008   0.0153
0.096   0.0088
spgr                 1      3    0.4443    0.51    0.5757    0.0138   0.0265
0.1663   0.0153
spgr      Diff (1-2)             0.0477  0.0967    0.1456    0.0129   0.0216
0.0621   0.0176
arw                  0      3    0.9032     1.4    1.8968    0.1041      0.2
1.2569   0.1155
arw                  1      3    -0.379  1.7333    3.8461    0.4428   0.8505
5.3451    0.491
arw       Diff (1-2)             -1.734  -0.333    1.0672    0.3701   0.6178
1.7753   0.5044

                                    T-Tests

              Variable    Method           Variances      DF    t Value    Pr
> |t|

              stress      Pooled           Equal             4      -0.02
0.9848
              stress      Satterthwaite    Unequal        3.04      -0.02
0.9851
              moe         Pooled           Equal             4       0.48
0.6577
              moe         Satterthwaite    Unequal        3.48       0.48
0.6612
              spgr        Pooled           Equal             4       5.48
0.0054
              spgr        Satterthwaite    Unequal         3.2       5.48
0.0101
```

```
              arw         Pooled           Equal            4      -0.66
0.5448
              arw         Satterthwaite    Unequal      2.22      -0.66
0.5707

                             Equality of Variances

                  Variable    Method       Num DF    Den DF    F Value    Pr >
F

                  stress      Folded F          2         2       3.55
0.4393
                  moe         Folded F          2         2       2.26
0.6133
                  spgr        Folded F          2         2       3.00
0.5000
                  arw         Folded F          2         2      18.08
0.1048

                               The REG Procedure
                                 Model: MODEL1
                          Dependent Variable: stress

                   Number of Observations Read           6
                   Number of Observations Used           6

                              Analysis of Variance

                                             Sum of           Mean
         Source                   DF        Squares         Square    F Value
Pr > F

         Model                     3       19457530        6485843       0.74
0.6186
         Error                     2       17537441        8768720
         Corrected Total           5       36994971


                     Root MSE           2961.20253    R-Square     0.5260
                     Dependent Mean          34386    Adj R-Sq    -0.1851
                     Coeff Var             8.61161

                              Parameter Estimates

                                    Parameter       Standard
              Variable     DF        Estimate          Error    t Value    Pr >
|t|

              Intercept     1           34428          11652       2.95
0.0980
              treat         1      -521.07466     2853.55803      -0.18
0.8719
              crown         1     -1233.53242     2808.93675      -0.44
0.7034
```

```
              arw           1     1714.22397     4546.73710       0.38
0.7424

                               The REG Procedure
                                 Model: MODEL1
                            Dependent Variable: moe

                    Number of Observations Read           6
                    Number of Observations Used           6

                             Analysis of Variance

                                             Sum of           Mean
         Source                   DF        Squares         Square    F Value
Pr > F

         Model                     3    5.212265E12    1.737422E12       0.46
0.7368

         Error                     2    7.479678E12    3.739839E12
         Corrected Total           5    1.269194E13


                      Root MSE              1933866    R-Square     0.4107
                      Dependent Mean       19141912    Adj R-Sq    -0.4733
                      Coeff Var            10.10279

                              Parameter Estimates

                                   Parameter       Standard
              Variable     DF       Estimate          Error    t Value    Pr >
|t|

              Intercept     1       22988740        7609859       3.02
0.0943
              treat         1        -483438        1863567      -0.26
0.8196
              crown         1       -1350235        1834426      -0.74
0.5383
              arw           1        -577429        2969328      -0.19
0.8638

                               The REG Procedure
                                 Model: MODEL1
                           Dependent Variable: spgr

                    Number of Observations Read           6
                    Number of Observations Used           6

                             Analysis of Variance

                                             Sum of           Mean
         Source                   DF        Squares         Square    F Value
Pr > F
```

```
         Model                     3        0.01535        0.00512      19.05
0.0503
         Error                     2     0.00053700     0.00026850
         Corrected Total           5        0.01588

                      Root MSE              0.01639    R-Square     0.9662
                      Dependent Mean        0.55833    Adj R-Sq     0.9155
                      Coeff Var             2.93480

                              Parameter Estimates

                                   Parameter       Standard
              Variable     DF       Estimate          Error    t Value    Pr >
|t|

              Intercept     1        0.55869        0.06448       8.66
0.0131
              treat         1       -0.10728        0.01579      -6.79
0.0210
              crown         1        0.00171        0.01554       0.11
0.9225
              arw           1        0.03183        0.02516       1.27
0.3333
```

Irrigated Suppressed

