Determining the Effect of Felling Method and Season of Year on Coppice Regeneration

by

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Abstract

There is increasing interest in plantations with the objective of producing biomass for energy and fuel. These types of plantations are called Short Rotation Woody Crops (SRWC). Popular SRWC species are Eucalypt (Eucalyptus spp.), Cottonwood (Populus deltoids) and Black Willow (Salix spp.). These species have in common strong growth rates, the capability to adapt to several weather conditions, the ability to coppice and rotations of 2-10 years. SRWC have generated interest for many forest products companies and timber producers and although they might help with the supply for the expected growth on the bioenergy and biofuels market, there are still several concerns about the best way to harvest them maximizing their ability to coppice. SRWC have elevated establishment and maintenance costs if compared to other type of plantations, but due the coppicing ability, the same plantation may be harvested up to 5 times without the need of establishing a new one. This will aid in the avoidance of the cost of establishing new plantations after the harvest. Study plots were installed at several locations in Florida, Mississippi and Arkansas, and were cut with a chainsaw and a shear head during summer and winter, to determine the effects of felling method and season on coppice regeneration. Thus, plots were divided in 4 treatments: shear-winter, saw-winter, shear-summer, saw-summer. Harvesting eucalypt trees during winter resulted in 96% of the stumps with coppice regeneration, while harvesting during summer resulted with 79% coppicing; however, there was no effect from felling method on coppice regeneration. A harvest season effect was observed on cottonwood, where harvesting during summer negatively affected coppice regeneration when compared to harvesting during winter. On the other hand, there was no significant effect observed on coppicing ability when trees were cut with the shear head or the chainsaw. Finally, no statistically significant difference was found on coppice regeneration of black willow when harvesting during winter or summer with a chainsaw or a shear head.

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I. Introduction

The increasing necessity of finding new alternatives to produce fuel and energy has never been so evident in the United States. Issues like the increasing population, dependence on foreign oil, and the declining availability of fossil fuels have made renewable energy sources, such as biomass, become a plausible and promising option to address these issues. Moreover, researchers and politicians have developed some ideas, where a major part of the nation's energy needs will be sourced from renewable fuels. One of these ideas is the 25x'25 Alliance (25 by 25), in which the goal is to replace 25% of the nation's fuel and energy consumption by some type of clean energy produced from renewables by the year 2025. Several states in the U.S. are joining alliances similar to the 25x'25, and as a result of that, a great amount of biomass will be required to produce clean energy and accomplish the goals. A considerable amount of that biomass will be allocated to woody biomass from harvest and forest products mill residues, but also from new plantations intended to supply new biofuel and bioenergy mills.

The woody biomass supply is currently coming from logging operations and mills' residues; however, they are not sufficient to meet the expected increase in market's needs. Recently, several companies and institutions have ventured into the short rotation woody crops (SRWC) supply system. According to the U.S. Department of Energy (2011), a SRWC is an intensively-managed plantation of a fast-growing tree species that produces large amount of biomass over a short period of time, usually less than 10 years, that can be shortened to as little as 3 years when coppiced, depending on the species and production method. In other words, a SRWC is defined as a plantation established to grow lignocellulosic material (wood) and biomass with the purpose of producing biofuel and bioenergy. The characteristics that define the SRWC are the ability to coppice, rotations between 2 and 10 years, and an impressive fast growth. It is also important to highlight that SRWC generally have very high costs. Tuskan (1998) specifies that SRWC involve appropriate site selection, use of improved clonal planting, extensive weed control, fertilization as required, pest control, and efficient harvesting and post-harvest processing. For this reason, to maximize the utilization of the plantation through the coppicing ability is fundamental. The coppicing ability is the ability that a tree has to regenerated new stems from the stump, after the harvest is performed. Depending on genetics, species, and other factors, the same plantation can be harvested up to five times (Langholtz et al., 2007) due the coppicing ability, thus reducing the costs and increasing the feasibility of the system.

The concept of SRWC became popular in U.S. in the early 1970's, when the U.S. Department of Energy (DOE) embraced this technology as a way of supplying biomass feedstock for the conversion to liquid transportation fuels (Tuskan, 1998; Ranney et al, 1987). Since the SRWC supply systems came into existence in the U.S., many studies have been implemented or undertaken to determine potential regions to establish SRWC plantations, suitable species for each region, and silvicultural practices. Also, genetic and biotechnological improvements have been realized (Tuskan, 1998). However, as with any other new technology, the research on SRWC must continue and several questions still remain unanswered.

Initially the efforts in SRWC supply systems focused on species-site trials within potential production regions, and as a result from these efforts the north-central, southeastern, northeastern and Pacific Northwest regions were defined as potential regions to establish SRWC. The popular and most promising species at that time were poplar (*Populus sp.*), sycamore (*Platanus occidentalis* L.), silver maple (*Acer saccharum* Marsh), and hybrid willow (*Salix sp.*), with poplar being the principal candidate through most of the defined regions (Tuskan, 1998). Although research projects and genetic improvements have been performed with poplar, there are some exotic species being used as SRWC in other parts of the world and could also be used in the U.S. territory, potentially producing better results than those obtained to date. One of the most promising species being introduced in plantations in the U.S. is the Eucalypt (*Eucalyptus sp.*). The Eucalypt is one of the most planted genera in the world, with more than 900 species. It has been extensively studied, planted, managed, and genetically improved, being able to adapt to several weather conditions and regions in the world. The United States Department of Energy (2011) states that poplar, southern pine, willow, and eucalypt, are the most likely woody energy crop species to be developed for bioenergy production today.

The short rotations may be attractive to landowners looking for quicker return on investment and also looking to diversify their land use. The wider variety of species, combined with all the research and genetic improvement made to those species, are making SRWC productions more viable (Alig et al., 2000), giving the landowners more options to venture on this “unknown” technology. As a result, there has been a considerable increase in total acres of commercial and test SRWC plantations in the southeast region, with a major focus on Eucalypt, Cottonwood and Willow.

Although the establishment of SRWC plantations is becoming popular in the SE region, and the introduction of new species with better and promising results have been proved possible, the biofuel and bioenergy markets are not yet completely developed. In countries and regions where a bioenergy market is already established, the development and use of machinery specialized to harvest SRWC is very common. However, in the U.S. the absence of a solid bioenergy market has discouraged the development of a system specialized in harvesting SRWC plantations, thus making the investment on a foreign machine not feasible.

The conventional whole-tree harvesting system, where a feller-buncher with a circular saw head fells and bunches the trees and a rubber-tired grapple skidder drags the trees to the loading deck, is the most common system used in the Southeast (Wilkerson et al., 2009). This system processes the trees at the loading deck. SRWC stands are planted with high density spacing and managed under 3 – 10 year rotations, which mean that large equipment, as those used in whole-tree systems, may not be feasible or productive, since they are designed to harvest large trees planted in larger spacing, and SRWC trees are small in diameter, possibly with more than one stem per stump (if coppice is used as management). Besides, SRWC trees may be processed at the stump to avoid dirt accumulation, which is not desired on fuel transformation. The utilization of smaller equipment, with low capital and maintenance cost, such as a feller-buncher with a shear head, may be a temporary option, while specialized machinery is being developed. However, this equipment may cause damage to the stump’s structure and bark, which could cause possible effects on coppice regeneration.

On the other hand, little is known about the optimal harvest scheduling in SRWC in the Southeast. The effect of the season of the harvest has always been a subject of interest. Theories state that harvesting during summer could damage the stump, preventing coppice, and thus limiting the harvest to the winter season. If these theories are confirmed, the impact on the developing SRWC supply systems in U.S. would be tremendous, with elevated economic challenges; however this theory has not been proven nor tested yet.

It is evident that further research in SRWC harvesting techniques and machinery is needed. This study will compare the effects of harvesting SRWC plantations in the Southeast region with a small shear-head and with a chainsaw (simulating a circular saw-head), and also examine the potential difference in coppice response between harvesting during winter and summer seasons.

II. Objectives

The objective of this study is to determine the potential effects of the felling method and the harvest season in coppice regeneration in short rotation woody crops in the Southeastern United States.

The specific objectives encompassed by this project are:

1. Compare the effects on short rotation woody crops' ability to coppice when felled with a shear-head or a chainsaw.
2. Determine if the short rotation woody crops' coppicing ability is affected by the season of year (winter or summer) in which the harvest is performed.
3. Determine if the damage caused to the stump and to its bark during the harvest operation have an effect on the coppice regeneration.
4. Evaluate the effect of the diameter of the stump at the cut level have an effect on coppice regeneration.

III. Literature Review

3.1 Short Rotation Woody Crops supply systems

Woody biomass represents a renewable resource with multiple industrial applications. It serves as feedstock for the pulp and paper industry but also can be planted specifically to address the feedstock need for the biofuels industry (Hinchee et al., 2009). The concept of short rotation woody crops (SRWC) became popular during the 1960’s and 1970’s (Tuskan, 1998). Short rotation forestry refers to the cultivation of fast growing deciduous tree species regenerating, generally through sprouts, using short rotation periods, intensive methods and dense stocking (Hytönen et al., 1995). In other words, SRWC are tree crops grown on short rotations, typically with more intensive management than timber plantations (White, 2010), in order to produce lignocellulosic material for bioenergy and fuel conversion.

SRWC are a renewable energy feedstock for biofuels, bioenergy, and bioproducts, which can be strategically placed in the landscape to conserve soil and water, recycle nutrients, and sequester carbon (Vance et al., 2010). Tamang (2005) found that given adequate soil preparation, high density SRWC plantations of *Eucalyptus* spp. can exclude cogongrass, speed dewatering in flooding areas, increase soil organic matter and facilitate growth of native understory vegetation. Being so, willow (*Salix spp.*) or cottonwood

(*Populus deltoides*), may produce similar environmental benefits as the ones found with eucalypt plantations.

According to Perlack et al. (1995), a successful SRWC is defined by:

- More than 80% survival of the material planted.
- Annual productivity greater than 10-12 dry tons/ha of harvested biomass.
- Uniformity in diameter, height and straightness.
- Less than $50/dry ton in delivered cost.

There are also other characteristics that distinguish the SRWC from other type of plantations, such as the extremely high density, the short rotations, and the ability to coppice. Establishment of SRWC is recommended at 1,200 – 1,400 stems ha^{-1}, to reduce establishment and harvesting costs (Tuskan, 1998). The rotation of a SRWC plantation may vary between 2 – 10 years, depending on the species used, the final product, and the region where it is established. The coppice regeneration is the ability a tree has to grow new stems from the stump. Coppicing will occur when apical control is blocked or destroyed by some extrinsic factor, like the harvest. Langholtz et al. (2007) states that SRWC systems use fast-growing tree species that coppice, and typically involve 3 – 5 harvests before replanting, with 2 – 10 years between harvests.

Coppice regeneration is a characteristic that most of the SRWC tree species share. However, some disadvantages have been noted. Tuskan (1998) declared that the use of coppice as a regeneration option has been almost eliminated. The advantage that it offers in improved yields are lost over longer rotations of 6 – 10 years, and the post-coppice tree form increases harvesting costs. Genetic improvement of the trees results in substantially greater increases in productivity compared to coppice. On the other hand, coppice regeneration reduces the establishment costs of new plantations (site preparation, seedlings, and planting costs), and increasing the productivity (or mean annual increment) when compared to the initial single-stem harvest (Dougherty and Wright, 2012; Hinchee et al., 2009; Kauter et al., 2003).

Increased productivity achieved by coppiced stems results from an established root system designed for a larger plant. Thus, the new coppiced trees can draw water and nutrients from a large soil volume and recycle carbohydrate reserves from the root tissues. Over multiple rotations root systems decline in vigor, and genetically improved clonal lines or seedlings can be planted (Steinbeck, 1978).

3.2 Introduction to Coppicing

The sprouts regeneration will occur when apical control is disturbed by some external factor. Zimmermann & Brown (1974) declared that the development of form in trees is controlled by growth regulators that emanate from the distal tip of a shoot. The two mechanisms in charge of controlling tree growth are the apical dominance, which is a temporary inhibition of the growth of axillary buds on a stem by an actively growing shoot tip and the apical control, which describes the regulation of overall tree shape by the terminal bud. The majority of tree species will only naturally produce secondary trunks when apical control is destroyed, hence terminating the hierarchical relationships which regulate the development of tree form. Thereby, coppice may be defined as the process whereby a tree develops secondary replacement trunks (Del Tredici, 2001).

The coppicing ability, and sprout morphology, will vary considerably by tree species. Also, several internal and external factors control the regeneration of new stems from the stump. It has been shown with many tree species that several factors such as cutting season, cutting equipment, stump height, tree diameter, tree age, growing site, spacing, and rotation length have an effect on coppice regeneration (Hytonen, 1996; Dougherty and Wright, 2012). Nonetheless, Ceulemans et al. (1996) declares that with the species *Salix* and *Populus*, depending upon management and product objectives, the particular hybrids grown, the length of the rotation, and the availability of improved clones or cultivars, a harvested stand may be naturally regenerated by coppice.

Ceulemans et al. (1996) compared the coppicing ability of the genus *Salix* (willow), *Eucalyptus* (eucalypt), and *Populus* (poplar) stating that in willow trees, the shoots develop from dormant axillary bud groups on the remaining basal parts of the harvested stems and on the original cutting stump. In eucalypt trees, the sprouts grow from epicormic buds embedded in the bark, which originate from axillary meristems. On the other hand, poplars of the *Leuce* section coppice primarily by way of root suckers, while poplars from the *Aigeiros* and *Tacamahaca* sections sprout primarily from the stump.

Opie et al. (1984) commented that all eucalypts have some capacity to produce epicormic shoots, which will arise from dormant buds that originate as meristematic tissue in the axils of the leaves. When the crown is removed by fire, insect attack, or harvest, dormant buds develop into epicormic shoots that are capable of completely replacing the crown.

3.3 Types of Sprouts

Additionally, Del Tredici (2001) classified sprouts according to the size of the stem that is sprouting, the number of sprouts produced, and the location of the sprouts in relation to the trunk. There are four basic types of sprouts morphologies displayed by temperate trees: collar sprouts, sprouts from specialized underground stems, sprouts from roots, and opportunistic sprouts.

3.3.1 Collar Sprouts

For the vast majority of trees the greatest potential for the production of secondary trunks is localized at the collar (Sutton & Tinus, 1983) which can be defined as the point on the seedling axis where the root and the shoot systems come together. In angiosperms and a few gymnosperms the collar on a tree originates from stem tissue immediately above the cotyledonary node. In mature trees the collar develops at or just below ground level and is readily identifiable by the presence of numerous suppressed buds that protrude out from the trunk. Suppressed buds grow slowly, just enough to keep pace with the radial growth of the trunk (Sakai et al., 1995; Wilson, 1968; Zimmermann & Brown, 1974). Typically there is a strong density gradient of suppressed buds along the trunk of the tree, with a maximum concentration at the collar that decreases as one moves up the trunk. Carbohydrate storage at the base of the trunk causes swelling and functions to support the growth and proliferation of suppressed buds and facilitate their development into leafy shoots following traumatic disturbance (Sakai et al., 1995). The sprouts can originate from below, above, or at ground level. If they originate from above ground level, they will be dependent on the primary trunk and root system for water and mineral nutrients (Wilson, 1968). However if they originate from below or at ground level, they will be in direct contact with soil and will have the opportunity to develop adventitious roots from the buried portions of their stem and become autonomous from the parent trunk (Sakai et al., 1995). Also, sprouts which arise from the collar of a mature tree are considered to be juvenile relative to the mature parts of the tree (Fontainer & Jonkers, 1976).

3.3.2 Sprouts from specialized underground stems

As opposed to collar sprouts, this sprout typically emerges some distance away from the primary trunk, which reduces the competition between the primary trunk and the sprout. The separation facilitates the autonomous development of the sprout later in life (Del Tredici, 2001). There are two types of specialized underground stems: lignotubers and rhizomes. The first consists of a basal swelling, produced by suppressed buds and axillary buds up on the stem that protrude out from the stem and may have a downward orientation (Del Tredici, 2001). The lignotuber will store and produce suppressed buds, carbohydrates and adventitious roots, which can facilitate resprouting following traumatic injury (Canadell & Zedler, 1995; James, 1984). Examples of trees that produce lignotubers are *Eucalyptus marginata*, *Tilia americana* and *Quercus suber*. On the other hand, rhizomes grow out from the base of the trunk and produce aerial stems some distance away from its parent (Del Tredici, 2001). Tree species such as *Querus virginiana*, *Prunus virginiana*, and some species of the genus *Populus* are example of trees that develop rhizomes. In general, the two types of specialized underground stems allow trees to survive the occurrence of frequent disturbance. Their sprouts have a strong potential to form adventitious roots and to develop into autonomous ramets, since they typically emerge from below ground (Del Tredici, 2001).

3.3.3 Sprouts from roots

From the anatomical perspective, the tree roots produce two basic types of shoot buds: additional buds and reparative buds. Additional buds are formed by the deep tissues (endogenously) of young, uninjured roots. They will grow enough to keep up with the diameter growth of the root, typically branching to form prominent bud clusters. Meanwhile, reparative buds are formed near the surface of the root (exogenously) in response to senescence or injury (Bosela & Ewers, 1997). Some trees produce new stems spontaneously as part of their normal development. Nonetheless, most of the trees do not begin suckering until the primary trunk has experienced some form of traumatic damage (Del Tredici, 2001). Suckering can be define as the production of shoots from the root system when the trunk of the tree has suffered some type of injury. Although the presence of a healthy trunk does not seem to inhibit the production of buds, it often suppresses their development into aerial shoots. Therefore, for most temperate trees, root sprouting appears to be primarily a reparative response that only secondarily results in clonal growth (Burns & Honkala, 1990).

3.3.4 Opportunistic sprouts

This type of sprout occurs only under specific environmental conditions. Layered sprouts develop from low-hanging lateral branches that produce roots where they come into contact with the soil. The sprout may eventually form vertical shoots that can develop into autonomous trunks when the parent branch rots away (Del Tredici, 2001). It has been proved that some species use this sprouting mechanism more to survive suppression than to increase population of the site (Hibbs and Fischer, 1979). Buds on the horizontal trunk of leaning or partially uprooted trees produce trunk sprouts, especially when they are growing on open sites with wet, peaty soils or on forested sites with moist soils and heavy shades (Del Tredici, 2001). This phenomenon has been documented mostly in conifers; however, it can also occur with some angiosperms, such as *Salix nigra* (Del Tredici, 2001; Burns and Honkala, 1990).

Regardless of the type of sprouting, the buds close to the point of the traumatic damage, be they on branches or the trunk, show the most vigorous growth. This is an indication that basal sprouting is generally an induced response. In other words, the primary purpose is to replace the damaged trunk (Del Tredici, 2001). However, most of the angiosperms trees produce numerous collar sprouts after logging. The majority of these sprouts will die within five to ten years, leaving only the most vigorous or the most firmly attached sprouts (Del Tredici, 2001; Burns & Honkala, 1990; Johnson, 1977; Wendel, 1975).

