Coppicing Evaluation in the Southeastern U.S. to Determine Harvesting Methods for Bioenergy Production

by

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Abstract

Renewable fuels are being tested as an alternative for fossil fuels. Woody biomass is an excellent source of renewable energy in terms of cost-benefit and availability. Short rotation woody crops (SRWC) meet intensive wood demand due their fast growth and ability to coppice. There are uncertainties related to the feasibility of harvesting multiple-stem trees with current technology. In this study we investigated the attributes of 2 SRWC species, 2 years after harvest. A logistic regression was fit in an attempt to determine whether trees per stump (2 or fewer; 3 or more) was affected by damage caused during harvest and the diameter classes of the stumps. The species used in this experiment were *Eucalyptus urograndis* in Florida, and *Populus deltoides* in Arkansas. We measured volume, stem crowding, and clump dimension of the coppiced trees 6 months after harvest, and then 2 years after harvest. Results from both species showed that stump diameter is positively related with stem crowding. Stem crowding was negatively affected by stump damage in eucalyptus trees. The scattering formation of the regenerated stems on each stump would not increase the difficulties of subsequent harvesting operations. At age 2, the volume found per stump increased almost linearly with stem crowding.

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I. Introduction

Renewable energy resources are an important topic today. Population growth combined with the depletion of limited oil deposits reinforce the need to develop alternative renewable sources of energy (Pimentel et al. 2002). Sustainable projects and government programs in many countries aim to encourage the consumption of renewable sources of energy and provide subsidies for large scale production of renewable energy.

Scientists have investigated many potential sources of renewable energy that can be used as feedstock to meet the massive worldwide demand for energy we currently face. But none of the most promising alternative sources of energy from biomass (e.g., corn, switchgrass, and wood) in the U.S. have proven to be as efficient as fossil fuels in terms of energy output and cost of production (Pimentel and Patzek 2005). Biomass energy or ‘’bioenergy’’, refers to the energy from plants and plant-derived material and have been commonly used throughout the world due to their renewable characteristics. Under the big umbrella of bioenergy resources, woody crops (e.g., *Eucalyptus* spp., *Salix* spp., and *Populus* spp.) designed to produce biomass feedstock (wood) for energy production have been noted as a reasonable alternative to fossil fuels (Hauk et al. 2014). As opposed to solar and wind power, where the energy response is exclusively dependent on weather conditions and time of day, the production of woody biomass can be adjusted to meet consumer demand (Hauk et al. 2014).

From a biophysical point of view, woody resources are abundant enough to supply a significant portion of the worldwide energy demand. In 2010, woody biomass supplied roughly 9% of the primary energy consumption of the world, which represented 65% of all renewable energy sources used in that year (Lauri et al. 2014). Despite the extensive use of woody biomass for producing energy, worldwide consumption is still significantly lower than the amount of remaining woody biomass resources (Lauri et al. 2014). However, the use of these resources is often limited by slow production. A potential strategy to minimize this issue is the adoption of fast growing tree species (Hinchee et al. 2009).

Not long ago, short rotation woody crops (SRWC) were shown to be an excellent choice for woody plantations for those seeking to produce attractive yields through the use of fast growing tree species. In the early 1970s, SRWC were initially characterized as woody supply systems that provide rapid growth of lignocellulosic fiber for use in the forest products industry and energy production (Tuskan, 1998). Today, the U.S. Department of Energy defines SRWC as intensively-managed tree species that can be harvested after 8 to 10 years, yielding large amounts of biomass (e.g., 8-14 dry tons/ha/year) (Kauter et al. 2003; Hauk et al. 2015). One negative aspect of the adoption of SRWC is that these crops require intensive maintenance, which increases costs. In general, SRWC demand closely monitored weed control, pest management, fertilization, close spacing of trees, use of genetically superior plants, and efficient harvest and post-harvest processing (Tuskan 1998). With coppicing and rapid growth, rotations can be reduced to 3 year cycles for some species. Coppice enables certain tree species to naturally regenerate stems from the stump after harvest. Choosing this option will decrease expenditures by avoiding re-establishment costs (i.e., re-planting).

The SRWC supply system was developed by the Department of Energy (DOE) within the Biofuels Feedstock Development Program (BFDP). BFDP projects have examined issues associated with the use of SRWC species. Poplars (*Populus* spp.), sycamore (*Platanus occidentalis* L.), silver maple (*Acer saccharum* March), and hybrid willow (*Salix* spp.) were previously considered to be model species for woody biomass production throughout most of the U.S. (Tuskan 1998). Eucalyptus (*Eucalyptus* spp.) on the other hand, is an exotic species that was introduced to the U.S. in the mid-1800s for use in wood fiber production (Cowles et al. 1995). As a SRWC species, eucalyptus has been shown to produce high yield rates, indicating potential for supplying biomass energy. The U.S. Department of Energy indicated that poplar, southern yellow pine, willow, and eucalyptus were the most promising crops for energy plantations.

Felling coppice plantations is generally time consuming due to the unfavorable harvesting conditions caused by the clump of stems. In these plantations, cutting multiple stems within the same cutting cycle can be fairly difficult with mechanized harvesting (Suchomel et al. 2011). Most SRWC are initially planted with relatively narrow spacing between trees (e.g., 1 m). In addition, coppiced stems are generally small, branchy, and diverse in shape (Schweier et al. 2015). Furthermore, stem crowding (number of stems per stump) might vary considerably depending on species, climate, and other factors including damage caused during prior harvesting, stump height and season of harvest (Hytönen 1994). Because most harvesting equipment is designed to operate in single-stem felling, there are uncertainties related to their productivity when managing multiple-stem trees. For these reasons, special mechanization and cutting techniques may be required.