```
                              The CORR Procedure

               4  Variables:    height   stress   moe      spgr

                               Simple Statistics

   Variable           N          Mean       Std Dev          Sum
Minimum       Maximum

   height            20       0.80700       0.74109      16.14000
0       2.59000
   stress            20         33289          2067        665770
30930         39093
   moe               20      18343431       3285700     366868616
13573943      25728793
   spgr              20       0.60900       0.05990      12.18000
0.52000       0.71000

                   Pearson Correlation Coefficients, N = 20
                          Prob > |r| under H0: Rho=0

                               height        stress           moe
spgr

                 height       1.00000       0.80242       0.76661      -
0.58491
                                             <.0001        <.0001
0.0068
```

```
                 stress       0.80242       1.00000       0.80184      -
0.56115
                               <.0001                      <.0001
0.0100

                 moe          0.76661       0.80184       1.00000      -
0.84989
                               <.0001        <.0001
<.0001

                 spgr        -0.58491      -0.56115      -0.84989
1.00000
                               0.0068        0.0100        <.0001
```

Irrigated Codominant

```
                              The CORR Procedure

               4  Variables:    height   stress   moe      spgr

                               Simple Statistics

   Variable           N          Mean       Std Dev           Sum
Minimum       Maximum

   height            75       2.47307       2.03084     185.48000
0       6.71000
   stress            75         33108          3188       2483093
23539         39900
   moe               75      19114128       3038688    1433559566
12358432      23933605
   spgr              75       0.58880       0.05319      44.16000
0.51000       0.70000

                   Pearson Correlation Coefficients, N = 75
                          Prob > |r| under H0: Rho=0

                               height        stress           moe
spgr

                 height       1.00000       0.48132       0.70953      -
0.77660
                                             <.0001        <.0001
<.0001

                 stress       0.48132       1.00000       0.83064      -
0.68727
                               <.0001                      <.0001
<.0001

                 moe          0.70953       0.83064       1.00000      -
0.89205
                               <.0001        <.0001
<.0001
```

```
                 spgr        -0.77660      -0.68727      -0.89205
1.00000
                               <.0001        <.0001        <.0001

                              Irrigated Dominant

                              The CORR Procedure

               4  Variables:    height   stress   moe      spgr

                               Simple Statistics

   Variable           N           Mean       Std Dev           Sum
Minimum       Maximum

   height            93        2.90151       2.79866     269.84000
0       8.99000
   stress            93          36686          3146       3411756
27469         45512
   moe               92       20979088       2355558    1930076061
15418746      25461808
   spgr              93        0.62000       0.05163      57.66000
0.54000       0.73000

                       Pearson Correlation Coefficients
                          Prob > |r| under H0: Rho=0
                            Number of Observations

                               height        stress           moe
spgr

                 height       1.00000      -0.00370       0.45925      -
0.71909
                                             0.9719        <.0001
<.0001
                                   93            93            92
93

                 stress      -0.00370       1.00000       0.63467      -
0.18131
                               0.9719                      <.0001
0.0820
                                   93            93            92
93

                 moe          0.45925       0.63467       1.00000      -
0.59641
                               <.0001        <.0001
<.0001
                                   92            92            92
92

                 spgr        -0.71909      -0.18131      -0.59641
1.00000
                               <.0001        0.0820        <.0001
```

```
                                   93            93            92
93
```

Fertigated Suppressed

```
                              The CORR Procedure

               4  Variables:    height   stress   moe      spgr

                               Simple Statistics

   Variable           N          Mean       Std Dev           Sum
Minimum       Maximum

   height            25       1.99240       1.55163      49.81000
0       5.18000
   stress            25         33459          3017        836478
28213         39955
   moe               25      19118746       2094873     477968638
15125257      23529483
   spgr              25       0.48720       0.02227      12.18000
0.45000       0.54000

                   Pearson Correlation Coefficients, N = 25
                          Prob > |r| under H0: Rho=0

                               height        stress           moe
spgr

                 height       1.00000       0.77563       0.78620      -
0.71384
                                             <.0001        <.0001
<.0001

                 stress       0.77563       1.00000       0.89666      -
0.51353
                               <.0001                      <.0001
0.0087

                 moe          0.78620       0.89666       1.00000      -
0.66223
                               <.0001        <.0001
0.0003

                 spgr        -0.71384      -0.51353      -0.66223
1.00000
                               <.0001        0.0087        0.0003
```

Fertigated Codominant