3.4 Factors affecting the coppicing ability

There are several factors that may affect coppice type, vigor and number of new stems. Season of harvest, felling method, height of stump, growing site, tree diameter, tree age, spacing, rotation length, and species influence the regeneration of coppice (De Souza et al., 1991; Ducrey and Turrel, 1992; Hytonen, 1994, 1996, 2001; Simões et al., 1972; Strong and Zavitovski, 1983).

3.4.1 Season of harvest

According to Hytönen, 1996, the reasons for differences in coppicing due to timing of the cutting are not fully understood. The highest number of sprouts for downy birch resulted from being cut back in the summer. Also, the buds of exotic willow species burst even when cut in late summer or early autumn, but in the beginning of winter, such sprouts were small and their moisture content was high. The study affirmed that one reason for poor coppicing vigor and increased stump mortality following late autumn cutting may be in the death of these small sprouts due to frost.

Additionally, Ceulemans et al. (1996) affirmed that dormant-season harvest ensures maximum sprout vigor, because sprouting is apparently severely decreased when stools are cut in an actively growing stage. This decrease may partly be attributable to low availability of carbohydrate reserves in roots after the onset of shoot growth during the first part of the growing season.

Steinbeck (1978) harvested Sycamore plots at various times throughout the year, and observed that the trees produced more sprouts than desirable regardless of timing of harvest, but the sprouts emerging in summer did not seem to match, for several growing seasons, the growth of sprouts originating after other harvesting dates.

Hytönen (1994) studied the effect of cutting season on coppicing and growth of exotic and native willows and downy birch in central Finland. The results showed that for the exotic willow, the dominant height at one growing season after summer harvest was, half of that when the cutting was done during the dormant period. Also, the heights of birch and native willows one growing season after cutting were affected by the cutting season, with the winter harvest resulting in highest stems. The results also showed that cutting during the growing season decreased the survival of exotic willows, however, the survival of native willow and birch was not affected by cutting season. Finally, the number of exotic willow sprouts per living stump was lower when the harvest was performed during summer, differing from the local willow and birch results, in which the highest number of stems per stump was noted on the summer cut.

Strong and Zavitovski (1983) studied the effect of the harvesting season on hybrid poplar coppicing. The results showed that stump survival was 92% for the harvests from September to May, 65% for the June harvest and less than 10% for the July and August harvest. The results conclude that coppicing ability of poplar in Wisconsin was affected by harvesting season. The study also concluded that the average height of dominant sprouts ranged from 0.9 for the June through August harvest to 2.3 meters for the dormant season harvests, and that the DBH of dominant sprouts of individuals harvested during dormant season was 0.9 cm, while the individuals harvested in September was 0.5 cm.

3.4.2 Harvesting equipment

In the U.S. the harvesting of SRWC relies upon traditional stop and go equipment for felling, followed by skidding to a common landing, chipping at the landing, with chips being blown into the back of tractor/trailer for transport to the conversion facility (Tuskan, 1998). Depending on the final product derived from the SRWC plantation, the harvesting equipment, as well as the whole harvesting operation, may vary. If the primary product is wood chips for pulp and paper, the stems will be debarked at the landing and the wood chips placed directly into a trailer and the bark and branches may be segregated into hog chip piles used as feedstock for direct combustion power production (Tuskan, 1998).

Simões et al. (1972) compared the effects of the cutting method on the coppice regeneration of *Eucalyptus saligna*, in the southeast region of Brazil. For their study they used a 10 year old plantation located in Mogi Guaçu, Brazil, and performed harvests using a regular chainsaw and an ax. The results of the study concluded that there was no difference in stump survival between the ax and the chainsaw (64% and 62% survival respectively). Furthermore, they concluded that there was no difference between the stems height of stumps cut with ax and stumps cut with chainsaw (2.83 m and 2.65 m respectively).

Harvesting damage inflicted on the stump during harvest may also affect the ability to coppice of the tree. In many cases, the harvesting damage is attributed to the equipment used. Hytönen (1994) studied the effects of harvesting damage on the sprouting and biomass yield of willows in central and southern Finland. The study consisted of two sites planted with *Salix aquatica*. The first site was planted during the spring of 1983 and cut three times, during fall of 1983, 1985 and 1987, with a final harvest occurred in 1990. The cutting was performed with a secateurs, or hand pruners, resulting in a smooth cutting surface, and with a brush saw, leaving a rougher cutting surface. Additionally, half of the stumps were damaged manually. Results for the first site showed that the difference in the measured parameters between the cutting methods were small during all rotation periods. However, the number of sprouts per stump was statistically different. In stumps cut with the brush saw, there were, on average, 1.2 sprouts more per stump than in stumps cut with secateurs. Also, damaging the stumps decreased survival by 8.8% in the first rotation, 10.7% in the second rotation, and 16.8% after seven growing seasons. The height of the sprouts produced by the damaged stumps was also lower (16 cm lower in the first rotation, and 12 cm at the second). The second site was also planted with *S. aquatica* in 1982, but was cut when 8 years old in 1991. The harvest at this site was performed using a chainsaw and a brush saw. Both treatments included a control, a light-weight Farmi Trac forwarder driving on the row of stumps, and manual damage of the stumps. The results on the second site showed no difference between the two cutting methods, but showed a lower number of sprouts per living stump on stumps damaged by the mini-forwarder and manually.

Crist et al. (1983) evaluated the effect of severing method and stump height on coppice growth in a short rotation intensively cultured *Populus* plantation one, two and three years after the harvest in Wisconsin. The variables measured during the study were total number of stems per stump, height and diameter (at 1 foot from the base) of each stem. They compared a shearing method to a normal chainsaw, and found that there were no effects on the coppice or differences between the methods, as long as the stumps did not result excessively damaged during the harvest. Among the stump height, they compared stumps with 3, 6 and 18 inches tall, and found that initially the height, diameter and number of stems varied between stump heights; however, as the trees grew, the larger and more vigorous stems would survive and dominate the stump, remaining between 1 and 3 stems for stump for all the heights.

3.4.3 Tree Species

There is a considerable variety of species that can be considered for SRWC, and as with every biological characteristic, the coppicing ability differs among the genus, and even among the species. According to Tuskan et al. (1994) the U.S. Department of Energy (DOE) initiated the Biofuels Feedstock Development Program (BFDP) in 1978, and during the first 15 years of the program more than 150 woody plant species were evaluated, selecting *Populus* spp., *Acer saccharinum*, and *Salix* spp. based on their productivity, adaptability and suitability as biomass feedstock.

Sakai & Sakai (1998), and Sakai et al. (1995; 1997) mentioned that sprouting involves at least two basic resource-allocation strategies. The first, called "Resprouters", involves the translocation of carbohydrate reserves from underground portions of the trunk and/or root system to support rapid sprouting following serious damage to the above ground portions of the plant. The other strategy is called "resource remobilization", which leads to the development of a multitrunked form in which each stem develops its own adventitious root system. Trees sprouting with the resource remobilization strategy will dramatically reduce sprouting after the removal of aboveground stems, in comparison with trees that use the resprouters strategy.

According to Hytönen (1996), there are considerable inter-species differences in the reaction to the timing of cutting. The study compared 5 willow species (native and exotic) and one birch specie, in northern Finland. Results proved that inter-species differences in survival were clearly evident. Contrary to the behavior of exotic willows, the survival of downy birch and indigenous willow species was not affected by the timing of cut, exceeding 80% throughout.

Ceulemans et al. (1996) made a comparison among eucalypt, poplar and willow characteristics including the sprouting ability of each species. Eucalypt plantations differ from poplar and willows in several ways. Eucalypts are evergreen species, differing from poplars and willows. One of the characteristics found in many eucalypt species, but not in willows and poplars, is the presence of lignotubers_which is associated with sprouting. As already mentioned before, eucalypt sprouts grow from epicormic buds embedded in the bark which originate from axillary buds, while the coppice regrowth on willow trees develop from dormant axillary bud groups on the remaining basal parts of the harvested stems. On the other hand, poplar trees will coppice primarily by way of root suckers, although young poplars may also produce sprouts from stumps.

Since eucalypts are an evergreen genus without a clear dormancy phase (Ceulemans et al., 1996) the seasonality of the sprouting is different than on the deciduous genera. Stems of eucalypt may sprout when felled at any time of the year, even in regions with a temperate or Mediterranean type of climate (Ceulemans et al., 1996).

Not only will the stump survival rate vary among species; the number of sprouts per stump also differs. Ceulemans et al. (1996) also made a comparison between the number of sprouts per stump in poplar, willow and eucalypt. The study indicated that in willows there were often 20 to 25 shoots per stump. Furthermore, the initial number of sprouts after harvest increased with successive rotations, because the number of buds depends on the number of remaining stem's parts on the harvested stool. However, the self-thinning rate is high, leaving no more than 25% of the sprouts at the end of the first growing season, and less than 10% after 3 – 4 years. On the other hand most poplar clones yielded from 5 to 8 sprouts (sometimes much more). In stands of Euramerican poplar harvested at 1 – 3 year intervals, harvested biomass increased over the first few coppice rotations, but then declined. Stump survival and number of sprouts per stump declined steadily with successive coppices.

In the case of eucalypt, the number of sprouts per stump may be very large. An average of 20 sprouts per stump was reported for 6.5 year old *E. camaldulensis* in Israel, at the end of the first year after felling. In Italy, an average of 7.5 sprouts per stump was found in *E. globulus* and *E. camaldulensis* (Ceulemans et al., 1996). There was a seasonality effect in the number of sprouts per stump, the maximum observed on stumps cut during spring. However, the seasonality was not observed in Portugal, where the number of sprouts per stump in *E. globulus* did not vary significantly with the time of harvest, at approximately 4.3 per stump (Ceulemans et al., 1996).

Cremer et al. (1984) affirm that the coppicing ability of the species of the genera *Eucalyptus* varies among them. In general, species with lignotubers coppice well and some of the others do not. However, *E. pilularis, E. grandis, E. sieberi,* and many forms of *E. camaldulensis* have no lignotubers, yet commonly coppice well.

Eucalypt, poplar and willow are similar in many aspects, but differ in others (Ceulemans et al., 1996). Although there are several tree species capable of regenerating coppice, their phenology gives the sprouts different morphologic and ecologic characteristics. This indicates that factors that affect the coppicing ability of a specific tree species may not affect the coppicing ability of trees from a different species.

IV. Materials and Methods

4.1 Site Description

Five sites were selected to determine the effect of the felling method and the season of year on the coppicing ability. The sites selected are located in south Florida, central Arkansas, and western Mississippi (Figure 1). Two felling methods were compared to determine the different effects they may have on coppice regeneration. They were a small shear-head and a chainsaw (to simulate the effect of a circular saw-head). The harvests took place at each study site in two different seasons of year: summer and winter. A randomized block design was the experimental design used to install the treatments at each study site, which were composed by a study plot divided into four treatments: summer/saw harvest, summer/shear harvest, winter/saw harvest, and winter/shear harvest. The study plots in all sites were ~1 acre in size. The specific area of the study plots were chosen in concordance with the landowners, seeking for good tree growth, and avoiding wet and marginal growing sites.

Since one of the objectives of the study is to compare the effects of the harvest season on coppice regeneration, it is important to explain the climate conditions for the study sites in each season, to comprehend the phenology of the trees at the time of harvest. The two seasons compared will be summer and winter; therefore weather conditions for the periods from December to March and May to August will be summarized, since harvests are planned to occur among these months.

All soil information of the study sites used in this project was obtained from the soil map of the USDA – Natural Resources Conservation Services Web Soil Survey (http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx). All historic weather data for this study was obtained online from the web page *weather underground* (http://www.wunderground.com/). It is also important to highlight that the weather stations are not located at the study sites; thus, we can deduce that there may be small differences between the temperature and precipitation data collected at the closest weather station to the temperature and precipitation occurred at the study site. Some weather stations were located considerably close to the study sites (approximately 5 – 10 miles), but none was located farther than 30 miles away.

Figure 1: Location of five sites selected for the project. Three in south Florida, one in central Arkansas and one in western Mississippi.

4.1.1 Evans Properties

The Evans Properties site is located in south Florida, about 10 miles west of Fort Pierce, at Latitude/Longitude coordinates: 27.398175,-80.490003. The soil type at this site is defined as Winder loamy sand, mostly composed by sand and loam, and was previously used for citrus plantations. The soil is a deep soil with the restrictive features at more than 80 inches deep and the water table is 12 to 18 inches deep. The site was planted with clonal *Eucalyptus urograndis* on 50 feet wide beds and was 2 years-old at the time of harvest. Trees were planted at 728 trees/acre, with 9 feet between rows by 6 feet between trees (Figure 3). The average DBH for the trees was 4.8 inches, ranging from 1.8 to 7.6 inches, and the average height was 45.6 feet. Due the configuration of the beds, there was a larger spacing of 14 feet every 5 rows, which allows for a furrow/drainage row between the beds. A study plot (Figure 2) was installed and divided in 8 subplots. A subplot consisted of a bedded area, therefore, 5 rows with approximately 20 trees per row, totaling around 100 trees per subplot, and 200 trees per treatment. The harvests at this site occurred during the months of December (winter harvest) of 2013 and May (summer harvest) of 2014. In total, 828 trees were felled.

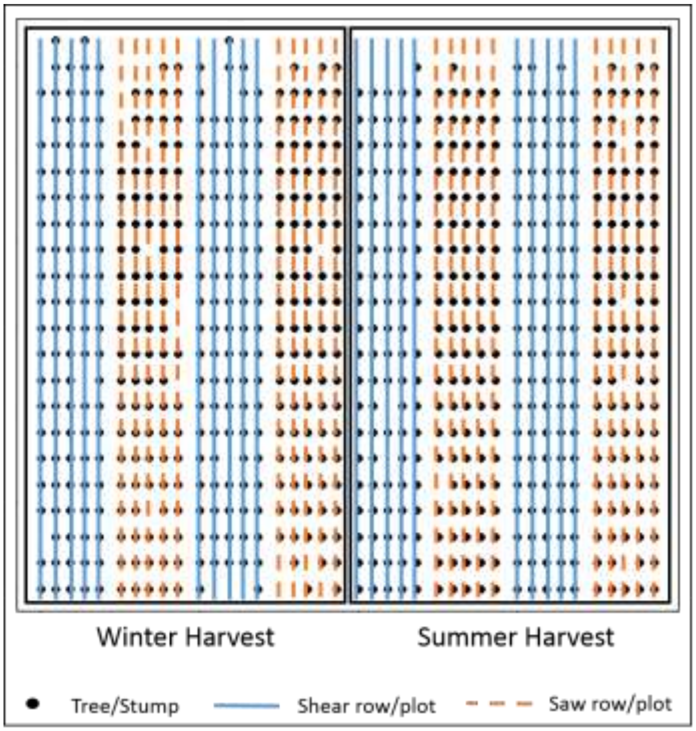

Figure 2: Layout of the study plot installed at Evans. The dots represent the number of tree per row. Each dot represents a harvested tree.

Figure 3: Evans Properties site. 50 foot wide bed with 5 rows at 9 feet apart and larger gap of 14 feet between beds.

The climate at this site is defined as tropical (under Köppen classification), with hot humid summers and mild winters. The rainy season for this region is defined between the months of June and December, with an average annual precipitation of 54 inches. During winter, the average temperature is 64°F, while during summer the average temperature is 80°F (Figure 4).

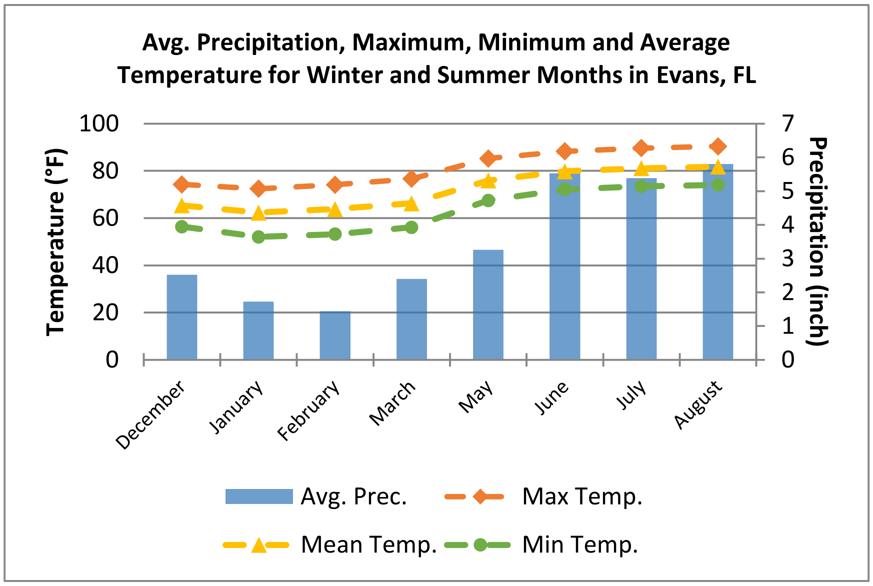

Figure 4: Average, maximum and minimum temperature on left axis and average precipitation on right axis at Evans Properties, FL, during winter and summer months.

4.1.2 ArborGen Bates

This site is also located in south Florida, about 9 miles southeast of Lake Placid, at Latitude/Longitude coordinates: 27.223599,-81.288292. The soil type is classified as Tequesta muck, mostly composed by sand. This is a poorly drained deep soil, with the restrictive features found at more than 80 inches deep and with a very superficial water table (12 – 18 inches). This site was planted with clonal *Eucalyptus urograndis*, the same clone planted at the Evans Properties site, and at the time of harvest it was 2 years old. Trees were planted at 1,282 trees/acre with 8 feet between rows by 4 feet between trees.

The trees at this site averaged 4.6 inches in DBH, ranging from 0.2 to 7.9 inches, and 57.9 feet in height. The study plot for this site was subdivided into 2 subplots (one for each season). Each subplot consisted of 15 rows, distributed between the two felling methods, resulting in 8 rows to shear and 7 rows to chainsaw (Figure 5). Each row had approximately 30 trees, totaling between 210 – 240 trees per treatment, 450 trees per subplot, and 900 trees in total.

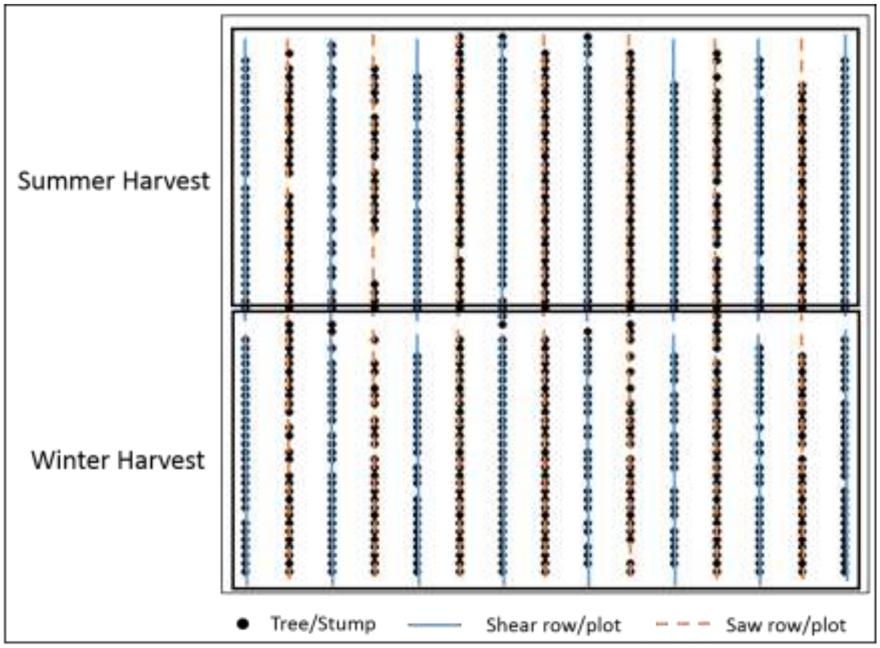

Figure 5: Layout of the study plot installed at Bates. The dots represent the number of trees per row. Each dot represents a harvested tree.