Feller-bunchers may prove more appropriate than harvesters for handling SRWC because of their compact design, and the different cutting heads that can be used (Schweier et al. 2015). Furthermore, small-scale feller-bunchers (e.g., skid-steers) have been considered an effective option for small-diameter-trees (Spinelli et al. 2007). These tractors have an even more compact design, smaller cutting heads, and have a lower purchase price when compared to purpose built feller-bunchers. Some studies have explored the complications of harvesting clumps (e.g. multiple-stem trees) with traditional machinery. McEwan et al. (2016) investigated the effects of number of stems per stump on cutting productivity of eucalyptus trees with a harvester. Results showed that the productivity was affected by the number and size of the stems, and also that selecting an optimum felling direction can be complicated because of stem agglomeration. Moreover, even small-scale feller-bunchers had difficulty in penetrating clumps without damaging adjacent stems and consequently negatively affecting productivity (Schweier et al. 2015). Due to the scattered formation of stems growing from coppiced stumps, a considerable amount of biomass could be either left behind, or grabbed by the machine operator in a second attempt by performing 2 cutting cycles on the same tree. In either case, there would be a negative impact on productivity.

Few studies have explored stem crowding and the physical characteristics of coppice plantations. This is especially true for the particular species used in this study; *Eucalyptus urograndis* and *Populus deltoides* and for the locations Florida and Arkansas. In this study, we analyzed the growth behavior of the first rotation coppice by collecting data on growth form, stem crowding, and stem mortality in order to determine whether current harvesting equipment is appropriate for felling those trees.

1.1 Objectives

The objective of this study is to evaluate coppice development of 2 species of short rotation woody crops in the southeastern U.S, following 2 years of growth.

The specific goals for this project are:

1. To examine the dimensions of multiple-stem coppiced trees to postulate effect on subsequent mechanized harvesting operations.
2. To analyze potential impacts caused by seasonality of harvesting on stem crowding and clump dimension of coppiced stems.
3. To examine potential differences on the final yield of coppice material that regenerated multiple-stem trees versus single-stem trees.

II. Literature Review

2.1 Role of Short Rotation Woody Crops

The concept of short rotation woody crops (SRWC) was first proposed in the late-1960s and early 1970s. Subsequently, the idea was embraced by the U.S. Department of Energy (DOE) as a potential biomass feedstock option for the production of biofuels (Tuskan 1998). Today, one of the largest SRWC organizations in the U.S. is the SRWC Operations Working Group. Their members include wood products companies, equipment manufacturers, utility companies, the USDA Forest Service, and many university researchers in the U.S. Its mission is to promote collective efforts for developing large scale SRWC plantings that comply with the principles of economic viability, ecological soundness, and social acceptance (Dickmann 2006).

SRWC are tree crops grown on short rotations that produce large amounts of biomass (White 2009). These crops have an average yield that is 2 to 3 times greater than the yield found in natural stands of traditional plantations (Hohenstein and Wright 1994). However, they require more inputs than other timber plantations. Silvicultural treatments for SRWC involve appropriate selection of planting site, appropriate spacing, pest and weed control, fertilization and other practices depending on the species to be planted. In terms of site limitations, water deficit is likely to be the most restricting factor (Tuskan 1998). On sites where water availability is not an issue, management-related factors such as rotation length and spacing are the most important attributes for a vigorous establishment of SRWC's plantations (Nassi O Di Nasso et al. 2010).

Additional characteristics that distinguish SRWC from other types of plantations include their recommended high density planting and the ability to coppice (Tuskan 1998). Dickmann (2006) points out that early SRWC practitioners worked with extremely high densities (5,000-20,000 stems ha $^{-1}$) and that these densities were still being used in studies that began in the 1960s and 1970s. These high density SRWC plantings resulted in higher yields and earlier peaks in mean annual increment (MAI) compared to low density plantations. Furthermore, weed control was only necessary for the initial 2 years after planting because the rapidly developed tree canopy prevented sunlight from reaching the understory. Establishment costs per hectare, however, were elevated. Although woody biomass was being produced extremely fast, its utilization was limited due to the physical aspect of the trees. The small diameters made mechanized harvesting more difficult and generated a low wood-bark ratio. More recent recommendations made by Tuskan (1998) suggest densities at 1,200 – 1,400 stems ha $^{-1}$ to avoid high establishment and harvesting expenses.

2.1.1 Coppice ability

Coppice enables certain tree species to naturally regenerate stems from the stump after being harvested. Most of the SRWC tree species share the ability to coppice. Coppice may decrease expenditures by reducing re-establishment costs (i.e. re-planting). Young re-sprouts will experience faster growth rates compared to seedling trees of the same age (Kauppi et al. 1988). Coppicing will increase volume production once the regrowth commences immediately after harvesting by taking advantage of a live and fully developed root system as the sprouts emerge from juvenile zones of the tree and from dormant buds (Ferm and Kauppi 1990). In this sense, the new sprouts will retain the juvenile characteristics acquired from the parental tree.

The regeneration of secondary sprouts on the vast majority of tree species will rise after the apical control is destroyed by some external factor (e.g. wind, fire, harvest). The apical control defines the overall tree shape by a terminal bud and is governed by growth tree regulators that emanate from the distal tip of a shoot (Tredici 2001). In simple terms, the majority of the tree species that coppice will only develop secondary trunks when the apical control is destroyed. Coppice will occur through different physiological processes and re-sprouting mechanisms that vary considerably depending on genera, species, and sections (Ceulemans et al. 1996).