```
                              The CORR Procedure

               4  Variables:    height   stress   moe      spgr

                               Simple Statistics
```

```
   Variable           N           Mean        Std Dev            Sum
Minimum       Maximum

   height            93        2.63656        2.04545      245.20000
0       7.01000
   stress            93          31179           4197        2899668
23842         38962
   moe               90       16624654        3652587     1496218872
9262148      22712068
   spgr              93        0.49559        0.03325       46.09000
0.43000       0.63000

                       Pearson Correlation Coefficients
                          Prob > |r| under H0: Rho=0
                            Number of Observations

                               height        stress           moe
spgr

                 height       1.00000       0.82839       0.83148
0.07207
                                             <.0001        <.0001
0.4924
                                   93            93            90
93

                 stress       0.82839       1.00000       0.87105
0.07944
                               <.0001                      <.0001
0.4491
                                   93            93            90
93

                 moe          0.83148       0.87105       1.00000
0.10278
                               <.0001        <.0001
0.3350
                                   90            90            90
90

                 spgr         0.07207       0.07944       0.10278
1.00000
                               0.4924        0.4491        0.3350
                                   93            93            90
93
```

Fertigated Dominant

```
                              The CORR Procedure

               4   Variables:    height    stress   moe      spgr

                               Simple Statistics
```

```
   Variable           N          Mean       Std Dev           Sum
Minimum       Maximum

   height           106       3.86057       2.41368     409.22000
0       8.99000
   stress           106         38956          2938       4129317
31874         45485
   moe              105      20668467       2496267    2170189009
15285305      25769990
   spgr             106       0.54009       0.02591      57.25000
0.48000       0.65000

                       Pearson Correlation Coefficients
                          Prob > |r| under H0: Rho=0
                            Number of Observations

                               height        stress           moe
spgr

                 height       1.00000       0.55542       0.63061      -
0.43398
                                             <.0001        <.0001
<.0001
                                  106           106           105
106

                 stress       0.55542       1.00000       0.70512      -
0.28417
                               <.0001                      <.0001
0.0032
                                  106           106           105
106

                 moe          0.63061       0.70512       1.00000      -
0.38074
                               <.0001        <.0001
<.0001
                                  105           105           105
105

                 spgr        -0.43398      -0.28417      -0.38074
1.00000
                               <.0001        0.0032        <.0001
                                  106           106           105
106
```

All Samples (n=412)

```
                              The TTEST Procedure

                                  Statistics

                               Lower CL          Upper CL  Lower CL
Upper CL
```

```
Variable  bole              N      Mean    Mean      Mean   Std Dev  Std Dev
Std Dev  Std Err

stress               0     85     36936   37712     38488    3127.4     3599
4239.4   390.37
stress               1    327     33836   34314     34791    4079.5   4392.3
4757.5   242.89
stress    Diff (1-2)             2383.2  3398.4    4413.6    3970.3   4241.9
4553.5   516.44
moe                  0     85    2.18E7  2.22E7    2.26E7     1.5E6   1.73E6
2.04E6   187517
moe                  1    322    1.82E7  1.86E7     1.9E7    2.99E6   3.22E6
3.49E6   179586
moe       Diff (1-2)             2.88E6   3.6E6    4.31E6    2.78E6   2.98E6
3.2E6   362787
spgr                 0     85    0.5379  0.5473    0.5567     0.038   0.0437
0.0515   0.0047
spgr                 1    327    0.5522  0.5596    0.5671    0.0638   0.0687
0.0744   0.0038
spgr      Diff (1-2)             -0.028  -0.012    0.0031    0.0602   0.0644
0.0691   0.0078

                                    T-Tests

              Variable    Method           Variances      DF    t Value    Pr
> |t|

              stress      Pooled           Equal         410       6.58
<.0001
              stress      Satterthwaite    Unequal       156       7.39
<.0001
              moe         Pooled           Equal         405       9.92
<.0001
              moe         Satterthwaite    Unequal       253      13.86
<.0001
              spgr        Pooled           Equal         410      -1.57
0.1161
              spgr        Satterthwaite    Unequal       205      -2.03
0.0435

                             Equality of Variances

                  Variable    Method      Num DF    Den DF    F Value    Pr >
F

                  stress      Folded F       326        84       1.49
0.0297
                  moe         Folded F       321        84       3.47
<.0001
                  spgr        Folded F       326        84       2.47
<.0001
```

VITA

Thomas Mason Jeffries III was born and raised in Culpeper, Virginia. Mason completed his Associates in Science at Germanna Community College while employed with Culpeper Wood Preservers. Mason completed his Bachelor of Science in forestry at Virginia Tech. After working with the Virgnia Department of Forestry, Mason returned to Virginia Tech to complete a Master of Science in Wood Science.