The climate is defined as tropical (under Köppen classification). Precipitation at this location is concentrated between June and December, with an annual average of 53 inches. Average temperature during winter is 64°F and 80°F during summer (Figure 6).

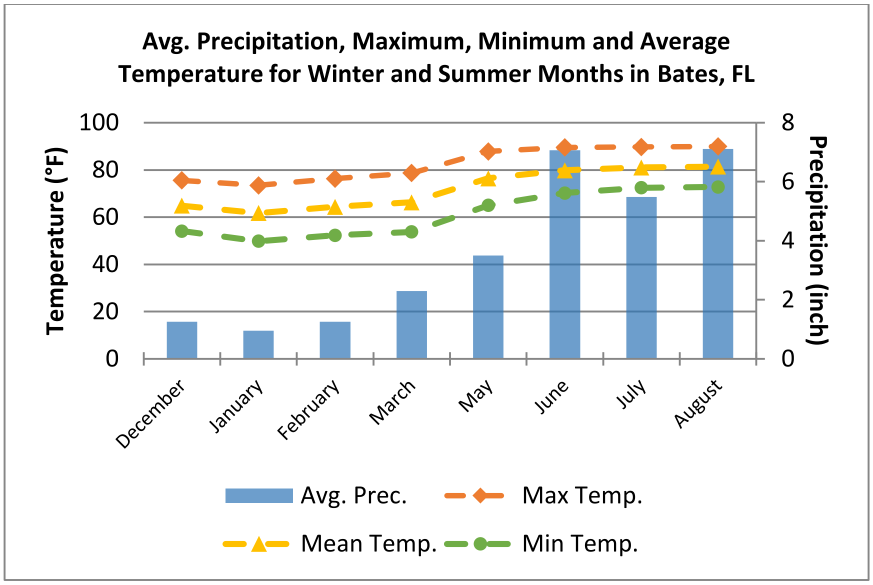

Figure 6: Average, maximum and minimum temperature on left axis and average precipitation on right axis, during winter and summer months, at ArborGen Bates, FL.

4.1.3 Lykes Ranch

Also located in south Florida, this site is about 7 miles south of Venus, at Latitude/Longitude coordinates: 26.993833, -81.341282, with a soil type classified as Immokalee sand, which is a sandy, poorly drained and deep soil, with the restrictive features found at more than 80 inches and the water table between 6 to 18 inches deep. The Lykes Ranch site consists of an 8 year old *Eucalyptus grandis* plantation. The mortality during early years of the plantation (probably during the first and second year) at this site was high, around 70-80%, likely due to high vegetative competition and scarce maintenance (Figure 7). As a consequence of the age and lower number of trees per acre due to high mortality, the DBH for this site averaged 7.4 inches, ranging from 3 to 13 inches. A study plot was installed at the site, and subdivided into 4 subplots. The subplots consisted of 5 and 6 rows, with approximately 5 trees per row, totaling between 25-30 trees per subplot. The winter harvest occurred in December of 2013, and a total of 105 trees were cut.

Figure 7: Lykes Ranch site with 8 years old *Eucalyptu grandis*. Large DBH and high mortality are visible.

This site has a tropical climate (under Köppen classification), with a similar precipitation regime explained in the previous study sites, and an annual average of 51 inches. During winter, the average temperature is 64°F and during summer, the average temperature tended to be 80°F (Figure 8).

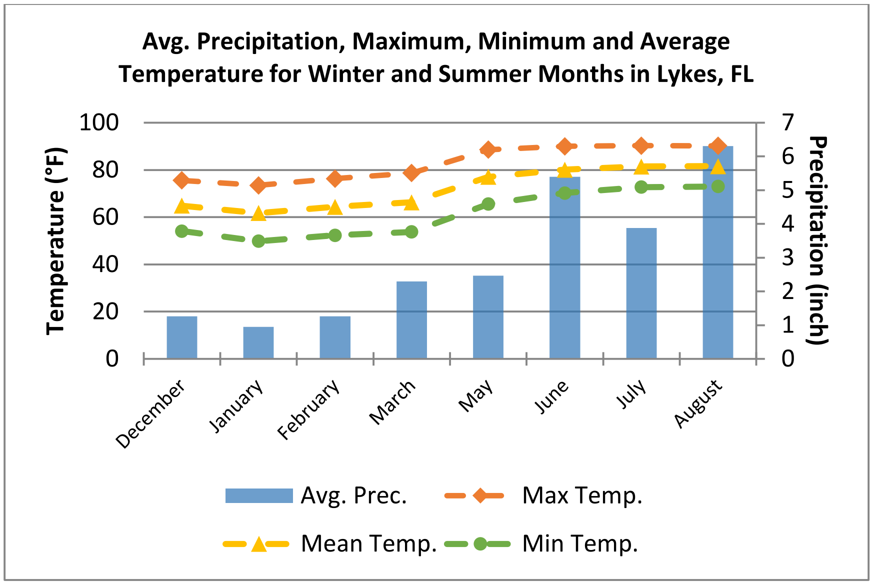

Figure 8: Average, maximum and minimum temperature on left axis and average precipitation on right axis at Lykes, FL, during winter and summer months.

4.1.4 Estes

The Estes site is located in central Arkansas, about 20 miles southeast of Little Rock, on the east side of the Arkansas River, and at Latitude/Longitude coordinates: 34.604027,-92.146046. Soil type for this site is classified as Keo silt loam, mostly composed by silt loam. This soil type is a well-drained, deep soil with the restrictive features and water table found at more than 80 inches deep. The site was planted with Cottonwood (*Populus deltoides*) that was 3 years-old at the time of the harvest. The DBH averaged 1.7 inches, ranging from 1 – 4 inches, and the average height was 29 feet. The plantation layout consists of double rows, with 2.5 foot spacing, separated by a 6 foot gap from the next double row. This plantation is also a spacing test, including 4 different spacing between trees, but was generally 2 feet. In this site two plots were installed, consisting of 6 double rows (one double row is equivalent to one row), equally divided between the felling methods, with approximately 70 trees per double row, totaling around

210 trees per treatment, and 420 trees per plot (Figure 9). The winter harvest occurred in the month of March of 2014, while the summer harvest occurred in the month of June of 2014. A total of 803 trees were harvested.

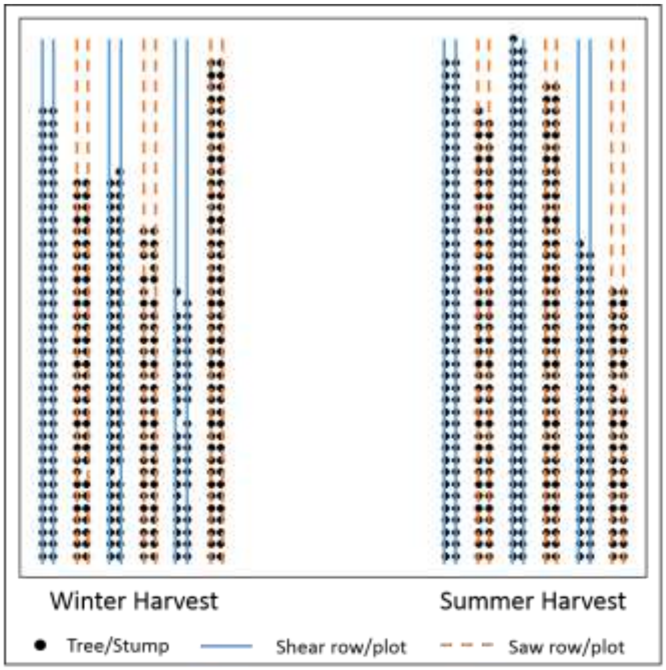

Figure 9: Layout of the study plots installed at Estes. The dots represent the number of trees per row. Each dot represents a harvested tree.

This study site has a climate defined as humid subtropical (under Köppen classification), with hot humid summers and mild to cool winter. Heavy rainfall occurs mostly during spring and fall, with spring being the most pronounced rainy season (Figure 10); average annual precipitation is around 50 inches. Snowfall may occur during winter. The average temperature during winter is 47°F and 80°F during summer.

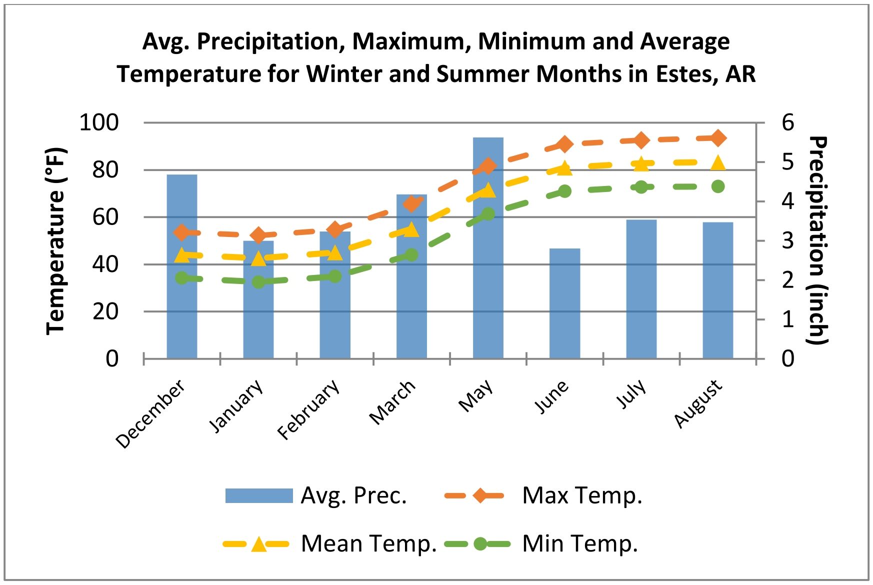

Figure 10: Average, maximum and minimum temperature on the left axis and average precipitation on right axis at Estes, AR, during winter and summer months.

4.1.5 Admire Tract

This site is located in Leland, Mississippi, approximately 10 miles east of Greenville, with the Latitude/Longitude coordinates at: 33.421484,-90.89633. The soil type at this site is defined as Bosket very fine sandy loam, composed by loam. This soil is moderately well drained, with the restrictive features found at more than 80 inches deep and the water table between 24 to 36 inches deep. The site was planted with Cottonwood (*Populus deltoides*) and Black Willow (*Salix spp.*); both were 5 years-old at the time of harvest. The average DBH and height for the Cottonwood was 4.7 inches (ranging from 1.3 to 11.2 inches) and 23.3 feet, respectively, and for the Black willow it was 3 inches (ranging from 0.6 to 7 inches) and 18.7 feet, respectively. The plantation at this site consists of a block of 600 trees for each species, in a 5 x 5 foot spacing. One study plot was installed in each species' block, and divided in two subplots, one per season. The subplots in the Black Willow consist of 14 rows, equally divided between the felling methods, with 20 trees per row, totaling approximately 140 trees per treatment, and 280 trees per subplot (Figure 11). The harvests occurred during the month of March (winter harvest) and June (summer harvest). A total of 583 trees were harvested. The Cottonwood block had a high mortality after the planting, reducing considerably the original number of 600 trees in the block; for this reason the subplots were installed according to the available number of trees, resulting in approximately 77 trees per treatment and 155 trees for each subplot (Figure 12). The harvests at the study site located in Mississippi were performed during the months of March (winter harvest) and June (summer harvest) of 2014. In total, 301 trees were felled.

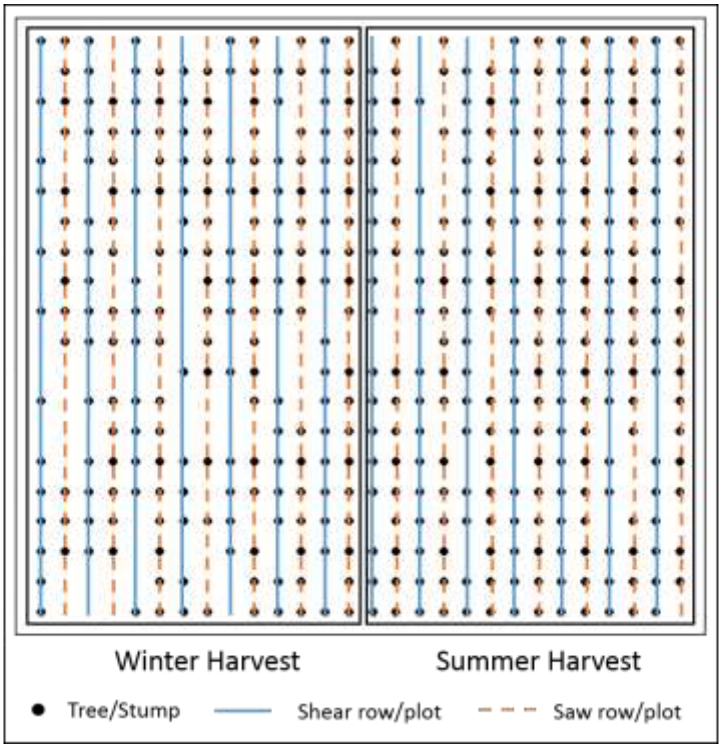

Figure 11: Layout of the study plot installed at the black willow site located in Admire. The dots represent the number of trees per row. Each dot represents a harvested tree.

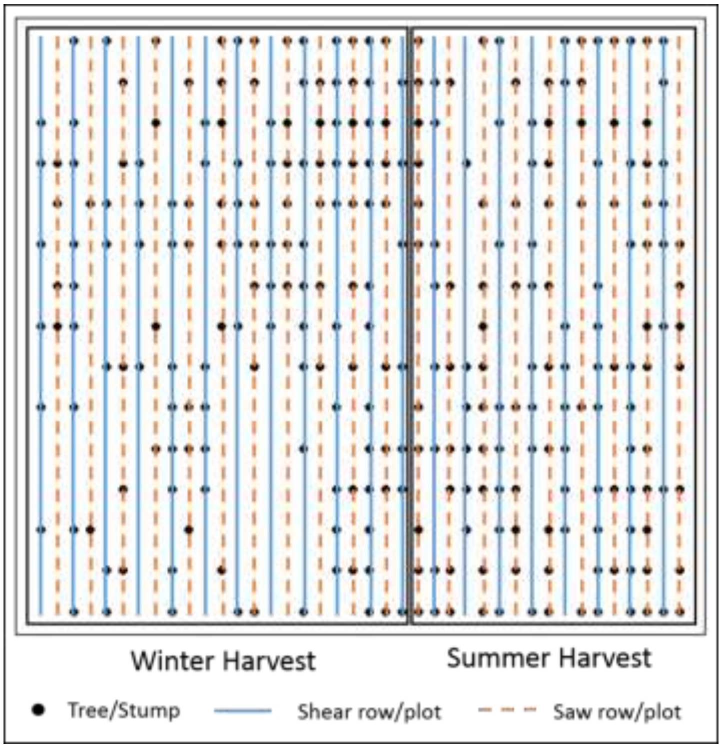

Figure 12: Layout of the study plot located at the cottonwood site in Admire. The dots represent the number of trees per row. Each dot represents a harvested tree.

The climate at this site is defined as humid subtropical, with long summers, and short mild winters. The rainfall is fairly evenly distributed through the year (Figure 13); however the area is subject to periods of drought and flood. Yearly average precipitation is 52 inches. The average temperature during winter is 46°F; snowfall may occur during this season. The temperature during summer averages 78°F.

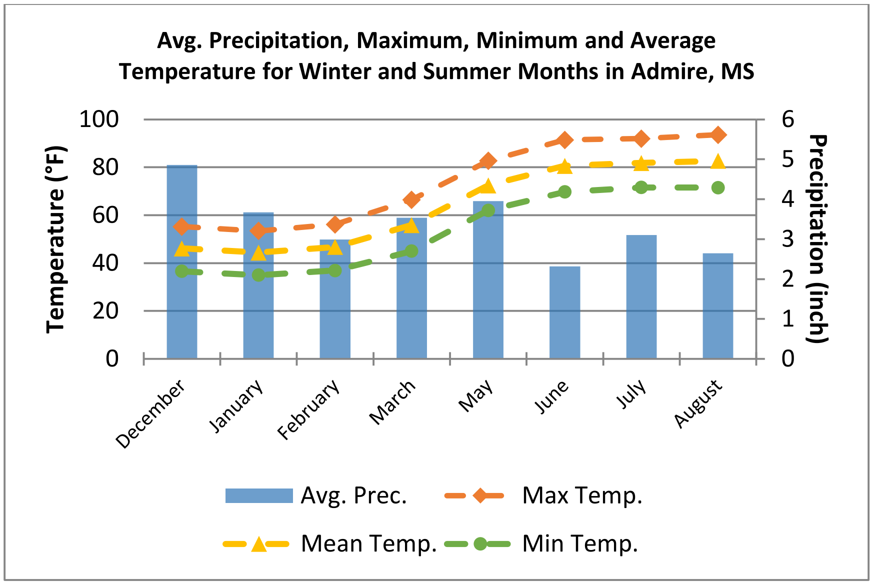

Figure 13: Average, maximum and minimum temperature on left axis and average precipitation, during winter and summer months, at Admire Tract, MS.

4.2 Equipment Specifications

The felling machine for shear felling was a skid steer (Caterpillar 289C track skid steer, Caterpillar 279D track skid steer or John Deere 329E track skid steer) with a Fecon FBS1400EXC bunching shear head. Saw cut trees were felled manually with a chainsaw. A Turbo Forest skidder (with 59 horsepower and 9,300 lbs.) was used at the Evans, Lykes and ArborGen Bates sites, in both harvest operations (winter and summer) while the trees at the Estes and Admire sites were hand-skidded, since their size was smaller and the distance to the pile was shorter.

4.2.1 Fecon FBS1400EXC Shear Head

The shear head used for the harvests on this study was a single knife bunching shear head manufactured by Fecon model FBS1400EXC. This equipment has a cutting capacity of 14 inches diameter, and its dimensions are 65 inches high, 48 inches wide and 43 inches deep. The total weight for the shear head is 1,800 lb., and its bunching capacity is 350 square inches. This head is equipped with an accumulator arm, which gives the ability to bunch several trees before dumping, one grabbing arm, one adjustable and moving knife, and one fixed knife, as illustrated in Figure 14. During the harvests, the range of trees cut per bunch was from one to 37. Due the small size of the trees felled at Estes and Admire – Black willow, the operator was able to cut and bunch up to 37 trees per bunch; while on the other sites the trees were larger, creating the need of sometimes cutting and felling one tree at a time. The hydraulic and electric connections of this head fit almost all skid steers models. Although this equipment has one moving and one fixed knife, the operator always allowed the knives to meet very close to the center of the tree when cutting it, leaving a clean cut with minimal damage on the stump.