2.2 SRWC Species

In the early 1980s, the U.S. Department of Energy (DOE), through the Biofuels Feedstock Development Program (BFDP), funded several studies focused on improving SRWC supply systems in the U.S. (Tuskan 1998). Initial studies were conducted exclusively on species-site trials within potential production regions, and a number of model species were selected to be planted in several sites across the country. These regions were primarily located in the north-central and southeastern portions of the U.S. with the predominant species being hybrid willow (*Salix* spp.), poplar (*Populus* spp.), silver maple (*Acer saccharum* Marsh), and sycamore (*Platanus occidentalis* L.) (Hohenstein and Wright 1994; Tuskan 1998). Only recently has the use of eucalyptus as a SRWC been considered. As a SRWC species, eucalyptus has been shown to produce excellent yield rates, indicating great potential for supplying biomass energy. Currently, the U.S. Department of Energy states that the most promising crops adopted for energy plantations are poplar, southern yellow pine, willow, and eucalypt.

Eucalyptus and poplars have biological characteristics in common that enable them to excel under intensive short rotation forestry systems. Ceulemans et al. (1996) highlighted these shared characteristics:

- High potential productive rates immediately after planting.
- High efficiency of wood accumulation in relation to total biomass produced.
- Rapid and reliable sprouting when coppiced.

2.2.1 Coppice factor of Populus spp.

Populus spp. or ‘’poplar’’ is a genus of the family Salicaceae. The most common sections that comprise this genus include *Populus* – aspen, *Aigeiros* – cottonwood, and *Tacamahaca* – balsam poplars (Stanturf et al. 2001). These species are considered to be the most promising SRWC of all potential species grown in temperate climates (Nassi O Di Nasso et al. 2010). Poplar are deciduous hardwood trees with a vigorous ability to coppice (Ceulemans et al. 1996). Poplars are often cultivated for energy production (Nassi O Di Nasso et al. 2010) due to their high yields of woody biomass and good combustion properties, which are essential elements for bioenergy material (Kauter et al. 2003).

When coppiced, poplars often yield 5 to 8 sprouts per stump (Ceulemans et al. 1996). Rotation lengths might vary depending on location and species, but generally they consist of very short intervals (i.e., 1-5 years) when used for bioenergy (Nassi O Di Nasso et al. 2010). Poplar trees are amendable to intensive short-rotation forestry due to their characteristics, including high wood productivity rates, reliable sprouting when coppiced, and good leaf area index (LAI) which is directly responsive to wood production (Ceulemans et al. 1996). Yields may vary considerably, and they depend on characteristics such as location, species or clone, spacing, and silvicultural treatments.

Poplars of the *Leuce* section (aspens and white poplars), and some from other sections, re-sprout primarily from root suckers, although young *Leuce* poplars may also produce sprouts from the stump. Poplars fom the *Aigeiros* and *Tacamahaca* sections sprout primarily from the stump (Ceulemans et al. 1996). Generally, sprouts that regenerate from stumps are less desirable than trees established from sprout suckers, cuttings or seedlings (Tredici 2001). Stump sprouts are usually short-lived and their form is often poor (Ceulemans et al. 1996).

2.2.2 Coppice factor of Eucalyptus spp.

Eucalyptus *(Eucalyptus spp.)* is a hardwood tree widely planted throughout the world. The attractiveness of this particular genus comes from its high yields generated over short periods of time. Currently, eucalyptus plantations are widely used for bioenergy production as well as for lumber and pulp. Eucalyptus species represent roughly 38% of all short-rotation plantations in the world, which equates to over half of the hardwood plantations (63%) (Seixas 2008). Eucalyptus are evergreen species, while many other SRWC such as willows and poplars are deciduous with a well-defined dormant season (Ceulemans et al. 1996).

When coppiced, eucalypt trees tend to produce a large number of sprouts per stump. In Israel, a 6.5 year old *E. camaldulensis* second rotation showed an average of 20 sprouts per stump at 3 x 3 spacing (Grunwald et al. 1974). In Italy, an average of 7.5 sprouts per stump was found in *E. globulus* and *E. camadulenses*, 24-36 months after the first harvest (O Ciancio and R Morandini 1971). There was only a slight seasonality effect in the number of sprouts per stump found in Israel and Italy. A study of *E. globulus* in Portugal (Pereira et al. 1984) however, reported no significant differences on the number of sprouts per stump during different seasons of harvest.

While poplar trees will coppice primarily from root suckers, eucalypt sprouts grow from epicormic buds embedded in the bark which originate from axillary meristems. Each axillary meristem carry one emergent primary bud that may or may not grow into new sprouts and a sequence of accessory buds which grow each year and keep pace with cambial growth (Ceulemans et al. 1996). Another important characteristic found in many eucalyptus species is the presence of lignotubers that are directly associated with their sprouting system. Lignotubers are swellings formed in the axils of the cotyledons of the seedlings (Tredici 2001).

2.3 Known harvest issues in coppice systems

Coppice regeneration and sprout morphology vary greatly among tree species. Nevertheless, it has been proven that many external factors are also responsible for the regeneration response. These factors include: tree age at harvesting time, tree diameter, growing site, spacing, stump height, cutting equipment, stump damage, rotation length and harvesting season (Strong and Zavitkovskj 1983; Hytönen 1994). Seasonal harvesting has been widely discussed and most studies have shown that the cutting season causes major impacts upon coppice regeneration of some SRWC species by compromising the re-sprouting capability of the stumps (Strong and Zavitkovskj 1983; Ceulemans et al. 1996; Souza et al. 2016).

2.3.1 Season of harvest

The effect of seasonal harvesting on hybrid poplar coppicing was studied by Strong and Zavitovski (1983). The results showed that harvesting during the growing season discouraged coppicing. Stump survival was 92% for harvests that occurred from September to May, and less than 10% for harvests that took place during July and August. The study also concluded that height and DBH exhibited a seasonal harvesting difference. Heights and DBH measurements were considerably greater on the trees harvested during their dormant season.

For temperate tree species such as *Eucalyptus obliqua, E. occidentalis,* and *Platanus occidentalis,* regrowth is maximized by harvests during winter and minimized by harvests that occur during mid-summer (Blake 1983). De Souza (2016) studied the influence of seasonal harvesting on the re-sprouting response of 3 different species of SRWC plantations in the southeastern U.S. The study showed that harvesting eucalyptus (*Eucalyptus urograndis*) and cottonwood (*Populus deltoides*) during winter results in higher survival rates than harvesting during the summer.

It is important to consider that other factors might influence the coppice response. For instance, deciduous trees have seasonal carbohydrate cycles that are different when compared with evergreen trees. In deciduous species, the reductions in carbohydrate reserves from the roots are often more dramatic by the end of spring when the growing season commences. Hence, the deposition of starch (the primary carbohydrate reserve) reaches its maximum accumulation in the roots during late summer/autumn. While evergreen trees also promote a cycle where they use some reserve carbohydrates from the roots during the early growing season, compared to deciduous species, the changes in concentration of reserves are often relatively small (Oppong et al. 2002).

2.3.2 Stem crowding

The abundance of regenerated sprouts per stump in coppice plantations can be managed by either artificial thinning or natural thinning (Ceulemans et al. 1996). Natural thinning, also known as self-thinning, occurs mostly among the smallest shoots which favors the longevity of large shoots whose dominance increases (Verlinden et al. 2015). Artificial thinning is performed to minimize competition for water and nutrients among trees growing in close proximity. Generally, the small shoots are the ones removed in order to favor the dominant stems. Thinning operations in clumps tend to reduce competition among sprouts developing from the same stump, which results in more vigorous growth for the remaining sprouts.

Since SRWC are established for diminishing general costs and maximizing biomass production, knowing the optimum number of sprouts growing in a stump in order to achieve the maximum volume of biomass is crucial. However, there are still uncertainties related to whether it is necessary to interfere with the natural re-sprouting by thinning stems down to the desired number or to let the competition among stems naturally carry out this function via self-thinning.

Cacau et al. (2008) investigated stem crowding behavior of coppiced eucalyptus stands in Brazil and found that thinning down to 2-3 stems per stump had no effect compared to self-thinning after 42 months, which indicated that thinning young coppiced eucalypt trees was not necessary. A similar study with eucalyptus clones showed that drastic reductions of leaf area caused by thinning might compromise the carbohydrate fixation responsible for the growth of dominant stems developing nearby (Souza et al. 2012). Both studies proved that thinning has no impact over self-thinning. These results, however, were achieved in a tropical area with very different site-related characteristics when compared with the southeastern climate of the U.S. and only eucalyptus species were studied on these experiments, whereas SRWC involves a broader range of trees. In addition, different species and clones may also impact stem crowding. For instance, Souza et al. (2012) investigated re-sprouting density in coppice eucalyptus clones in Brazil. Among several clones evaluated, the variation GG100 (*Eucalyptus urophylla* x *Eucalyptus grandis*) resulted in a greater average number of stems per stump (3.5), while the hybrids *Eucalyptus urophylla*, *Eucalyptus camaldulensis* and *Eucalyptus camaldulensis* × *Eucalyptus grandis* only ranged from 1.8 to 2.2 stems per stump

For poplars, the number of shoots that re-sprout relies heavily on the species used (Ceulemans et al. 1996; Verlinden et al. 2015). Generally due to the self-thinning, the number of sprouts can be reduced up to 75% within the first growing year (Verlinden et al. 2015). Laureysens et al. (2003) investigated population dynamics of multiple poplar (*Populus*) clones. Significant clonal differences were found in stump mortality, biomass production, and number of stems per stump. The average number of stems per stump varied not only among the clones tested, but also in different rotations of harvesting. While the first rotation coppice ranged between 3 and 7 stems per stump, the second coppice resulted in an increase in shoot density ranging from 8 to 19 stems per stump. Similar results were found in Nassi O Di Nasso et al. (2010) where the number of shoots would increase after each rotation of harvest.

2.3.3 Rotation length of SRWC

The re-sprouting vigor and the lifetime of the regenerated stems from SRWC are directly dependent on the chosen rotation length (Kauter et al. 2003). Inappropriate cutting cycles can increase mortality of stumps, which completely inhibits regeneration during the next rotation. Many studies indicate a strong relationship between cutting-cycles and the productivity of SRWC stands (Deckmyn et al. 2004). In a long-term study in Italy, Nassi O Di Nasso et al. (2010) evaluated the biomass production of a 12-year-old plantation of poplar (*Populus deltoides*) under different cutting cycles (1-, 2-, and 3-years). Results showed different stump survival rates among treatments. There was a very rapid mortality rate under a 1-year cutting cycle, which resulted in only 5% stump survival after 7 years. By the end of the trial (12 years after first harvest), survival rates for 2- and 3-year cycles ranged on average from 15% to 29%, respectively. In addition, growth parameters such as stem size and number of stems per stump were found to significantly depend on cutting cycles.