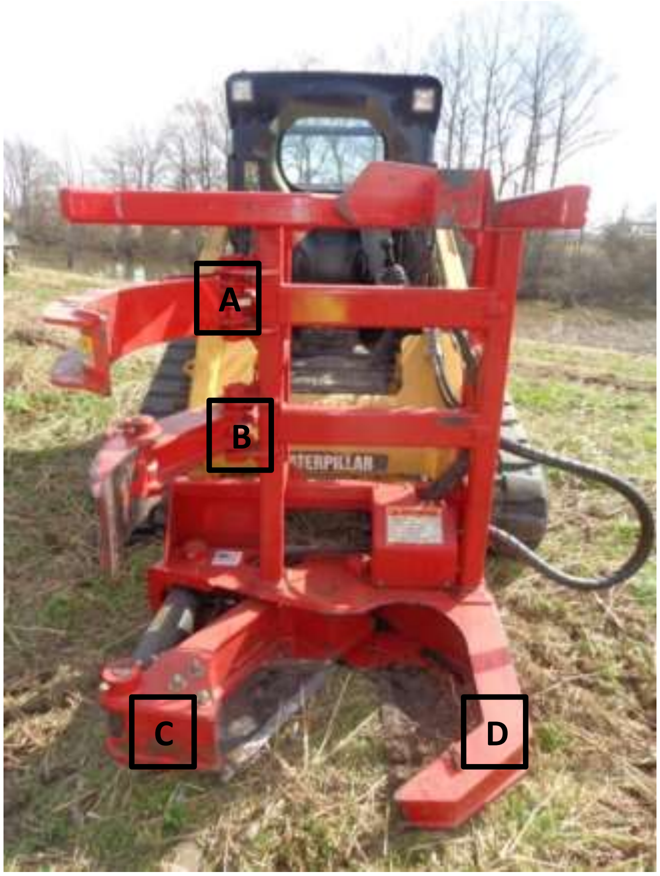

Figure 14: Fecon shear head with (a) grabbing arm, (b) accumulator arm, (c) moving knife, and (d) fixed knife.

4.2.2 Caterpillar 289C

The CAT 289C track skid steer (Figure 15) was used on the winter harvest performed at the Evans, ArborGen and Lykes sites in Florida, and at the Admire site in Mississippi. This is a 10,365 lb. machine, with 78 inches wide, 45 inches width between tracks, and 16.5 inches wide tracks. The ground contact area of this machine is 2,504 square inches, the length of the tracks on the ground is 69.6 inches, and the ground pressure is equivalent to 4.1 lbs/inch^2.

4.2.3 Caterpillar 279D

The CAT 279D track skid steer was used during the winter harvest performed at the Estes site in Arkansas. This machine is very similar to the CAT 289C, with an operational weight of 9,893 lb., a total width of 78 inches, 41 inches wide between tracks, and 18 inches wide tracks. The ground pressure produced by this equipment is equivalent to 4.4 lbs/inch^2, with a ground contact area of 2,272 square inches and a track length of 64.2 inches.

Figure 15: Caterpillar 289C track skid steer used during the winter harvest at Evans, ArborGen, Lykes, and Admire sites.

4.2.4 John Deere 329E

The John Deere 329E track skid steer (Figure 16) was used to perform the summer harvest at all sites. Although this machine is very similar to the CAT equipment, the operator observed that it was faster cutting and moving due to greater hydraulic flow rates. The total operational weight of this equipment is 11,500 lb., with a total machine width of

79 inches, a distance between tracks of 47 inches, and 16 inches wide tracks. The total track length in contact with the ground for this equipment is 63 inches, with a ground contact area of 2,022 square inches, for a total ground pressure of 5.7 lbs/inch^2.

Figure 16: John Deere 329E track skid steer used during summer harvest in all sites.

4.3 Harvesting Methodology

The orientation of the rows (long axis) in the study plots was preferable from east to west to allow full sunlight reception and to minimize light competition. However, due to the small size of most of the sites and some harvesting limitations, the only site where it was possible to install the east-west directional study plot was the Evans site. On the Estes study site, a buffer of one double row at each side of the plot and five to seven trees at the end was cut to minimize light competition, on the other sites the entire plantation was harvested thus eliminating the light competition.

The layout or design of the plantations was fundamental to the selection of the harvesting treatment. The ideal methodology was the completely randomized design, randomly cutting each tree, and controlling the effect of extraneous variables. However, due to physical and spatial limitations, and to facilitate the felling operation, it was not possible to implement the random design. As a consequence, alternating the felling equipment between rows, harvesting one row with the chainsaw and the adjacent row with the shear-head (Figure 17) was the selected experimental design. This methodology was implemented in three of the four sites: ArborGen Bates, Estes and Admire. On both the ArborGen and Admire sites, the harvest was conducted using one type of cut for every other row, while, in the Estes site, since every double row was equivalent to one row, the felling type was alternated every double row. In order to facilitate the felling, bunching and the skidding of the trees, the harvest was performed row after row, alternating the equipment after a row was cut; this was not the most productive methodology; however, the objectives of this project do not focus on productivity, hence it was not an issue.

Figure 17: Alternating rows methodology implemented at most of sites. Each flag color belongs to a felling equipment.

At the Evans site, the layout of the plantation and the 50 feet wide beds produced a difference in yield between rows due to soil quality. If the alternating rows methodology was implemented in this site, there could have been a row effect on the study. Consequently, the methodology used on this site was to harvest five rows (which consist on an entire bed) with one equipment type and then alternate the equipment type on the following bed, thus creating plots consisting of five rows. In this case, the most efficient way to harvest was to cut and bunch the five rows in each treatment with one felling method and then proceed to harvest the following five rows using the alternate felling type, facilitating both the felling and skidding operations.

After completion of the harvest at each site, an evaluation of damage caused to the stump and stump bark was performed. According to studies previously mentioned in this project, bark damage may have a significant effect on the coppice regeneration. For this study, five damage classes were specified, each representing the percentage of the bark of the stump that resulted damaged: 0 (0%), 1 (1-25%), 2 (26-50%), 3 (51-75%), and 4 (>75%). Additionally, the diameter of the stump's cut surface was measured for each stump, to account for the effect that diameter may have on the coppice regeneration. For practical purposes the diameter of cut surface will be called DGL in this project. It was also noted whether the damage to the bark was caused by the felling method or equipment driving over the stumps. Whenever a rubber tire or track mark was noted at the stump, the damage was determined to be caused by the skid steer's track or skidder's tire and not the cutting operation. Harvest damage caused to the stumps was also noted. The type of harvest damage observed were: barber chair, missing chunk(s), fiber pull, split, and shattered stump. Different from the bark damage, the harvest damage was caused to the structural part of the stump, or to the wood, and not to the exterior part.

4.5 Coppice Evaluation

The field evaluation of the coppice response occurred 5 months after the winter harvest and 6 months after the summer harvest. The one-month difference between evaluations appeared to have little impact, since the stumps had sufficient time to regenerate sprouts in both cases. It is important to highlight that from the winter harvest until the measurement date, 147 days with growing conditions past, while 152 growing days past between the summer harvest and the evaluation date. This is relevant for the cottonwood and black willow species but not for the eucalyptus, since it is an evergreen species. The winter harvest of the cottonwood and black willow occurred in late winter/beginning of spring, and buds were already visible in some of the felled trees.

For the coppice evaluation, each stump was individually analyzed. If the stump presented any new stems regenerated, it was recorded as a live stump. However, if it had no new stems it was recorded as a “dead” stump. The number of new stems regenerated was counted at each stump. If the sprout was regenerated directly from the stump, it was counted, but if it was regenerated from the base of another sprout, it was not counted. Additionally, the height of each stump’s dominant sprout was noted. A dominant sprout was the tallest one among all the sprouts in the same stump.

4.6 Data Analysis

The data analysis for this project used statistical tools, charts and tables to determine the effects that the independent variables (felling equipment, harvest season, and bark and stump damage) have on the dependent variables (coppice response), which were classified as the coppicing ability (or stump survival) and the number of new stems regenerated per stump. Additionally, DGL and skidder damage (when existing) were considered, since they could be related to coppicing ability of the cut trees. R Software (V3.1.2 for Windows) was used to perform the analysis. The Generalized Linear Mixed Model (GLMM) analysis was used to compare the coppicing response of the stumps. The results presented at this study are supported by the appropriate statistical tests resulted from the "glmer" function of package "lme4" from R. The supporting statistics consist of z-values with the associated p-values, obtained from Wald Z tests, which are recommended for analysis of this type (Bolker et al., 2008; Bolker, 2015; Bates, 2006; Unpublished; Berridge and Crouchley, 2011).

Although each stump was individually evaluated, due the experimental design, the harvesting methodology, and the layout of the study plots, a random effect of rows nested into plot was accounted for the Evans and Lykes sites, while a random effect of rows was accounted for at the other sites. As a consequence, plots (for Evans and Lykes) and rows (for the other sites) were considered as the experimental unit, and not the stump. The variable "coppicing ability" was a binary variable, evaluated according to the successful coppicing or not by the stump, being labelled as zero (0) or one (1) depending on the response. As a result, this variable falls into the "binomial" family structure for analysis with the GLMM procedure. On the other hand, the variable "number of new stems regenerated" was evaluated according to the number of new sprouts grown after the harvest. It was a continuous variable that fell into the "poisson" family structure for the analysis with the GLMM procedure. Each study site was individually analyzed, with the utilization of a full model.

Table 1: Models used to determine the felling techniques on coppice regeneration.

Site	#	Model
Evans	1	$CR \sim FM/S + Dam + FM{:}Dam + DGL + HD + SD + (1 \mid Plot/Row)$
	2	$NS \sim FM/S + Dam + FM{:}Dam + DGL + HD + SD + (1 \mid Plot/Row)$
Lykes	3	$CR \sim FM + Dam + FM{:}Dam + DGL + HD + SD + (1 \mid Plot/Row)$
	4	$NS \sim FM + Dam + FM{:}Dam + DGL + HD + SD + (1 \mid Plot/Row)$
Estes	5	$CR \sim FM/S + Dam + FM{:}Dam + DGL + HD + (1 \mid Row)$
	6	$NS \sim FM/S + Dam + FM{:}Dam + DGL + HD + (1 \mid Row)$
Admire	7	$CR \sim FM/S + Dam + FM{:}Dam + DGL + HD + (1 \mid Row)$
	8	$NS \sim FM/S + Dam + FM{:}Dam + DGL + HD + (1 \mid Row)$

CR=Coppice regeneration
S=Season (winter and summer)
FM=Felling Method (shear and chainsaw)
Dam=Bark Damage Class
DGL=Diameter at Ground Level (inch)
HD=Harvest Damage Type
SD=Skidder Damage
NS=Number of New Sprouts
: = Interaction between

The same variables were included in all the models, with exclusion of *SK* which was only present on the eucalyptus sites. Since the objectives of the project are to determine the effects of harvesting techniques on coppice regeneration, a model selection was not necessary, only utilizing the full model to determine the variables that affected the regeneration of coppice. Although all models included all the variables studied in this project, only the effects of variables that resulted statistically significant are explained and addressed in the results chapter. If a variable did not have significant effect on coppice regeneration, it was not explained in the results chapter. However, a summary table with the p-values of all variables included in the models is displayed for each species studied on this project.

V. Results and Discussions

After the coppice evaluation, it was decided that the Bates study site would not be included on the analysis. Although this site was planted with the same clone and the trees were the same age as the trees at Evans, and the harvest was performed at the same time and with the same equipment, the survival rate was below 30% for each season. No logical explanation was found for this behavior, with possible reasons being herbicide application or height of cut. Freeze damage was discarded since the summer harvest showed similar survival to the winter harvest. In addition to the Bates site, a summer effect could not be determined at the Lykes site, since the summer harvest was not performed. The trees at Lykes were larger than expected, with some reaching the shear head capacity of 14 inches, causing problems to its operation. For this reason, it was decided not to perform the summer harvest. However, a comparison between felling methods was performed for the winter harvest. Although the effect of season on coppice regeneration was calculated for all study sites, and the results are reported, the experimental design of the plots was not the ideal. Hence, it can be inferred that the results presented for the effects of season on coppice regeneration can be suggested but not considered definitive.

It is important to have knowledge about the mean DGL and bark damage distribution of each study site before studying the dependent variables, since they both could have an effect on the coppicing ability (Hytonen, 1994, 1996, 2001; Simões et al., 1972; Ducrey and Turrel, 1992; Strong and Zavitovski, 1983; De Souza et al., 1991). Consequently, a diameter distribution of the stumps DGL was developed for each study site to better illustrate this parameter. In addition, the stump bark damage was classified by felling method for each study site, resulting in the creation of a bark damage distribution for each felling type.

5.1 Eucalyptus sites

5.1.1 Evans Properties

The average DGL of the trees was 5.2 inches, with a minimum of 1.3 and a maximum of 9.5 inches, while the Basal Area (BA) was calculated to be 103.0 ft^2. Descriptive statistics for the DGL are listed by season and equipment in Table 2. The larger mean DGL for the trees cut during the summer harvest may be attributed to the 5 months difference between the harvests in which the trees had more time to grow.

Table 2: Key statistics of the DGL of harvested eucalypt trees at Evans.

	N	Mean DGL (inch)	Max DGL (inch)	Min DGL (inch)	Standard Deviation
Summer					
Saw	210	5.4	7.7	2.4	1.1
Shear	209	5.7	9.5	1.3	1.3
Total	**419**	**5.5**			
Winter					
Saw	198	4.7	6.8	1.8	1.1
Shear	211	4.9	7.6	2.2	1.0
Total	**409**	**4.8**			
Overall	**828**	**5.1**			

The DGL distribution showed a normal distribution, in which the majority of the harvested trees had a diameter on the range of the mean DGL value (Figure 18). This corresponded to the observed homogeneity of the plantation.

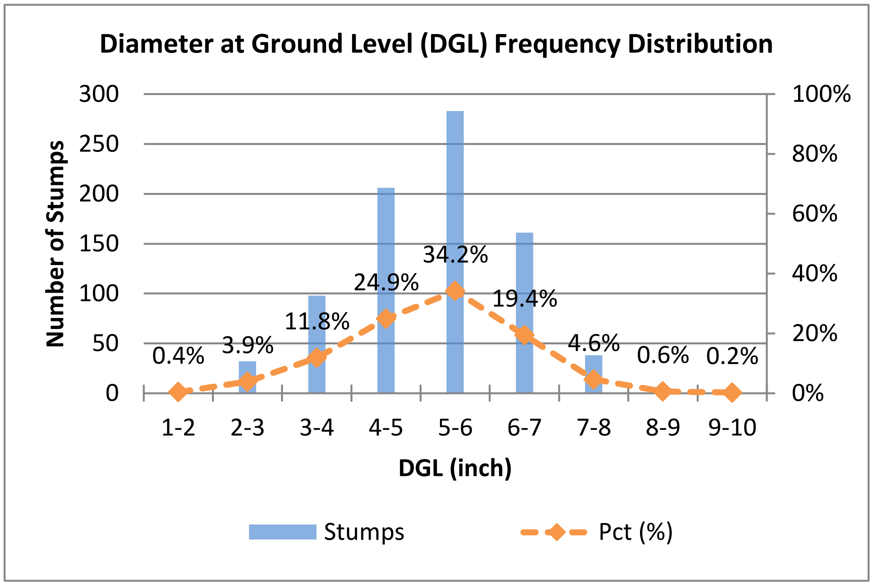

Figure 18: Frequency Distribution chart of the Diameter at Ground Level (DGL) of eucalypt trees harvested at the Evans Properties study site.

A summary of the bark damage caused to the stumps is presented in Table 3. The total number of stumps cut with shear was slightly higher than the stumps cut with saw. The majority of the stumps for both equipment types fell within the bark damage classes 0, 1 and 2. However, the shear head generally caused more damage to the bark of the stumps than the saw. On bark damage classes 0, 1 and 2, sawed stumps were present in higher numbers than sheared stumps; while in bark damage classes 4 and 5, sheared stumps were present in higher numbers.

Table 3: Bark damage distribution of the stumps cut at Evans, by felling method.

	0	1	2	3	4	Overall
Saw						
Summer	19	89	50	28	24	210
Winter	16	56	64	34	28	198
Total	**35**	**145**	**114**	**62**	**52**	**408**
Shear						
Summer	2	45	48	53	62	210
Winter	18	68	62	28	37	213
Total	**20**	**113**	**110**	**81**	**99**	**423**
Overall	**55**	**258**	**224**	**143**	**151**	**831**

5.1.2 Lykes Ranch

The mean DGL of trees cut at this site was 7.4 inches, ranging from 2.5 to 13.2 inches. The BA for the winter harvest was calculated to be 31.4 ft^2. Descriptive statistics for the DGL of the harvested trees are summarized in Table 4.

Table 4: Key statistics of the DGL of harvested eucalypt trees at Lykes

Equipment	N	Mean DGL (inch)	Max DGL (inch)	Min DGL (inch)	Standard Deviation
Saw	59	7.2	11.9	3.0	2.1
Shear	46	7.8	13.2	2.5	2.6
Overall	**105**	**7.4**			

The DGL frequency distribution of the harvested trees shows a normal distribution (Figure 19), in which the majority of the harvested trees were present in the center of the distribution (around the mean DGL) with low number of trees present on the edges. However, due to the wide variation of the DGL (ranging from 2 to 13 inches), the distribution was spread over all the DGL classes.

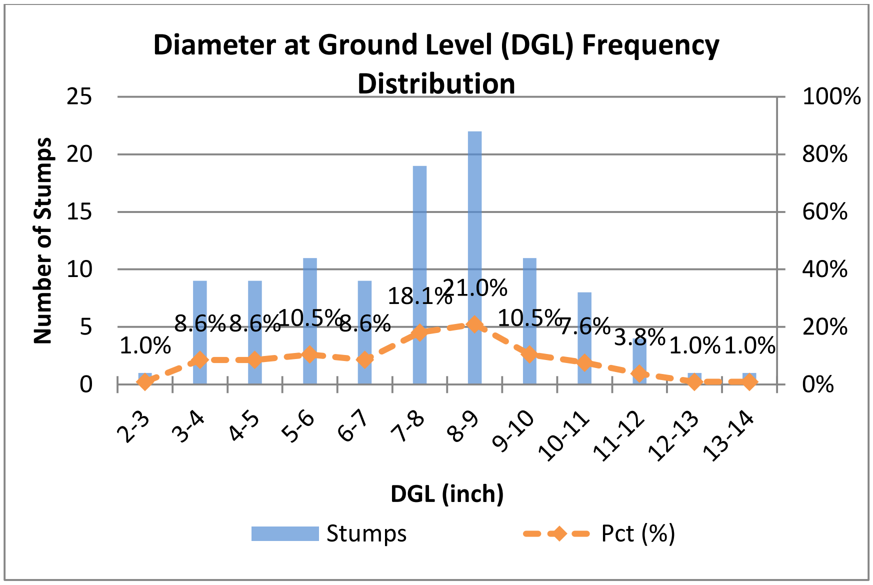

Figure 19: Frequency Distribution chart of the DGL of eucalypt trees harvested at Lykes Ranch study site.