In most timber plantations, the year when MAI peaks will determine the rotation length when maximum yield is the ultimate goal. Tree species and site characteristics are fundamental factors that dictate when the highest MAI of a plantation will occur. However, the density of SRWC also influences the year of maximum annual production. As many studies have previously reported, density and rotation length are closely related (Nassi O Di Nasso et al. 2010). Close-spacing plantations promote early MAI peaks in most cases, while wider-spaced plantations ensure the highest long-term biomass yields (Proe et al. 2002). Kauter (2003) states that for very short rotations (e.g., 3-4 years), close spacing is required. Dense stands in long rotation lengths (e.g., 7-10 years), however, reduce the growth vigor and also the number of shoots per stump when coppice is used (Johansson 1999; Kauter et al. 2003;).

2.3.4 Harvesting SRWC

Harvesting operations represent the highest input costs for SRWC management (Berhongaray et al. 2013). It is important to keep harvesting costs low in order to maintain the financial viability of the system. In the U.S. and Europe, some manufacturers have developed downsized feller-bunchers that are better suited to harvest small-diameter trees (Spinelli et al. 2007). Due to their smaller sizes, small-scale machines are more suited to operate within dense plantations of small trees. In addition, the capital investment is generally lower when compared to traditional machinery.

Feller-bunchers are generally more suited than harvesters when harvesting multi-stem coppiced trees, since they are more compact and have heads that approach the stems with less difficulty and can gather multiple trees (Schweier et al. 2015). One of the greatest challenges for harvesters is the physical difficulty involved with approaching multiple stems growing from a single stump. Small-scale feller-bunchers, such as skid-steers, have been considered an effective option for felling energy crops (Wilhoit and Rummer 1999). These tractors have an even more compact design, smaller cutting heads, and weigh less than traditional feller-bunchers.

According to product specifications of multiple manufactures from the U.S. and Canada (DFM, FECON, and DAVCO), cutting heads of small-scale feller-bunchers are designed to handle small trees, less than 38 centimeters in diameter. The utilization of small cutting heads better serves the needs of energy plantations, because these plantations are usually set up with narrow spacing, producing small and branchy stems (Schweier et al. 2015). The two known systems of small cutting heads used in North America are disc saw and shear head, which differ in their cutting mechanisms. Other essential features of cutting heads include the grabbing and accumulator arms. When using a shear head in a clump, the grabbing arm makes the first contact, hugging the bundle of stems together as the stems are severed at their base with a single cut. On the other hand, when using a saw head, the saw makes the first contact with the stem during the cuts. Subsequently the grabbing arms will perform the collection of stems. The accumulator arm allows the operator to repeat this cycle without having to dump the previous stems after they were cut. However, the process of felling trees may be limited by the capability of these grabbing arms for grasping multiple-stem trees with a single swing (Schweier et al. 2015; McEwan et al. 2016).

Schweier et.al. (2015) studied the productivity aspects of harvesting coppiced SRWC trees with different small-scale feller-bunchers. A felling study of single-stem and multiple-stemmed coppice (7-26 years old) of hybrid poplar, chestnut, mixed oak, and black locust trials was performed in Italy. Productivity in the single-stem stands were up to 10 times higher than that recorded in the multi-stem coppice stands. In this study, each stem was cut individually from the same stump, which explains the slower productivity for cutting the multi-stem trees. Although it was found that the circumference of the clump had no influence on time consumption, the order of cutting, size and number of stems significantly affected cycle-time for harvesting these trees.

McEwan et al. (2016) conducted a time study analysis on a harvester in order to determine whether stem crowding had an impact on harvesting productivity in *Eucalyptus urograndis* stands in South Africa. The trees were approximately 11 years-old and they predominantly consisted of single and double-stem stumps with very few occurrences of 3 stems per stump. The regression analysis performed on this experiment indicated that both tree size and stem crowding had a significant effect on the productivity of the harvester. Productivity was found to increase with stem size and decrease with number of stems per stump.

Alternative cutting machines have been proposed. In 2003, efforts to develop a harvesting system for willow biomass crops in the U.S. were based on a tractor that was designed to cut and chip willow crops in one pass. Results from the first trial indicated that the chipper produced an unacceptable number of long stringers and chips of inconsistent size and quality. In 2008, Case New Holland started an effort to develop a single pass harvesting system for willow biomass crops. The proposed machine contained a prototype short rotation coppice header (130FB) on a forage harvester (FR9000). The main abilities of these machines include harvesting double rows of stumps containing stems up to 120 mm in diameter, and to produce specific sizes of chips (Eisenbies et al. 2014).

Harvesting operations on coppiced trees can be technically difficult due to the accumulation of stems growing from the same stump. Most of the current equipment for tree harvesting is designed to function in single-stem plantations instead of multiple-stem. New cutting technology for SRWC has been proposed in an attempt to handle these harvesting challenges efficiently. However, research must continue to determine which approaches and techniques should be used to handle these harvesting challenges efficiently.

III. Materials and Methods

3.1 Site Description

Two sites were selected for this study. The sites are located in south Florida and central Arkansas (Figure 1). Sites were established during a previous study (Souza et al. 2016). The sites had split plot designs with season of harvest and a treatment for felling method for each plot. The study plots in both sites were approximately 2 acres in size, 1 acre per treatment.

The distance between the closest weather station where the data were collected and each study site was 5 miles in Florida and 10 miles in Arkansas. All soil information was obtained online from the soil map of the USDA – Natural Resources Conservation Services Soil Survey (http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx), and all historic weather from the web page *weather underground* (https://www.wunderground.com/).

Figure 1: Location of 2 study sites. One in South Florida, and one in Central Arkansas.

3.1.1 Fort Pierce, FL

This study site is located in South Florida, at coordinates: 27.3981,-80.4900. The soil type is classified as Winder loamy sand, mainly composed of sand and loam. This soil is a deep soil with restrictive features at more than 2 m deep and a water table found at approximately 30 to 45 m deep. This location was previously bedded for use for citrus plantations. Due to the bed configuration, there was a wider spacing of 4.2 m, between every 5 rows, which allowed for drainage in between the beds. The site was planted with clonal *Eucalyptus urograndis* on 15 m wide beds and was 2 years-old at the time of harvest in 2013. The planting spacing was 2.7 m between rows by 1.8 m between trees, which resulted in a density of 1800 trees/ha. The average DBH was 12 cm, and the average height was 14 m.

The study plot was divided into 2 treatments – summer and winter harvest. Each treatment consisted of 4 beds, with 5 rows of approximately 20 trees per row, totaling approximately 400 trees per treatment. Initial harvests at this site occurred during the months of December of 2013 and May of 2014 for the winter (dormant) and summer (growing) season treatments, respectively (Figures 2, 3, and 4).

Figure 2: Eucalyptus site. Picture taken right after harvest (winter harvest treatment). 15 m wide bed with 5 rows at 2.8 m apart, with a gap of 4.2 m between beds.

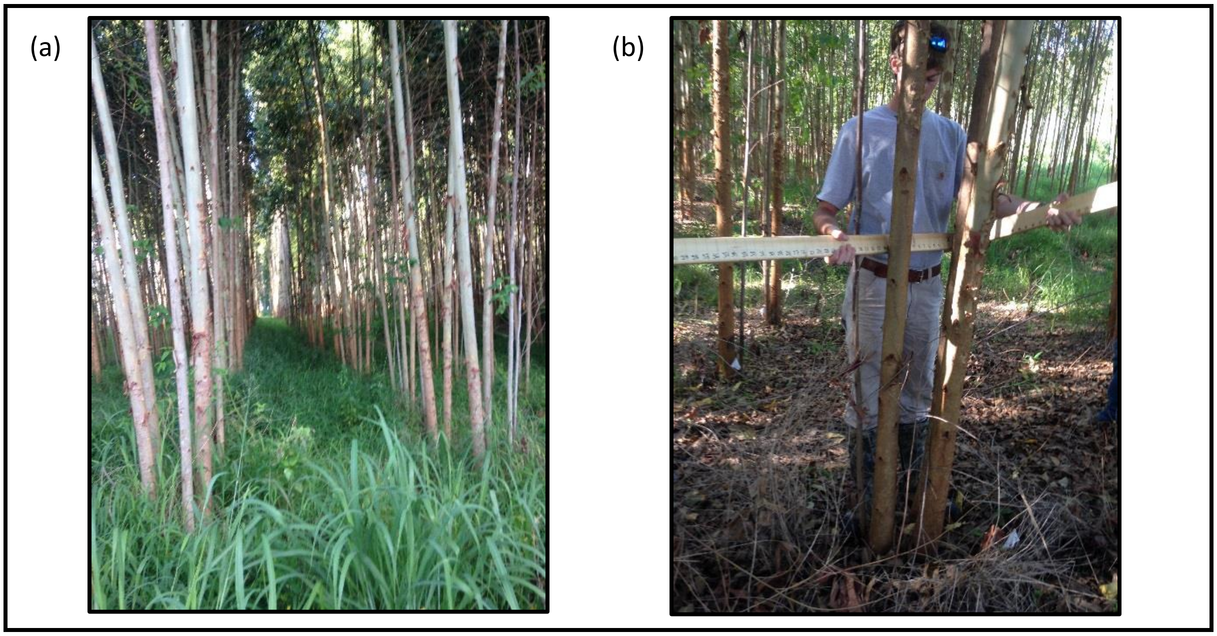

Figure 3: Eucalypts site: (a): Picture taken from the same site as Figure 2, 2 years after harvesting. (b): Clump dimension measurement.