Compared to the other sites, the difference in total number of harvested trees between the two felling equipment was not large; however, since the total number of harvested trees was considerably lower than in other sites, the percentage difference between the number of harvested trees by each felling equipment was higher, almost 12%. Of the 105 felled trees, 59 were felled using the chainsaw and 48 with the shear head (Table 5).

Table 5: Bark damage distribution of the stumps cut at Lykes, by felling method.

	Stumps' Bark Damage Class					
Equipment	**0**	**1**	**2**	**3**	**4**	**Total**
Saw	1	21	20	7	10	**59**
Shear	0	7	20	11	8	**48**
Total	**1**	**28**	**40**	**18**	**18**	**105**

5.1.3 Effects of felling method and season on eucalypt coppice regeneration

The effects of the felling method and season on coppicing regeneration of eucalypt were determined using the previously described statistical models 1 and 2, at Evans, and 3 and 4, at Lykes Ranch (Table 6). Models 1 and 3 were used to determine the effects on stump survival, while models 2 and 4 were used to determine the effects on the number of sprouts regenerated per stump.

The significance of the factors were determined at α = 0.05. A summary of the significant p-values for the felling method and harvest season effect on coppice regeneration of the eucalypt sites is displayed in Table 6.

Table 6: P-values for effects of felling method and season on coppice regeneration of eucalyptus plantations, with significant ones highlighted.

Site	Season on stump survival	Season on number of sprouts/stump	Felling method on stump survival	Felling method on number of sprouts/stump
Evans	0.00781	0.7749	0.15988	0.0792
Lykes	N/A	N/A	0.995	0.841460

The ANOVA analysis of model 1, used at Evans, proved it to be significant at α = 0.05. The ANOVA table (Table 7) shows that the predictor variables included in this model are related to stump survival.

Table 7: Analysis of Variance for Model 1 used at Evans

	Df	Deviance	Chi Squared	Chi Df	P-value
Model 1	16	466.96	29.395	12	0.003441
Null model	4	496.36			

Model 1:

$$\boldsymbol{CR \sim FM/S + Dam + FM{:}Dam + DGL + HD + SD + (1 \mid Plot/Row)}$$

The ANOVA analysis of model 2, used at Evans, proved it to be significant at α = 0.05. The ANOVA table (Table 8) shows that the variables included in this model are related to the variability of the regeneration of sprouts per stump.

Table 8: Analysis of Variance of Model 2; used at Evans.

	Df	Deviance	Chi Squared	Chi Df	P-value
Model 2	16	2910.1	40.54	12	5.849^{-5}
Null model	4	2950.6			

Model 2:

$$\boldsymbol{NS \sim FM/S + Dam + FM{:}Dam + DGL + HD + SD + (1 \mid Plot/Row)}$$

At the Evans site a total of 409 trees were cut during the winter harvest and 419 during the summer harvest. Figure 20 displays the harvest season effect on the coppicing ability, where 96% of the trees felled during the winter harvest successfully regenerated new sprouts, while only 79% of the trees felled during the summer harvest regenerated new sprouts. Although eucalypt is an evergreen species, and the literature review mentioned it could coppice regardless of the season, the winter harvest presented better survival rate than the summer. This pattern may be explained with the fact that the period of rain in south Florida occurs during summer, and although eucalypt is an evergreen species, it may store higher levels of carbohydrates during the drought period, maximizing the regeneration of coppice if harvest occurs during winter.

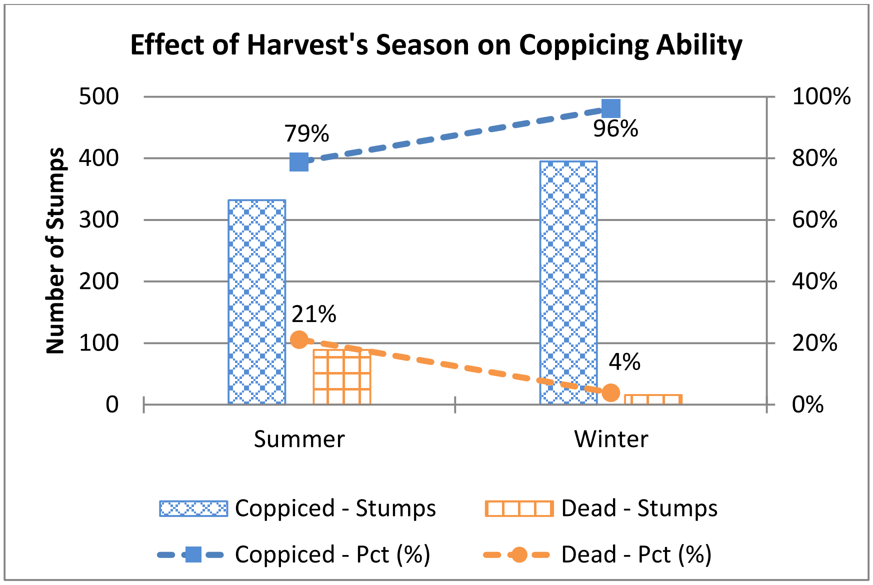

Figure 20: Effect of season on stump survival of eucalypt harvested at Evans.

According to the GLMM analysis, the trees cut during the winter harvest were 21.3 (19.1 – 23.6; 95% C.L.) times as likely to regenerate coppice as trees cut during the summer harvest (Table 9).

Table 9: Model results of Model 1 used at Evans. Details obtained from GLMM procedure. Significant variables were found at α = 0.05.

	Estimate (odds ratios)	Std. Error	z-value	P-value
Intercept	21.327	1.08798	2.706	0.00682
[1]Winter	17.993	1.11342	2.879	0.00398
[2]Bark damage	0.535797	0.2179	-2.863	0.00419
[3]Shear:Damage	2.134644	0.2726	2.781	0.00541

[1] Compared to summer.

[2] Bark damage classes.

[3] Interaction between shear head and bark damage.

5.1.4 Other factors affecting coppice regeneration of eucalypt

For the effects of DGL, bark and stump damage, and resulting interactions on the coppice regeneration of eucalypt, models 1 and 2, were used at Evans, and 3 and 4 were used at Lykes. A summary of the p-values for the variables above mentioned is presented in Table 10, with the significant at α = 0.05 highlighted.

Table 10: P-values for effects of DGL, bark and stump damage, and skidder on coppice regeneration of eucalyptus plantations, with significant variables highlighted.

Stump survival						
Site	DGL	Bark damage	Stump damage	Seas:Equip	Equip:Barkdam	Skidder
Evans	0.71721	0.00417	0.63962	0.24139	0.00540	0.60259
Lykes	0.101	0.729	0.309	N/A	0.637	0.675

Number of sprouts/stump						
Site	DGL	Bark damage	Stump damage	Seas:Equip	Equip:Barkdam	Skidder
Evans	5.43e-06	0.2500	0.1488	0.8156	0.4526	0.7945
Lykes	1.77e-08	0.106615	0.321423	N/A	0.144492	0.166956

The effect of the bark damage on the stump survival of eucalypt trees from Evans is illustrated in Figure 21. Higher damage on the bark of the stump negatively affected the ability to coppice. In total, 55 trees felled were classified under the bark damage class 0 and 52 (95%) of those trees successfully regenerated coppice; while 151 of trees felled were classified under the bark damage class 4 and only 125 (83%) of those trees were successful in regenerating coppice. This is probably because the axillary buds that regenerate sprouts in eucalypt trees are located under the bark, and damaging the bark may damage or expose those buds, affecting the coppice regeneration.

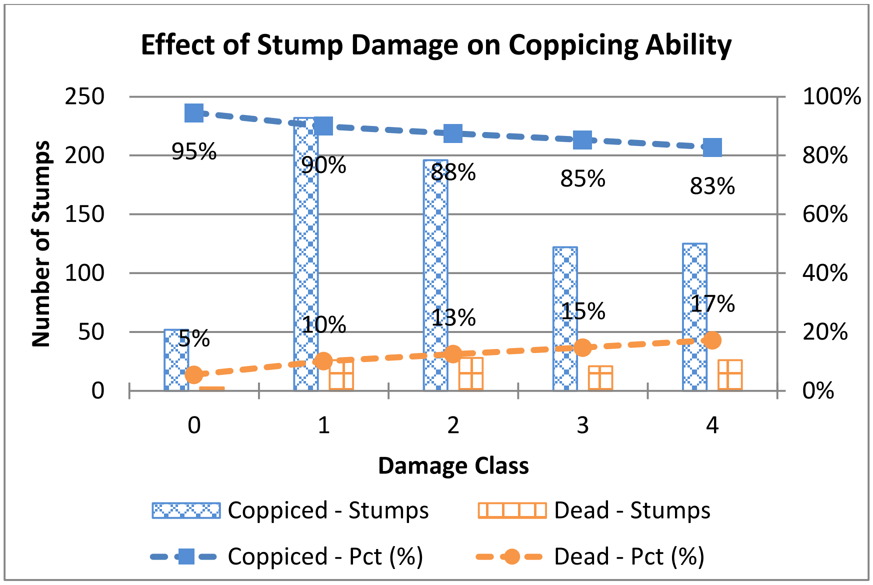

Figure 21: Effect of the bark damage on the stump survival of eucalypt trees harvested at Evans.

According to the statistical parameters obtained with the GLMM procedure, stumps without bark damage were 0.54 (0.11 – 0.96; 95% C.L.) times as likely to coppice as stumps with bark damage (previously presented in Table 9). This indicated that increasing bark damage negatively affected coppicing ability of eucalypt trees at Evans.

In addition to the bark damage, a significant effect of an interaction between the shear and the bark damage was detected at Evans. For trees cut with the shear head, not causing damage to the bark resulted in 100% of coppice regeneration (Figure 22). However, the results showed that when bark damage was present at higher levels (class 4) the stumps survival rate was higher than when damage was moderate (classes 2 and 3) and as much as when damage was low (class 1). On the other hand, for stumps cut with the chainsaw, stumps with bark damage class 4 had lower survival rates than the stumps with the other damage classes. Inferring that when cutting with the chainsaw, higher bark damage affects the stump survival, while when cutting with the shear head higher bark damage may have similar effects that when damage is low.

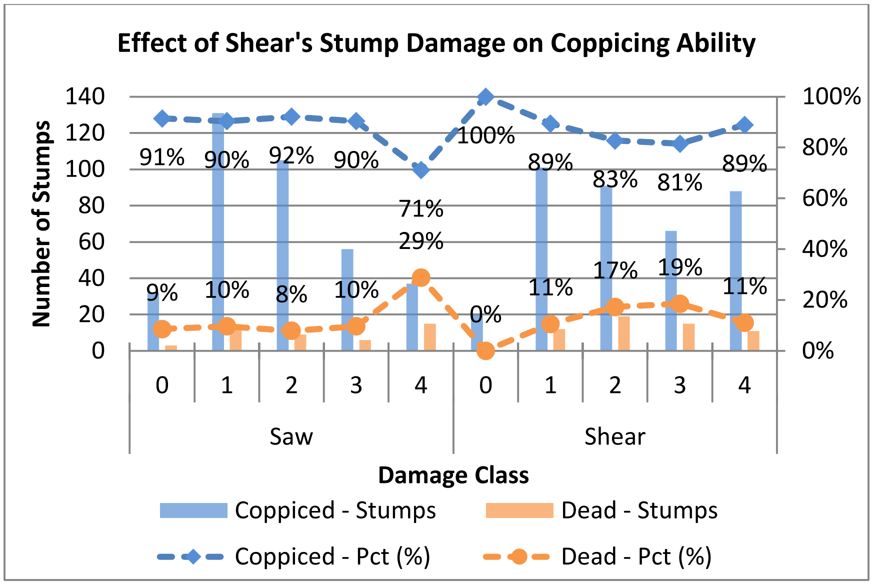

Figure 22: Effect of the interaction between shear head and bark damage, affecting the survival of the stumps at Evans site.

After analyzing the model with the GLMM procedure, the conclusion was that stumps harvested with the shear head were 2.13 (1.60 – 2.67;95% C.L.) as likely to coppice when bark damage was severe as stumps cut with the chainsaw and with severe bark damage. The model results are summarized above in Table 9.

The number of sprouts regenerated per stump resulted statistically significantly affected by the DGL at the Evans site. Stumps with larger diameters generally regenerated a larger number of sprouts (Figure 23). Smaller stumps, with DGL range between 1 – 2, regenerated an average of 3 sprouts per stump, and larger stumps, with DGL on the range between 8 – 9, averaged 6.7 sprouts per stump regenerated. This pattern was expected, due the higher number of buds on larger stumps.

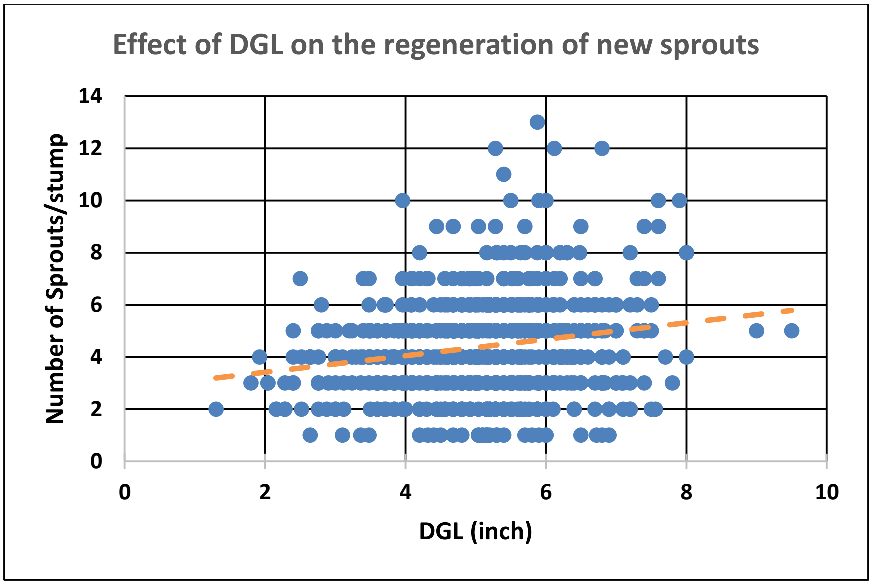

Figure 23: Scatter plot of the effect of DGL on the number of sprouts per stump on Evans.

The GLMM procedure indicates that for each 1 inch increase in DGL, stumps regenerated 1.09 (1.06 – 1.13; 95% C.L.) times as many new sprouts. Model results to support this conclusion are summarized in Table 11. The ANOVA table for this model (Table 8) was previously shown and proved the model to be significant explaining the number of sprouts per stump.

Table 11: Model 2 details obtained from GLMM procedure, for the effect of DGL on number of sprouts per stump in eucalypt at Evans.

	Estimate (odd ratios)	**Std. Error**	**z value**	**P-value**
Intercept	3.052863	0.119211	9.362	0.00001
[1]DGL	1.095588	0.018443	4.950	7.42^{-7}

[1]Diameter of the stump at cut level, in inches.

On the other hand, the DGL of the eucalypt trees cut at Lykes was the only variable that showed significant effect on coppice regeneration, affecting the number of sprouts per stump (p-value: 0.0001).

Figure 24 illustrates how the DGL had an impact on the number of sprouts regenerated per stump. There is a positive linear relation between number of new sprouts regenerated and the DGL. The smaller stumps at Lykes, with DGL between 2 – 4 inches, regenerated an average of 4.4 new sprouts, while the larger stumps, with DGL between 10 – 12 inches, regenerated an average of 13.8 sprouts.

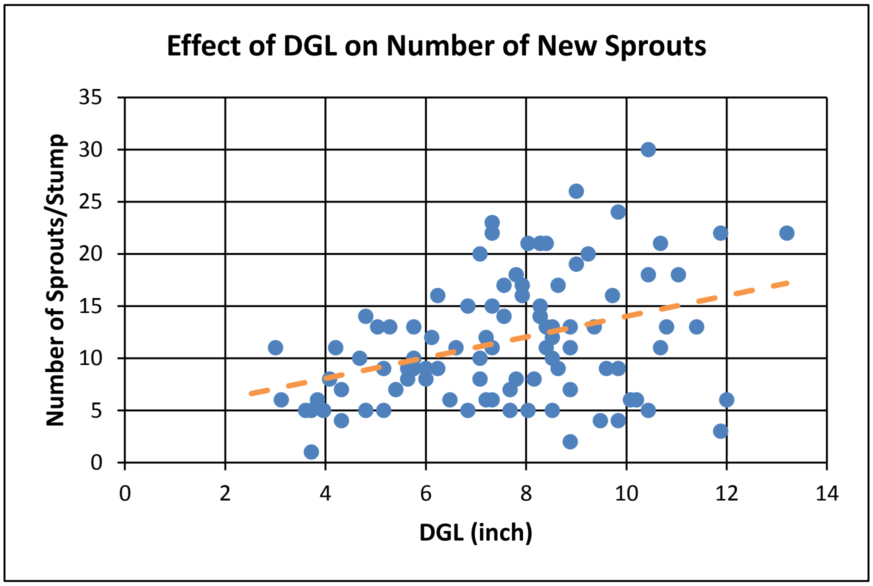

Figure 24: Scatter plot of the effect of DGL on the number of sprouts per stump on Lykes.

The ANOVA table (Table 12) summarizes that the predictor variables included in model 4 proved to be significant in the number of sprouts regenerated per stump at the Lykes site.

Table 12: Analysis of Variance of Model 4, used at Lykes.

	Df	Deviance	Chi Squared	Chi Df	P-value
Model 4	14	621.90	54.223	11	1.075^{-7}
Null model	3	676.13			

Model 4:

$$\boldsymbol{NS \sim FM + Dam + FM{:}Dam + DGL + HD + SD + (1 \mid Plot/Row)}$$

The GLMM procedure indicated that for eucalypt trees cut at Lykes, for each 1 inch increase on stump diameter, stumps regenerated 1.10 (1.07 – 1.13; 95% C.L.) as many sprouts. The results from the Model 4 used at this site are listed in Table 13, supporting this conclusion.

Table 13: Model 4 details obtained from GLMM procedure, in eucalypt site at Lykes. Significant variables found at $\alpha = 0.05$.

	Estimate (odd ratios)	**Std. Error**	**z value**	**P-value**
Intercept	5.063561	0.19727	8.223	0.00001
[1]DGL	1.097791	0.01643	5.679	1.35^{-8}

[1] Diameter of the stump at cut level, in inches.

5.2 Cottonwood sites

5.2.1 Estes

The mean DGL for trees felled on the site was 1.9 inches, ranging from 0.4 to 4.8 inches (Table 14). The BA was calculated at 12.7 ft^2. Similarly to the other sites, the DGL of trees harvest during summer was larger than the DGL of trees harvested during winter, due to the 3 months difference between the harvests.

Table 14: Key Statistics of the DGL of harvested cottonwood trees at Estes.

	N	Mean DGL (inch)	Max DGL (inch)	Min DGL (inch)	Standard deviation
Summer					
Saw	225	2.2	4.8	0.4	0.8
Shear	200	2.1	3.7	0.5	0.7
Total	**425**	**2.1**			
Winter					
Saw	201	1.7	3.3	0.4	0.7
Shear	177	1.7	3.5	0.5	0.6
Total	**378**	**1.7**			
Overall	**803**	**1.9**			

The DGL frequency distribution for trees harvested at this site also showed a normal shape (Figure 25). The majority of the harvested trees had a DGL in the range of the mean DGL.

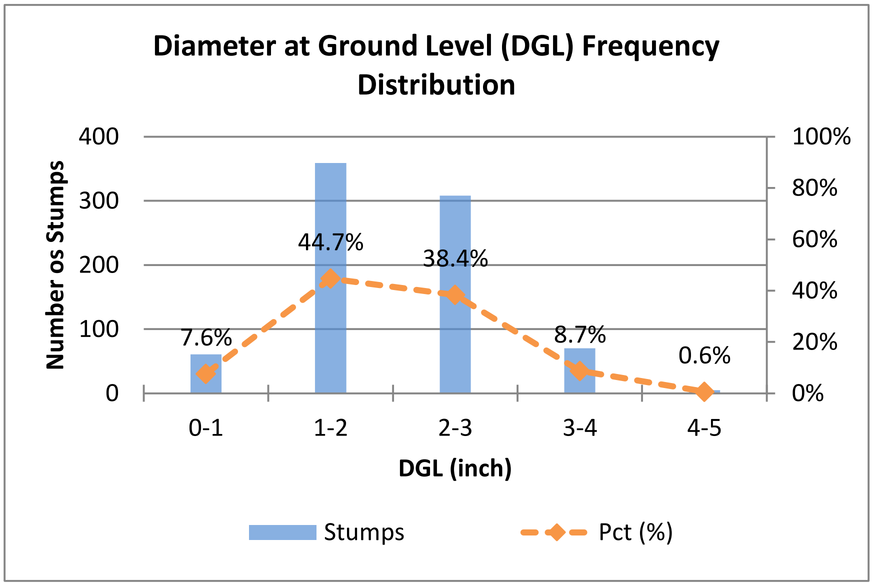

Figure 25: Frequency Distribution chart of the DGL of cottonwood trees harvested at Estes.

The damage caused to the bark was higher when the harvest was performed with the shear head. Approximately 89% of the trees cut with the chainsaw had bark damage classified under class 0, while only 11% of trees cut with the shear head were classified in the bark damage class 0 (Table 15). However, despite the number of stumps cut with the shear head with no bark damage was low, most of the sheared stumps were classified under class damage 1 and 2. This indicates that while damage was more frequent it was minimal.

Table 15: Bark damage distribution of the stumps cut at Estes, by felling method.

	0	1	2	3	4	Overall
Saw						
Summer	182	39	3	1	0	225
Winter	175	18	6	0	2	201
Total	**357**	**57**	**9**	**1**	**2**	**426**
Shear						
Summer	16	53	54	32	45	200
Winter	28	59	47	24	21	179
Total	**44**	**112**	**101**	**56**	**66**	**379**
Overall	**401**	**169**	**110**	**57**	**68**	**805**

5.2.2 Admire Cottonwood

The DGL averaged 4.6 inches for this site, with a minimum of 1.3 inches and a maximum of 11.2 inches, and the calculation of the BA resulted in 36.3 ft^2. The mean DGL of trees harvested during both harvest showed similar results: trees harvested during winter averaged 4.7 inches, while trees harvested during summer averaged 4.5 inches. Some key statistics about the DGL are presented in Table 16.

Table 16: Key statistics of the DGL of harvested cottonwood trees at Admire site.

	N	Mean DGL (inch)	Max DGL (inch)	Min DGL (inch)	Standard Deviation
Summer					
Saw	79	4.5	8.2	2.1	1.4
Shear	67	4.4	9.1	2.0	1.7
Total	**146**	**4.5**			
Winter					
Saw	67	4.5	8.0	1.3	1.5
Shear	88	4.8	11.2	1.7	2.2
Total	**155**	**4.7**			
Overall	**301**	**4.6**			

The frequency distribution of the DGL of harvested trees is illustrated in Figure 26. The distribution is slightly skewed to the right, with a fewer number of trees with DGL below the mean; however, it is possible to observe that the majority of the harvested trees are located in the mean DGL class, and in the classes immediately next to the mean class.

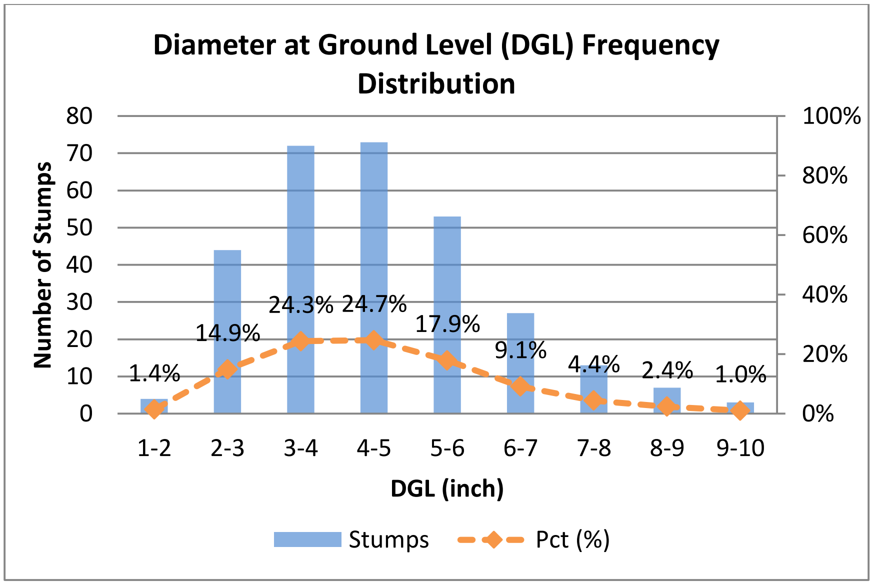

Figure 26: Frequency Distribution chart of the DGL of cottonwood trees harvested at Admire.

Most stumps at this site were not damaged. Table 17 shows that for trees cut with both felling equipment, about 70% of them did not receive damage on their bark.

Table 17: Bark Damage distribution of the cottonwood stumps cut at Admire, by felling method.

	0	1	2	3	4	Overall
Saw						
Summer	40	29	9	0	1	79
Winter	63	3	1	0		67
Total	**103**	**32**	**10**	**0**	**1**	**146**
Shear						
Summer	48	15	2	1	1	67
Winter	64	20	3	0	1	88
Total	**112**	**35**	**5**	**1**	**2**	**155**
Overall	**215**	**67**	**15**	**1**	**3**	**301**

5.2.3 Effects of felling method and season on cottonwood coppice regeneration

The models used to determine the effect of felling method and season of year on coppice regeneration of cottonwood trees at Estes were Model 5 and 6, while Model 7 and Model 8 were used to analyze the Admire site. Model 5 and 7 were used to determine the effects of the factors on stump survival, while Model 6 and 8 were used to determine the effects of the factors on the number of sprouts per stump. Table 18 summarizes the significance at α = 0.05 of the factors felling method and season included in the models.

Table 18: P-values for the effect of felling method and season on coppice regeneration of cottonwood plantations, with significance highlighted.

Site	Season on stump survival	Season on number of sprouts/stump	Felling method on stump survival	Felling method on number of sprouts/stump
Estes	0.000372	0.4913	0.081431	0.3139
Admire	0.9982	0.0698	0.0762	0.0350

The ANOVA analysis of Model 5, used at the Estes study site, proved it to be significant at α = 0.05. The ANOVA table presented below (Table 19) supports this conclusion, proving that the variables included explain cottonwood stumps survival.

Table 19: Analysis of Variance of Model 5 used at Estes

	Df	Deviance	Chi Squared	Chi Df	P-value
Model 5	12	516.37	27.992	9	0.0009567
Null model	3	544.36			

Model 5:

$$CR \sim FM/S + Dam + FM{:}Dam + DGL + HD + (1 \mid Row)$$

Among all the study sites, the season effect was most noticed at the Estes site. The season variable was the only significant variable on the stump survival at this site (p-value: 0.000372). A total of 803 trees were cut during the harvests. As Figure 27 illustrates, 98% of trees harvested during the winter were successful in regenerating coppice, while only 49% of trees harvested during summer regenerated coppice. Performing the harvest during the summer negatively affected the coppicing ability of more than 50% of the stumps.

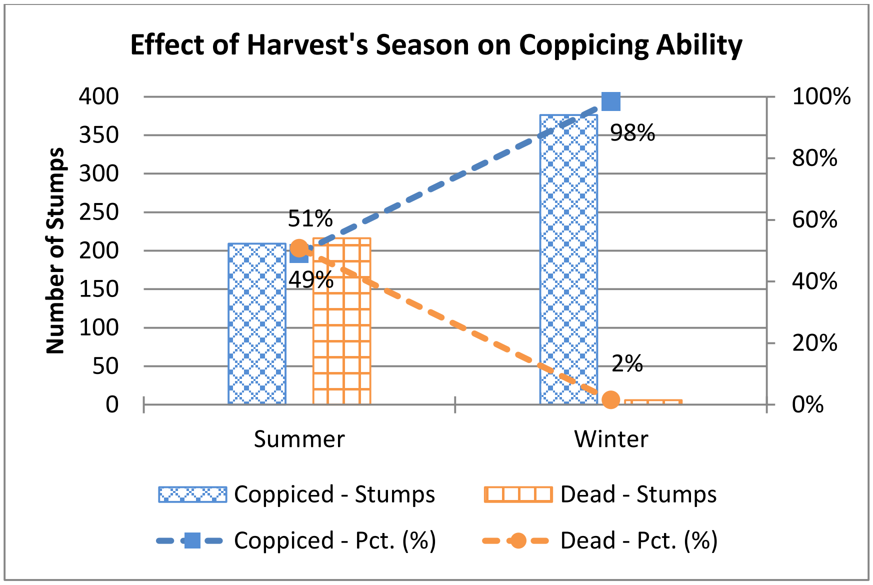

Figure 27: Effect of harvest season on the survival of cottonwood stumps at Estes.

According to the GLMM procedure performed on the effect of season on coppicing ability, trees cut during the winter harvest were 15.49 (13.99 – 17.00; 95% C.L.) times as likely to regenerate coppice after the harvest as trees cut during summer harvest. Model results supporting this conclusion are listed in Table 20.

Table 20: Model 5, used in Estes analysis to determine effect on stump survival. Details obtained from GLMM procedure.

	Estimate (odd ratios)	**Std. Error**	**z value**	**P-value**
Intercept	3.637149	0.5812	2.222	0.026306
[1]Winter	15.49473	0.7699	3.559	0.000372
[2]Winter:Shear	33.72367	1.4759	2.384	0.017135
[3]Shear:Damage	0.4038951	0.4223	-2.147	0.031821

[1]Compared to summer
[2]Interaction between winter and shear head
[3]Interaction between shear and bark damage

On the other hand, the felling equipment had a significant effect on the number of new sprouts per stump of felled cottonwood at the Admire site (p-value: 0.0350). The

ANOVA analysis of the Model 8, used to determine this effect, showed that the included factors are related to the number of sprouts per stump (Table 21).

Table 21: Analysis of Variance of Model 8 used at Admire planted with cottonwood

	Df	Deviance	Chi Squared	Chi Df	P-value
Model 8	12	1277.5	127.79	9	0.0001
Null model	3	1405.3			

Model 8:

$$\boldsymbol{NS \sim FM/S + Dam + FM{:}Dam + DGL + HD + (1|Row)}$$

On average, stumps cut with the shear head regenerated 5.7 sprouts, while stumps cut with the chainsaw regenerated 4.7 sprouts. Although sheared stumps regenerated more sprouts per stump, there is no certainty of the importance of regenerating more sprouts. The GLMM procedure indicated that stumps cut with the shear head regenerated 1.22 (1.03 – 1.40; 95% C.L.) times as many sprouts as stumps cut with the chainsaw (Table 22).

Table 22: Model 8, used in analysis of number of sprouts per stump of cottonwood at Admire. Details obtained from GLMM procedure.

	Estimate (odd ratios)	Std. Error	z value	P-value
Intercept	2.525452	0.09995	9.269	0.0001
[1]Shear	1.219365	0.09408	2.108	0.0350
[2]DGL	1.161172	0.01424	10.495	0.0001

[1] Compared to the chainsaw

[2] Diameter of stump at cut level, in inches

5.2.4 Other factors affecting coppice regeneration of cottonwood

To determine the effects of DGL, bark and stump damage, and pertinent interactions on the coppice regeneration of cottonwood, models 5 and 6 were used at the Estes site and models 7 and 8 were used at the Admire site. Model 5 and 7 were used to determine the factors affecting stump survival, while Model 6 and 8 were used to determine factors affecting number of sprouts per stump. Table 23 presents the significance (p-value) of each factor on coppice regeneration. Significance was determined at α = 0.05.

Table 23: P-values for the effect of DGL, bark and stump damage, and interactions on coppice regeneration of cottonwood plantations, with significance highlighted.

			Stump survival		
Site	DGL	Bark damage	Stump damage	Seas:Equip	Equip:Barkdam
Estes	0.342348	0.183808	0.995610	0.017135	0.031821
Admire	0.0073	0.2692	0.9997	0.9983	0.0523
			Number of sprouts/stump		
Site	DGL	Bark damage	Stump damage	Seas:Equip	Equip:Barkdam
Estes	0.0001	0.9094	0.0732	0.1488	0.3093
Admire	0.0001	0.7340	0.1641	0.7031	0.8142

The analysis of variance performed to Model 5, used at the Estes study site, showed significant relation with the stump survival, at α = 0.05, as already mentioned earlier (Table 19).

In addition to the season, a significant effect, at level α = 0.05, was observed for an interaction between harvest season and felling method (p-value: 0.017135) and for an interaction between felling method and bark damage (0.031821) on the stump survival of cottonwood at Estes.

The interaction between the shear head and the season is graphically illustrated in Figure 28. Despite the stumps survival rates being higher when harvest is performed during winter, the difference between shear-winter harvest and shear-summer harvest is considerably large and inverse. In all treatments, the survival rate of the stumps was higher than the mortality rate, however on the case of the shear-summer harvest the survival rate was only 26%, with remaining 74% of the stumps considered dead or not coppiced. On the other hand, the survival rate of the shear stumps felled during winter was 99%. This means that the season effect observed, and previously mentioned, is highly explained by the interaction between the shear head and the season.

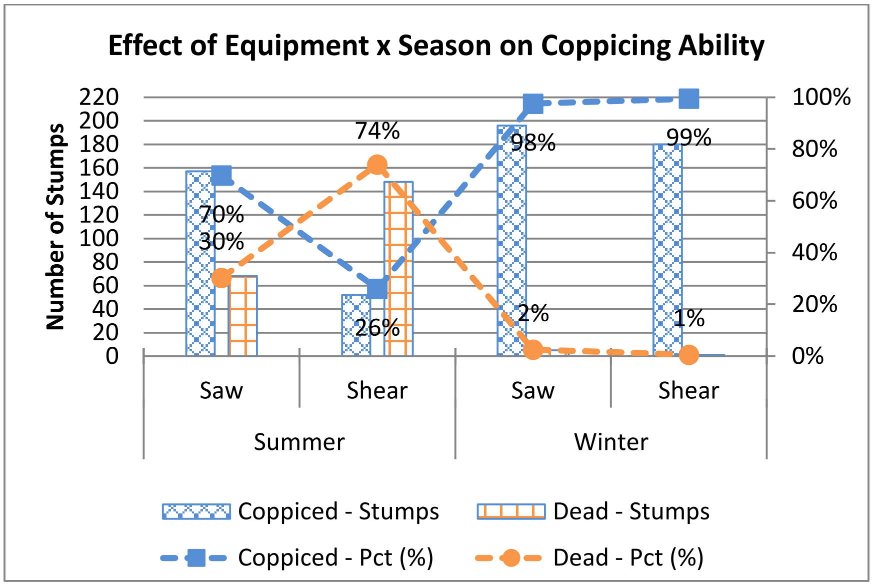

Figure 28: Interaction between the felling equipment (shear head) and harvest season (winter) on the effect of stump survival at Estes.

As indicated by the GLMM procedure, the stumps cut with the shear head during the winter were 33.7 (30.83 – 36.62; 95% C.L.) times as likely to regenerate coppice as stumps cut with the shear head during the summer. Model results to support this conclusion are listed in Table 20.

The interaction between the shear head and the bark damage was another interaction determined to be significant on the survival of cottonwood stumps at Estes. Figure 29 compares the effects of the bark damage on stump survival when felling with the shear head and when felling with the chainsaw. Stumps felled with the chainsaw had less damage on their bark, when compared to shear stumps. Additionally, the few number of stumps cut with the chainsaw that had bark damage were highly successful in coppicing, while the coppicing success of the stumps cut with shear head had a negative linear relation with bark damage; the more severe damage, the lower the survival rate resulted.

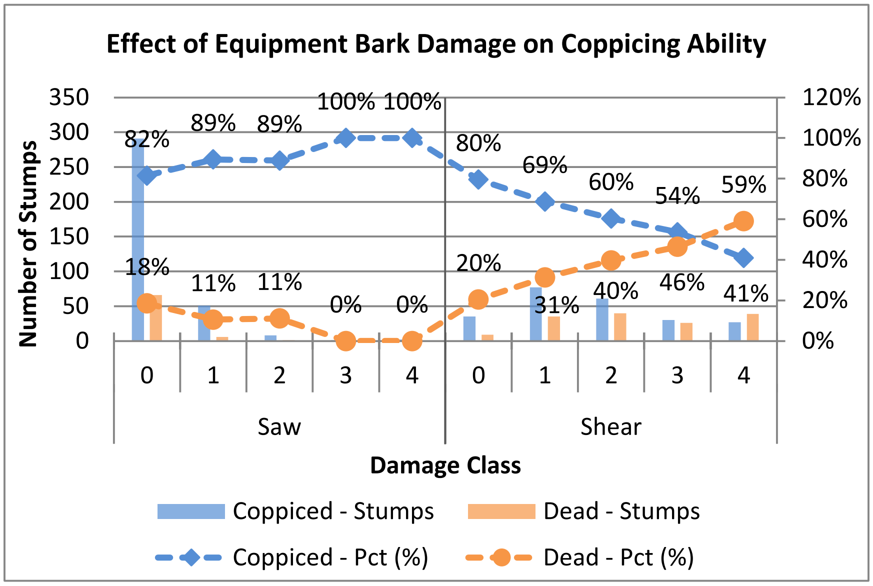

Figure 29: Interaction between the felling method (shear) and bark damage on stump survival of trees felled at Estes.