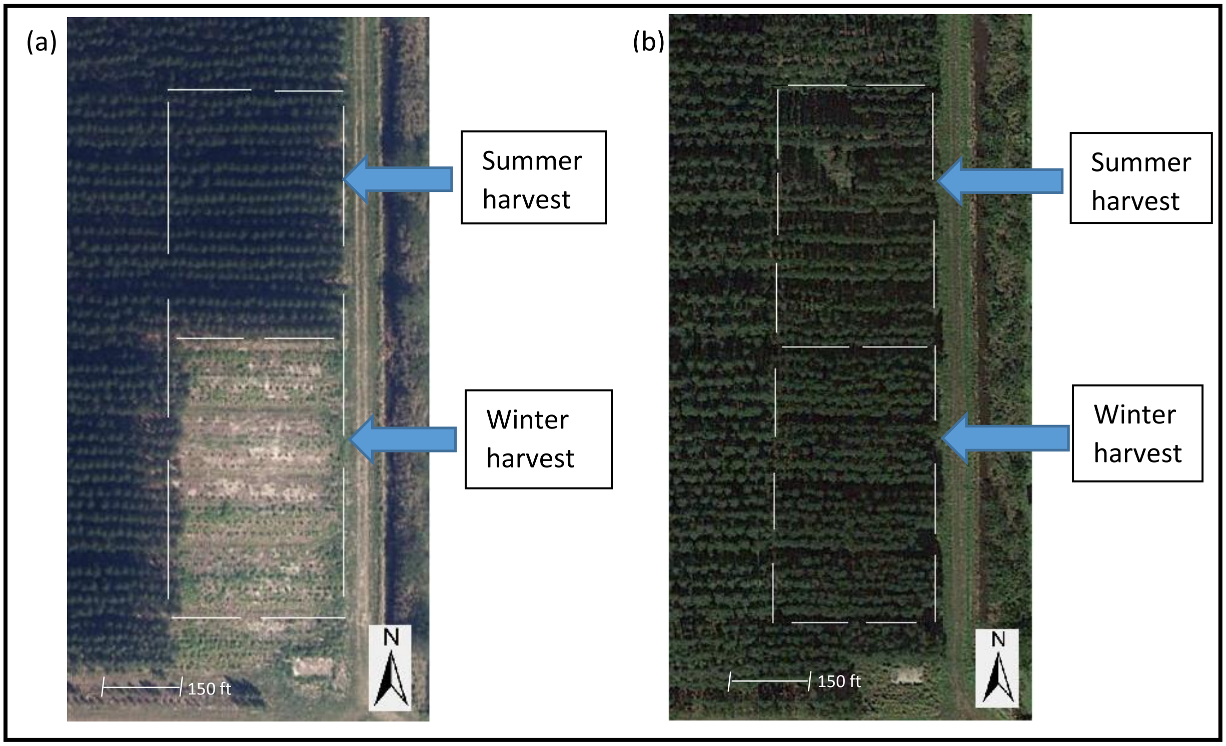

Figure 4: Aerial footage of seasonal treatments: (a): Picture taken shortly after winter treatment was harvested. (b): Picture taken 2 years after winter treatment harvest, and 1.5 years after summer treatment harvest.

3.1.2 Little Rock, AR

The cottonwood study site is in central Arkansas, approximately 32 kilometers southeast of Little Rock, on the east side of the Arkansas River (coordinates: 34.6040, -92.0160). The soil type is classified as Keo silt loam, mostly composed by silt loam. This type of soil is considered deep-soil, well-drained with the restrictive features and water table found at a depth of over 2 m. This site was planted with Cottonwood (*Populus deltoides*) seedlings, and at the time of harvesting, this plantation was approximately 3 years old and single-stemmed. Spacing was set with a double row system; 0.7 m spacing between trees in a row, with 1.8 m apart from the next double row. The DBH averaged 4.6 cm, and the height average was 8.8 m. Two treatments were installed for harvesting the trees – summer and winter harvest. Each treatment consisted of 6 double rows with approximately 70 trees per double row, totaling approximately 420 trees per treatment. The dates of harvest were March of 2014 in the winter plot, and June of 2014 in the summer plot.

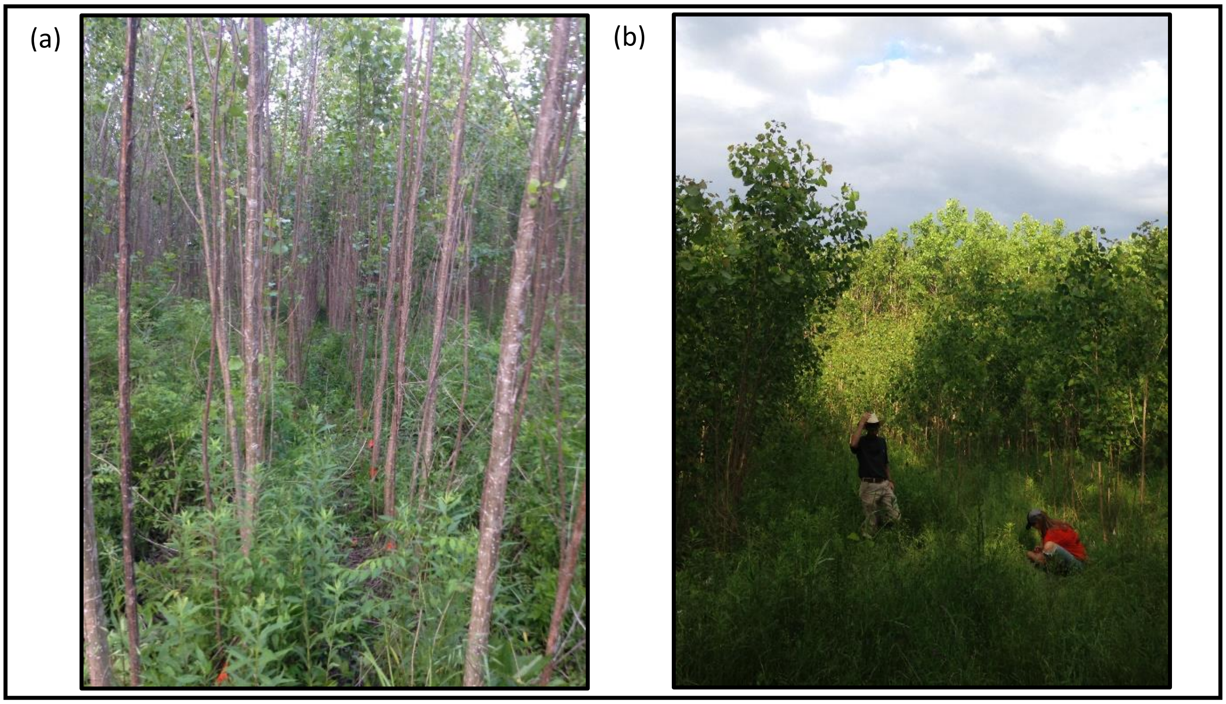

Figure 5: (a): Winter plot of coppice cottonwood at age 2. (b) Summer plot of coppice cottonwood at age 2.