The GLMM procedure indicated that stumps cut with the shear head, and with bark damage, were 0.40 (-0.42 – 1.23; 95% C.L.) times as likely to regenerate coppice as stumps felled with the chainsaw and with bark damage present. The model results for this conclusion are presented in Table 20.

The DGL of the stumps had a significant effect on the stump survival of trees cut at Admire. Figure 30 illustrates how the stumps with larger DGL resulted in better survival rates than the stumps with a smaller DGL. This pattern may be explained with the fact that larger stumps probably have a larger root system, which can capture higher amount of nutrients and water, suppressing the growth or regeneration of new sprouts by the stumps with smaller DGL.

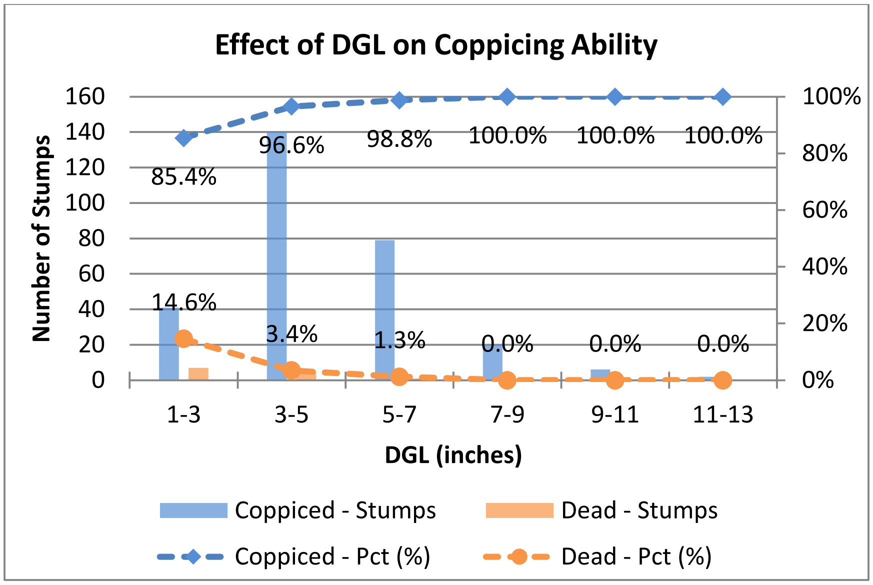

Figure 30: Effect of the DGL on the stump survival at Admire.

Table 24 includes the results of the ANOVA, which indicate that Model 7 was significant for stump survival of trees cut at the Admire study site. According to the GLMM procedure of the survival of the stumps at Admire, for each 1 inch increase in the DGL, the stumps were 2.26 (1.67 – 2.86; 95% C.L.) times as likely to regenerate coppice (Table 25).

Table 24: Analysis of Variance of Model 7 used at Admire planted with cottonwood.

	Df	Deviance	Chi Squared	Chi Df	P-value
Model 7	13	72.281	31.225	10	0.0005386
Null model	3	103.506			

Model 7:

$$\boldsymbol{CR \sim FM/S + Dam + FM{:}Dam + DGL + HD + (1 \mid Row)}$$

Table 25: Details of Model 7 used at Admire site, to determine effects on stump survival.

	Estimate (odd ratios)	Std. Error	z value	P-value
Intercept	5.833436^{-13}	79.45	0.000	0.9997
[1]DGL	2.263925	3.046^{-1}	2.683	0.0073

---

[1] Diameter of the stump at cut level, in inches.

The DGL of the stumps also had a significant effect on the number of new sprouts, both in the Estes (p-value: 0.0001) and Admire (p-value: 0.0001) study sites. Model 6 was used to analyze the effects on trees cut at Estes, while Model 8 was used to analyze the Admire study site. The ANOVA analysis (Table 26) of Model 6, used at Estes, proved it to be significant at $\alpha = 0.05$, and proves that the variables included in the model are related to number of new sprouts. Table 21, previously presented, shows the results of the ANOVA analysis, which determined the parameters included to be significant explaining the number of sprouts at Admire.

Table 26: Analysis of Variance of Model 6 used at Estes planted with cottonwood

	Df	Deviance	Chi Squared	Chi Df	P-value
Model 6	12	1980.1	248.77	6	0.0001
Null model	3	2228.8			

Model 6:

$$\boldsymbol{NS \sim FM/S + Dam + FM{:}Dam + DGL + HD + (1|Row)}$$

At the Estes study site, it was observed that stumps with a larger DGL regenerated more sprouts, when compared to stumps with a smaller DGL. On average, the stumps with DGL between 0 and 1 inch regenerated 1.4 sprouts, while the stumps with larger DGL regenerated up to 12.6 sprouts (Figure 31).

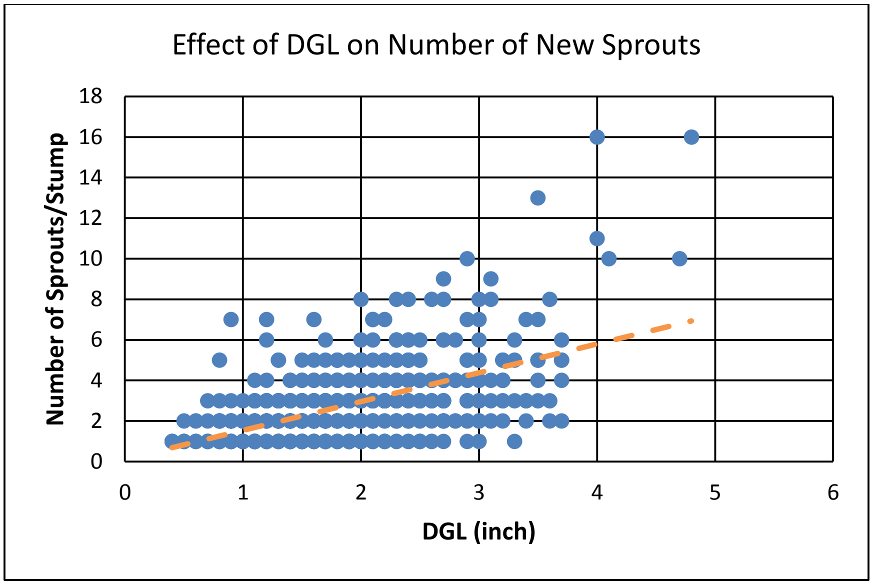

Figure 31: scatter plot for the effect of the DGL of the stumps on the number of sprouts regenerated per stump, at Estes.

After performing the GLMM procedure, it was determined that for each 1 inch increase in stump diameter, the cottonwood stumps at Estes regenerated 1.66 (1.59 – 1.73; 95% C.L.) as many sprouts. The model results supporting the GLMM conclusion are listed below in Table 27.

Table 27: Model 6, used in analysis of number of sprouts per stump of cottonwood at Estes. Details obtained from GLMM procedure. Significant variables are highlighted.

	Estimate (odd ratios)	**Std. Error**	**z value**	**Pr(>|z|)**
Intercept	0.8679328	0.120026	-1.180	0.2380
[1]DGL	1.658343	0.034441	14.686	0.0001

[1]Diameter of the stump at cut level, in inches.

The results were similar at Admire, where stumps with a smaller DGL regenerated less sprouts than stumps with a larger DGL (Figure 31). On average, stumps with lower DGL regenerated 2.7 sprouts, while the stumps with larger DGL regenerated an average of 8.5 sprouts. This pattern, in both sites, is pertinent, since the stumps with larger DGL have more buds that can develop to form new stems to replace the material removed during harvest.

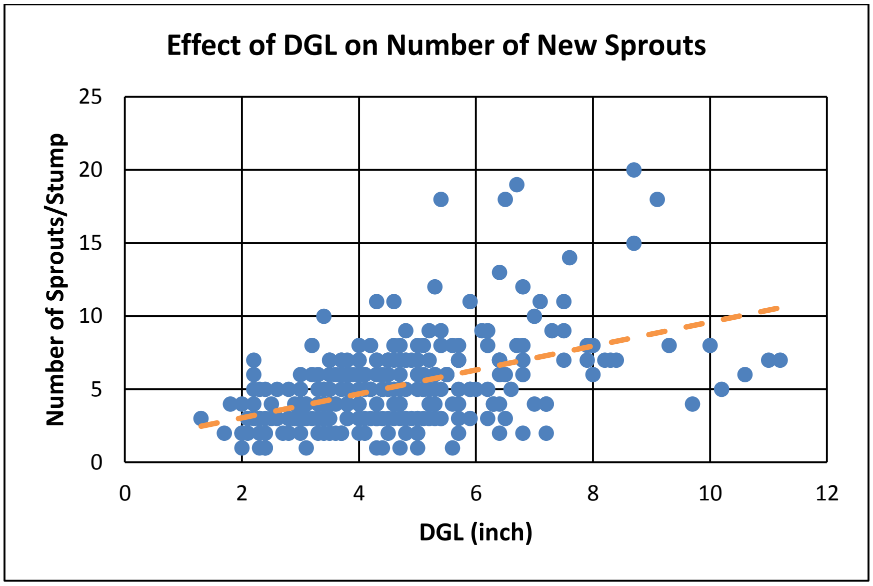

Figure 32: Scatter plot for the effect of the stump DGL on the number of new sprouts per stump at Admire.

The GLMM procedure for the effect of DGL on number of sprouts indicated that for each 1 inch increase in stump's diameter, stumps regenerated 1.16 (1.13 – 1.18; 95% C.L) as many sprouts. The model results supporting this conclusion were previously listed in Table 22.

5.3 Black Willow site

The average DGL for harvested black willow trees was 2.9 inches. The average DGL for trees harvested during summer was 2.7 inches, while for trees harvested during winter was 3 inches (Table 28). The BA at this site was calculated to be 28.6 ft^2.

Table 28: Key statistics of the DGL of harvested black willow trees at Admire site.

	N	Mean DGL (inch)	Max DGL (inch)	Min DGL (inch)	Standard Deviation
Summer					
Saw	162	2.7	7.4	0.6	1.0
Shear	143	2.8	8.3	0.8	1.1
Total	**305**	**2.7**			
Winter					
Saw	150	2.9	6.3	0.6	1.2
Shear	128	3.1	7.0	1.1	1.2
Total	**278**	**3.0**			
Overall	**583**	**2.8**			

The DGL frequency distribution of the black willow trees seemed skewed to the right (Figure 33). However, it is possible to observe that the majority of the harvested trees (~84%) were located in the mean DGL class or the classes immediately before and after the mean. Trees harvested at this site had homogeneous DGL, although a low number of trees (located on the edges of the plantation) had larger DGL. This could be the reason why the distribution looks skewed.

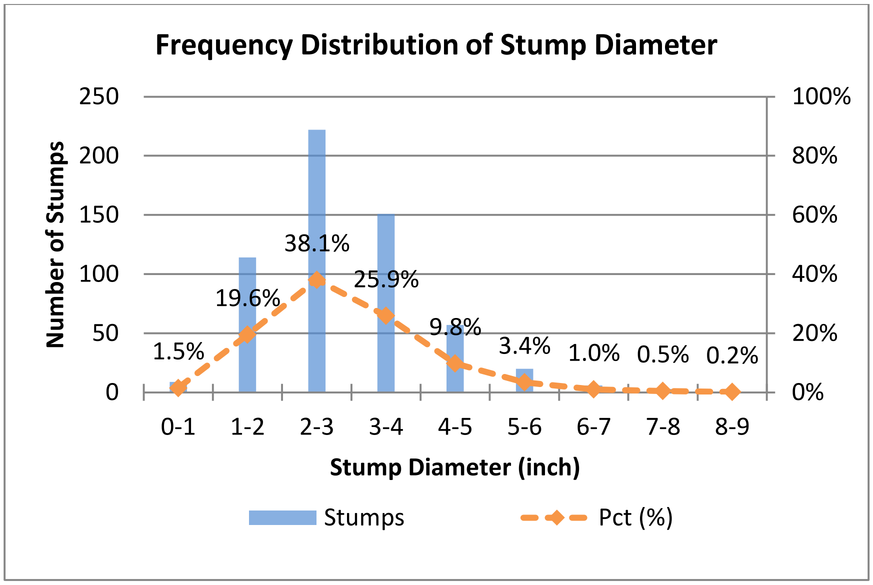

Figure 33: Frequency Distribution chart of the DGL of black willow trees harvested at Admire study site.

At this site, the bark on the stumps of trees cut with the shear head exhibited more damage. Table 29 shows that the majority of trees cut with the chainsaw had a bark damage correspondent to classes 0, 1 and 2. Of the 312 trees cut with the chainsaw, 223 (which represent 71% of the total) corresponded to bark damage class 0. For the 271 trees cut with the shear head, only 62 (representing 23% of the total), were classified under the bark damage class 0.

Table 29: Bark Damage distribution of the black willow stumps cut at Admire, by felling method.

	0	**1**	**2**	**3**	**4**	**Overall**
Saw						
Summer	95	45	13	4	5	162
Winter	128	18	4			150
Total	**223**	**63**	**17**	**4**	**5**	**312**
Shear						
Summer	8	59	45	11	20	143
Winter	54	62	5	3	5	129
Total	**62**	**121**	**50**	**14**	**25**	**272**
Overall	**285**	**184**	**67**	**18**	**30**	**584**

5.3.1 Effect of felling method and harvest season on coppice regeneration of black willow

The models used to determine the effect of felling method and season of year on coppice regeneration of black willow were Model 7 and Model 8. As occurred with the cottonwood plot in Admire, Model 7 was used to determine the significance of the variables on the stump survival rate, while Model 8 was used to determine the significance on the number of sprouts. The significance of the variables were determined at $\alpha = 0.05$. The p-values obtained for the effects of felling method and season on coppice regeneration are summarized in Table 30.

Table 30: P-values for the effect of felling method and season on coppice regeneration of black willow trees, with the significant highlighted.

Site	Season on stump survival	Season on number of sprouts/stump	Felling method on stump survival	Felling method on number of sprouts/stump
Admire	0.9094	0.0001	0.9027	0.4709

As observed, while harvest season affected the number of new sprouts per stump, season did not cause any effect on the coppice regeneration. The ANOVA analysis (Table 31) proved that Model 8 indicated significance in explaining the regeneration of sprouts per stump of black willow trees, at $\alpha = 0.05$.

Table 31: Analysis of Variance of Model 8 used at Admire planted with black willow.

	Df	Deviance	Chi Squared	Chi Df	P-value
Model 8	14	2654.8	192.51	11	0.0001
Null model	3	2847.3			

Model 8:

$$\boldsymbol{NS \sim FM/S + Dam + FM{:}Dam + DGL + HD + (1|Row)}$$

It was observed that the average number of sprouts regenerated per stump was higher when the harvest was performed during summer than when performed during winter. Figure 34 illustrates this difference, proving that stumps cut during summer averaged 6.2 sprouts per stump while stumps cut during winter average 4.5 sprouts per stump. This pattern differs from what was observed with the other species, where no significant effect of season was observed on number of sprouts per stump. This difference, although unexpected, may be explained with the fact that when the winter harvest was performed, the trees already showed signs of being in growing season, with some leaf buds on their branches.

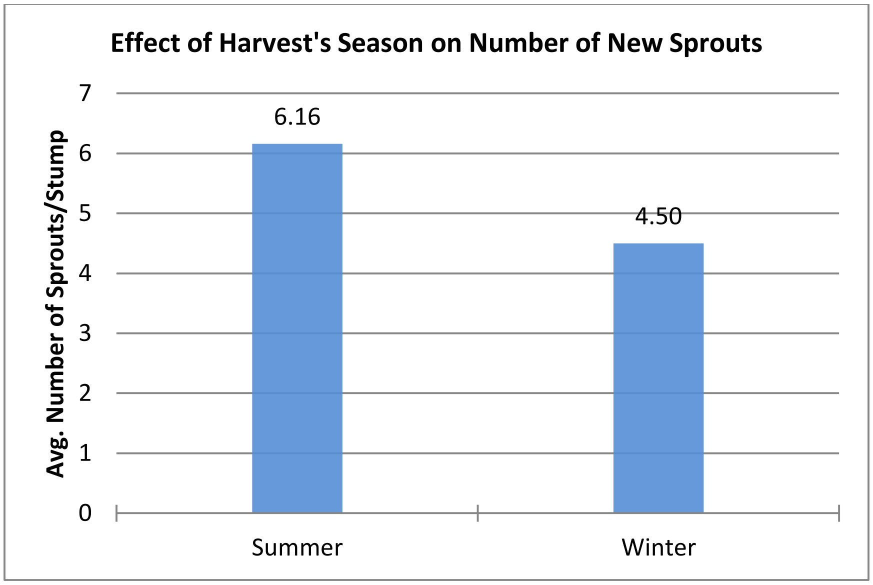

Figure 34: Average number of sprouts per stump regenerated at each harvest season, at Admire site planted with black willow.

The GLMM procedure used for this analysis indicated that when trees were felled during summer they regenerated 1.60 (1.47 – 1.72; 95% C.L.) times as many sprouts as when trees were felled during winter (Table 32).

Table 32: Model 8, used in analysis of number of sprouts per stump of black willow. Details obtained from GLMM procedure.

	Estimate (odd ratios)	**Std. Error**	**z value**	**Pr(>|z|)**
Intercept	3.643956	0.06275	20.608	0.0001
[1]Summer	1.594978	0.06225	-7.499	0.0001
[2]DGL	1.221244	0.01537	13.001	0.0001

[1]Compared to winter

[2]Diamter of the stump at cut level, in inches

5.3.2 Other factors affecting coppice regeneration of black willow

To test for the other factors besides felling method and season affecting coppice regeneration of black willow, the same models were used. Model 7 was used to determine the effect of DGL, bark and stump damage, and possible interactions, on the survival of the stumps; while Model 8 was used to determine the effects of the same factors on the number of sprouts per stump. A list of the p-values, determined at α = 0.05, is provided in Table 33.

Table 33: P-values for the effect of DGL, bark and stump damage, and interactions on coppice regeneration of black willow plantation, with significance highlighted.

Stump survival					
Site	DGL	Bark damage	Stump damage	Seas:Equip	Equip:Barkdam
Admire	0.0188	0.0834	0.3713	0.9962	0.6666
Number of sprouts/stump					
Site	DGL	Bark damage	Stump damage	Seas:Equip	Equip:Barkdam
Admire	0.0001	0.2391	0.3232	0.0506	0.4834

The DGL was determined to have an effect on the coppice regeneration of black willow, both in the stump survival (p-value: 0.0188) and in the number of sprouts regenerated per stump (0.0001). The ANOVA table (Table 34) proved that, after the analysis of variance performed on Model 7, used with the black willow, the included parameters are related to the survival of the stumps. Also, the Model 8, used at the same site, already proved significance (Table 31) to explain the number of sprouts per stump.

Table 34: Analysis of Variance of Model 7 used at Admire planted with black willow.

	Df	**Deviance**	**Chi Squared**	**Chi Df**	**P-value**
Model 7	14	162.34	23.393	11	0.01555
Null model	3	185.73			

Model 7:

$$\boldsymbol{CR \sim FM/S + Dam + FM{:}Dam + DGL + HD + (1\,|\,Row)}$$

The effect of the stump's DGL on the stump survival of black willow trees is illustrated in Figure 35. The stumps with the lowest DGL class had lower survival rates when compared to the higher DGL classes. This pattern may be explained because of the competition between the stumps for nutrients and water. Stumps with higher DGL probably had a better root system, which captured more nutrients than small DGL trees, suppressing the development of sprouts by these smaller trees.

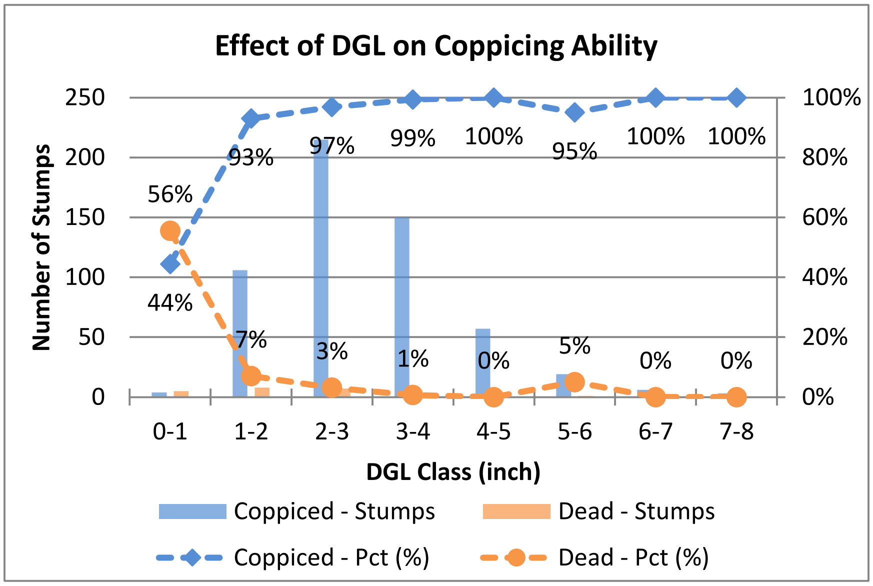

Figure 35: Effect of the stump’s DGL on the survival of the black willow trees felled at Admire.

According to the GLMM procedure performed to the stump survival of black willow trees, for each 1 inch increase in stump DGL, the stumps were 2.00 (1.42 – 2.59; 95% C.L.) times as likely to regenerate coppice. The model results supporting this conclusion are presented in Table 35.

Table 35: Model 7, used in analysis of number of sprouts per stump of black willow. Details obtained from GLMM procedure.

	Estimate (odd ratios)	**Std. Error**	**z value**	**Pr(>|z|)**
Intercept	12.146	1.022	2.444	0.0145
[1]DGL	2.004912	0.2962	2.349	0.0188

[1]Diameter of stump at cut level, in inches.

The DGL of the black willow stumps also had a significant effect on the number of new sprouts per stump. A positive linear relation was observed between the DGL and the number of sprouts per stump, where stumps with larger DGL, generally regenerated a larger number of sprouts. Stumps located on the smallest DGL class averaged 1.44 sprouts, while the stumps on the largest DGL classes averaged up to 9 sprouts. This linear relation is illustrated in Figure 36.

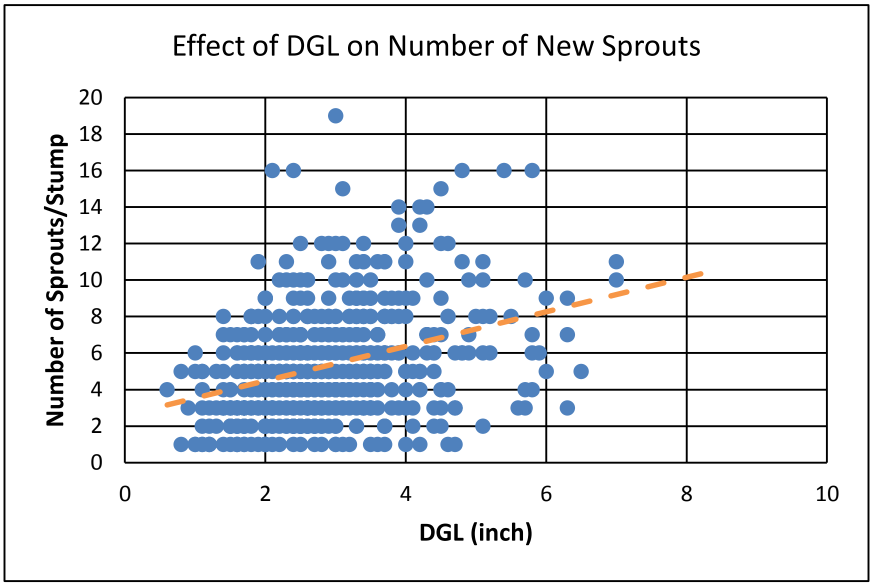

Figure 36: Scatter plot of the effect of the DGL on the number of new sprouts regenerated per stump of black willow harvested at Admire.

After performing the GLMM procedure, it was estimated that for each 1 inch increase in stump DGL, stumps of black willow regenerated 1.22 (1.19 – 1.25; 95% C.L.) as many sprouts. Model results for this conclusion were previously presented in Table 32.

IV. Conclusions

This project studied the effect of the felling method and the season of year on coppice regeneration of eucalypt, cottonwood and black willow trees. However, besides felling equipment and harvest season, several other factors were considered when determining effects on coppicing ability and number of new sprouts regenerated after harvest.

Despite analyzing the effects of season on coppice, operational harvesting restrictions affected the experimental design. For this reason, the results presented should not be considered as definitive, and further research is recommended to determine the effect of season on coppice regeneration.

4.1 Stump Survival

Results showed that harvesting eucalypt, at the Evans study site, during winter resulted in higher stump survival when compared to summer harvest. No season effect was observed at the Lykes study site. The difference in the results between the two sites might be due the different species of eucalypt planted at each site (*E. urograndis* at Evans and *E. grandis* at Lykes). The season effect observed at Evans showed that survival rate of stumps cut during winter was 17% higher than the survival rate of stumps cut during summer. This difference was not expected, since eucalypt is an evergreen specie; however, the difference might be attributed to the precipitation regime of the region, which is higher during summer. Furthermore, bark damage resulted significant to determine the survival of eucalypt stumps. It was concluded that higher bark damage affects the regeneration of coppice. A harvest operation, with minimal impact on the bark of the stump, is recommended to ensure higher survival rates. No effect of felling equipment was observed; concluding that the utilization of a shear head might be considered as a less costly alternative to harvest eucalypt plantations.

Similar results were observed at the cottonwood sites. A season effect was observed at the Estes site, where the winter harvest presented better results than summer harvest, while no effect was observed at the Admire site. The season effect observed at Estes showed that winter cut stumps had a survival 49% higher than stumps cut during summer. This result was expected, since cottonwood trees tend to accumulate carbohydrates during the dormant season, which supports the regeneration of sprouts when the main stem is harvested. In addition, a stump diameter effect was observed on the survival of the stumps, where stumps with larger diameter had better survival rates. This result was also expected, since the number of shoot buds present on the stump is higher on stumps with larger diameter; also, the competition between the stumps may reduce the chances of sprouting of the stumps with smaller diameter, since their root system does not have the same ability to capture nutrients and water. An effect of felling method was not observed with this species, also concluding that the utilization of a shear head may be an alternative to the chainsaw or circular-saw feller-buncher.

On the black willow site, neither the harvest season nor the felling equipment had a significant effect on the stump survival. This indicates that either type of felling method can be used to harvest this species, and the harvest can be performed the entire year, regardless of the season or phenology of the tree. However, a similar diameter effect to the one observed with cottonwood was observed on the survival of the stumps (larger stumps were more successful).

4.2 Number of sprouts per stump

Although the number of sprouts regenerated per stump was studied, it is very important to deepen the study on the importance of this factor. It was found that depending on the species, the number of sprouts per stump was affected by DGL, felling method, and harvest season. However, the DGL of the stump was consistent in showing statistically significant effect on the number of sprouts for all the species. In all cases, stumps with larger DGL regenerated more sprouts per stump, which is pertinent due the higher number of shoot buds present on larger stumps.

Nonetheless, the importance of the number of sprouts regenerated per stump is not yet clear. There is no certainty if having several sprouts per stump results better than having one sprout per stump. Perhaps having a single sprout regenerated per stump may be more desirable, depending on the goal of implementing a coppice plantation. In addition, there is knowledge of occurrence of self-pruning after a determined time after the harvest, in which the coppiced stumps will automatically eliminate the smaller stems, maintaining only the dominants or one single main stem.

In conclusion, the season effect observed on the stump survival of eucalypt and cottonwood may imply an economic impact on the SRWC supply, restricting the harvest to the winter harvest. However, the utilization of the shear head can be recommended as a possible felling method to harvest SRWC, since it does not have an effect on the survival of the stumps; which could reduce the costs of actual harvests operations used at SRWC plantations.

Literature Cited

25’x25’: America’s Energy Future. http://www.25by25.org/

Alig, R. J., Adams, D. M., McCarl, B. A., Ince, P. J. 2000. “Economic Potential of Short-Rotation Woody Crops on Agricultural Land for Pulp Fiber Production in the United States.” Forest Product Journal. Vol. 50(5): 67-74.

Bates, D. 2006. “[R] lmer, p-values and all that.” https://stat.ethz.ch/pipermail/r-help/2006-May/094765.html.

Bates, D. Unpublished. “lme4: Mixed-effects modeling with R.” http://lme4.r-forge.r-project.org/book/

Berridge, D., Crouchley, R. 2011. “Multivariate generalized linear mixed models using R.” CRC Press, Boca Raton, Florida. 257 pp.

Bolker, B. 2015. “GLMM for ecologists and evolutionary biologists.” http://glmm.wikidot.com/

Bolker, B., Brooks, M., Clark, C., Geange, S., Poulsen, J., Stevens, M. H., White, J. S. 2008. “Generalized linear mixed models: a practical guide for ecology and evolution.” Trends in Ecology and Evolutions. Vol. 24(3): 127-135.

Bosela, M. J., Ewers, F. W. 1997. “The Mode of Origin of Root Buds and Root Sprouts in the Clonal Tree *Sassafras albidum* (Lauraceae).” American Journal of Botany. Vol. 84(11): 1466-1481.

Burns, R. M., Honkala, B. H. 1990. “Silvics of North America. Volume 2, Hardwoods.” Forest Service, United States Department of Agriculture. Agriculture Handbook 654: 876 pp.

Canadell, J., Zedler, P. H. 1995. “Underground Structures of Woody Plants in the Mediterranean Ecosystems of Australia, California and Chile.” In: M. T. Kalin Arroyo, P. H. Zedler and M. D. Fox (Eds.), Ecology and Biogeography of Mediterranean Ecosystems in Chile, California and Australia. Springer-Verlag. New York. 177-210 pp.

Ceulemans, R., McDonald, A. J. S., Pereira, J. S. 1996. "A Comparison among Eucalypt, Poplar and Willow Characteristics with Particular Reference to a Coppice, Growth-modelling Approach." Biomass and Bioenergy. Vol. 11(2/3): 215-231.

Cremer, K. W., Cromer, R. N., Florence, R. G. 1984. "Stand Establishment." In: W. E. Hillis and A. G. Brown (Eds.), Eucalypts for Wood Production. CSIRO/Academic Press, Melbourne, Australia. Chapter 4: 81-135 pp.

De Souza, J. A., Zen, S., Gibertoni, P. E., Sanchez, O. A. 1991. "Observações Preliminares de Alguns Fatores que Afetam a Brotação do Eucalipto." Circular Técnica N° 177: 9 pp.

Del Tredici, P. 2001. "Sprouting in Temperate Trees: A Morphological and Ecological Review." The Botanical Review. Vol. 67(2): 121-140.

Dougherty, D., Wright, J. 2012. "Silviculture and Economic Evaluation of Eucalypt Plantations in the Southern U.S." Bioresources. Vol. 7(2): 1994-2001.

Ducrey, M., Turrel, M. 1992. "Influence of Cutting Methods and Dates on Stump Sprouting in Holm oak (*Quercus ilex* L.) Coppice." Ann. Sci. For. Vol. 49: 449-464.

Fontainer, E. J., Jonkers, H. 1976. "Juvenility and Maturity of Plants as Influenced by their Ontogenetical and Physiological Ageing." Acta Horticulturae 56: 37-44.

Hibbs, D. E., Fischer, B. C. 1979. "Sexual and Vegetative Reproduction of Striped Maple (*Acer pensylvanicum* L.)." Bulletin of the Torrey Botanical Club. Vol. 106(3): 222-227.

Hinchee, M., Rottmann, W., Mullinax, L., Zhang, C., Chang, S., Cunningham, M., Pearson, L., Nehra, N. 2009. Short-Rotation Woody Crops for Bioenergy and Biofuels Applications." In Vitro Cell. Dev. Biol. – Plant. Vol. 45: 619-629.

Hytönen, J. 1994. "Effect of Cutting Season, Stump Height and Harvest Damage on Coppicing and Biomass Production of Willow and Birch." Biomass and Bioenergy. Vol. 6(5): 349-357.

Hytönen, J. 1996. "Biomass Production and Nutrition of Short-Rotation Plantations." The Finish Forest Research Institute. Research Papers 586: 61 pp.

Hytönen, J., Issakainen, J. 2001. "Effect of Repeated Harvesting on Biomass Production and Sprouting of *Betula pubescens*." Biomass and Bioenergy. Vol. 20: 237-245.

Hytönen, J., Saarsalmi, A., Rossi, P. 1995. "Biomass Production and Nutrient Uptake of Short-Rotation Plantations." Silva Fennica. Vol. 29(2): 117-139.

James, S. 1984. "Lignotubers and Burls – Their Structure, Function and Ecological Significance in Mediterranean Ecosystems." The Botanical Review. Vol 50(3): 225-266.

Johnson, P. S. 1977. "Predicting Oak Stump Sprouting and Sprout Development in the Missouri Ozarks." USDA Forest Service. Research Paper NC-149: 11 pp.

Kauter, D., Lewandowski, I., Claupein, W. 2003. "Quantity and Quality of Harvestable Biomass from Populus Short-Rotation Coppice for Solid Fuel use – A review of the Physiological Basis and Management Influences." Biomass and Bioenergy. Vol. 24: 411-427.

Langholtz, M., Carter, D. R., Rockwood, D. L., Alavalapati, J. R. R., Green, A. 2005. "Effect of Dendroremediation Incentives in the Profitability of Short-Rotation Woody Cropping of *Eucalyptus grandis*." Forest Policy and Economics. Vol. 7: 806-817.

Langholtz, M., Carter, D. R., Rockwood, D. L., Alavalapati, J. R. R. 2007. "The Economic Feasibility of Reclaiming Phosphate Mined Lands with Short-Rotation Woody Crops in Florida." Journal of Forest Economics. Vol. 12: 237-249.

Opie, J. E., Curtin, R. A., Incoll, W. D. 1984. "Stand Management". In: W.E. Hillis and A. G. Brown (Eds.), Eucalypts for Wood Production. CSIRO/Academic Press, Melbourne, Australia. Chapter 9, 179-197 pp.

Perlack, R. D., Wright, L. L., Huston, M. A., Schramm, W. E. 1995. "Biomass Fuel from Woody Crops for Electric Power Generation." Oak Ridge National Laboratory. ORNL-6871. Oak Ridge, Tennessee. 61 pp.

Ranney, J. W., Wright, L. L., Layton, P. A. "Hardwood Energy Crops: The Technology of Intensive Culture." Journal of Forestry. Vol. 85(9): 17-28.

Sakai, A., Ohsawa, T., Ohsawa, M. 1995. "Adaptive Significance of Sprouting of *Euptelea polyandra*, a Deciduous Tree Growing on Steep Slopes with Shallow Soil." J. Plant. Res. 108: 377-386.

Sakai, A., Sakai, S. 1998. "A Test for the Resource Mobilization Hypothesis: Tree Sprouting Using Carbohydrates from Above-ground Parts." Annals of Botany. Vol. 82: 213-216.

Sakai, A., Sakai, S., Akiyama, F. 1997. “Do Sprouting Tree Species on Erosion-prone Sites Carry Large Reserves of Resources?” Annals of Botany. Vol. 79: 625-630.

Simões, J. W., Pereira, R. A. G., Tanaka, O. K., Pompeu, R. M. 1972. “Efeitos da Ferramenta de Corte sobre a Regeneração do Eucalipto.” Revista IPEF. Vol. 4: 3-10.

Steinbeck, K. 1978. “Intensively Managed Short-Rotation Coppice Forests.” In: E. T. Choong and J. L. Chambers (Eds.), Energy and the Southern Forest. Louisiana State University, Baton Rouge, Louisiana. 123-129 pp.

Strong, T. F., Zavitovski, J. 1983. “Effect of Harvesting Season on Hybrid Poplar Coppicing.” In: E. A. Hansen (Ed.), Intensive Plantation Culture: 12 years Research. USDA Forest Service. Gen. Tech. Rep. NC-91: 54-57

Sutton, R. F., Tinus R. W. 1983. “Root and Root System Terminology.” Society of American Foresters. Forest Sci. Monograph 24: 137 pp.

Tamang, B. 2005. “Vegetation and Soil Quality Changes Associated with Reclaiming Phosphate-mine Clay settling areas with Fast-growing Trees.” Master of Science Thesis. University of Florida, Gainesville, Florida. 133 pp.

Tuskan, G. A. 1998. “Short-Rotation Woody Crop Supply Systems in the United States: What do we know and what do we need to know?” Biomass and Bioenergy. Vol. 14(4): 307-315.

Tuskan, G. A., Downing, M. E., Wright, L. L. 1994. “Current Status and Future Direction for the U.S. Department of Energy’s Short Rotation Woody Crop Research.” In: B. J. Stokes and T. P. McDonald (Eds.), Proceedings of the IEA/BA Taks IX, Activity 1 International Conferences: Mechanization in Short-Rotation, Intensive Culture (SRIC) Forestry. http://www.woodycrops.org/NR/rdonlyres/BF9B2067-FDB0-49B0-9543-8EEA03A415FD/1661/Proceedings1.pdf

Vance D. E., Maguire, D. A., Zalesny Jr., R. S. 2010. “Research Strategies for Increasing Productivity of Intensively Managed Forest Plantations.” Journal of Forestry. Vol. 108: 183-192.

White, E. M. 2010. “Woody Biomass for Bioenergy and Biofuels in the United States – A Briefing Paper.” General Technical Report PNW-GTR-825. Department of Agriculture, Forest Service, Pacific Northwest Research Station. Portland, Oregon. 45 pp.

Wilkerson, E. G., Perlack, R.D. 2009. “Resource Assessment, Economics and Technology for Collection and Harvesting.” In: B. D. Solomon and V.A. Luzadis (Eds.), Renewable Energy from Forest Resources in the United States. New York, NY: Routledge. 69-91 pp.

Wilson, B. F. 1968. “Red Maple Stump Sprouts: Development the First Year.” Harvard Forest Paper 28: 10 pp.

Zimmerman, M. H., Brown, C. L. 1974. “Trees: Structure and Function.” Springer-Verlag. New York. 336 pp.