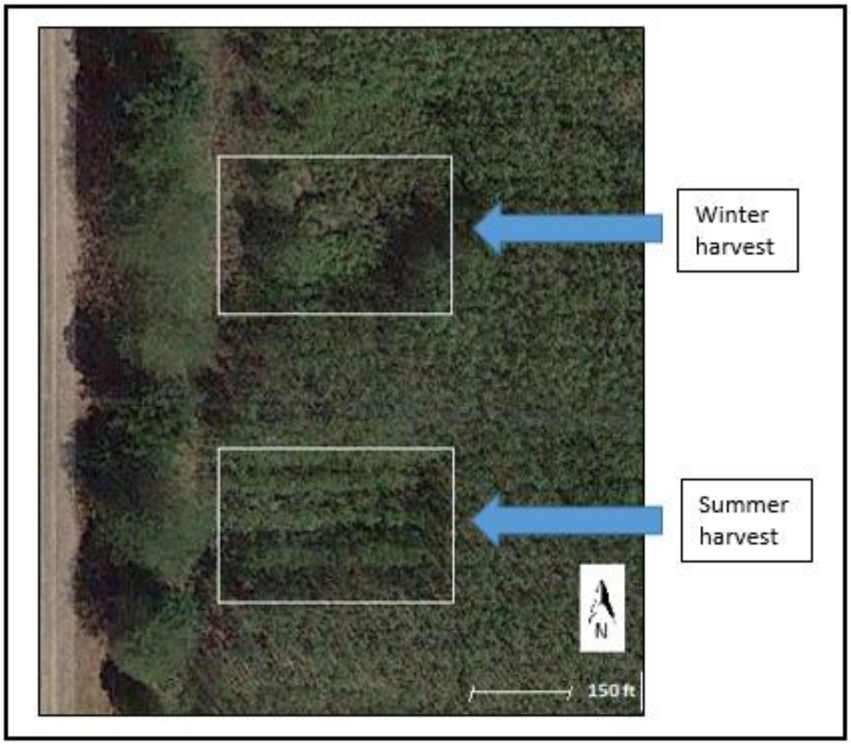

Figure 6: Aerial footage of seasonal treatments at approximately 2.5 years after winter harvest, and 2 years after summer harvest.

3.2 Evaluation schedule

Each plot was visited twice for data collection. In order to be more accurate and fairly divide the period of evaluations by growing seasons for winter and summer plots, we used growing degree days to schedule subsequent visits to each plot. After harvesting, the assessments in summer and winter plots occurred at approximately 6 months (1st evaluation) and 2 years (2nd evaluation) (Table 1). All information regarding growing degree days were obtained online from *Weather Underground* (https://www.wunderground.com/; http://www.degreedays.net/). The degree days of each site were calculated by dividing the average temperature of each day (i.e. the sum of maximum temperature and minimum temperature divided by 2), and subtracting the ‘’temperature base’’. The temperature base is the temperature below which plant development stops. Most crops have their own temperature base well defined (e.g. canola, mustard, pea). The temperature at which growth starts for woody plants in the

U.S. is approximately 7.2° to 12.7° C; to standardize the calculations for determining a growing degree day, the temperature base has been set at 50° C (Miller et al. 2001; Siegert, N. W. et al. 2015). Hence, 10° C was the temperature base used for calculating growing degree days for both eucalyptus and cottonwood sites.

Table 1: Growing degree days (GDD) for each treatment and species.

Assessments	Location	Species	GDD ≈ Months (summer plots)	GDD ≈ Months (winter plots)
1st Evaluation	Florida	*E. urograndis*	5460 ≈ 6	2935 ≈ 5
	Arkansas	*P. deltoides*	3760 ≈ 7	4440 ≈ 7
2nd Evaluation	Florida	*E. urograndis*	17,630 ≈ 24	17,190 ≈ 24
	Arkansas	*P. deltoides*	11,073 ≈ 23	11,201 ≈ 22

3.3 Clump Dimension Analysis

The dispersion of the stems was collected during the second evaluations (i.e. after 2 years of coppice growth) at both sites: Eucalyptus – June 2016; Cottonwood – May 2016. Schweier et al. (2015) measured total clump circumference at breast height, but harvested each stem individually. The method for this study provided more detail regarding individual stem distribution and the associated limitation to current cutting heads. The methodology used for data collection involved developing a two dimensional ruler (i.e. x and y axis). The dimension of multi-stem stumps was analyzed in a way so that the first stem (arbitrary chosen) was repeatedly recorded as the initial vertex, or "stem A'' (i.e. x = 0, y = 0). Other stems were recorded according to their spatial position within the ''x'' and ''y'' axis relative to stem A. For example, if a second stem "stem B" was located 10 dm apart from the first stem, its position would be recorded as either (0, 10) or (10, 0). For instance, in case of a third stem "stem C" and so forth, its location would be recorded according to its ''coordinates'' (i.e. x, y) in relation to the initial vertex (i.e. stem A: 0, 0) (Figure 7).

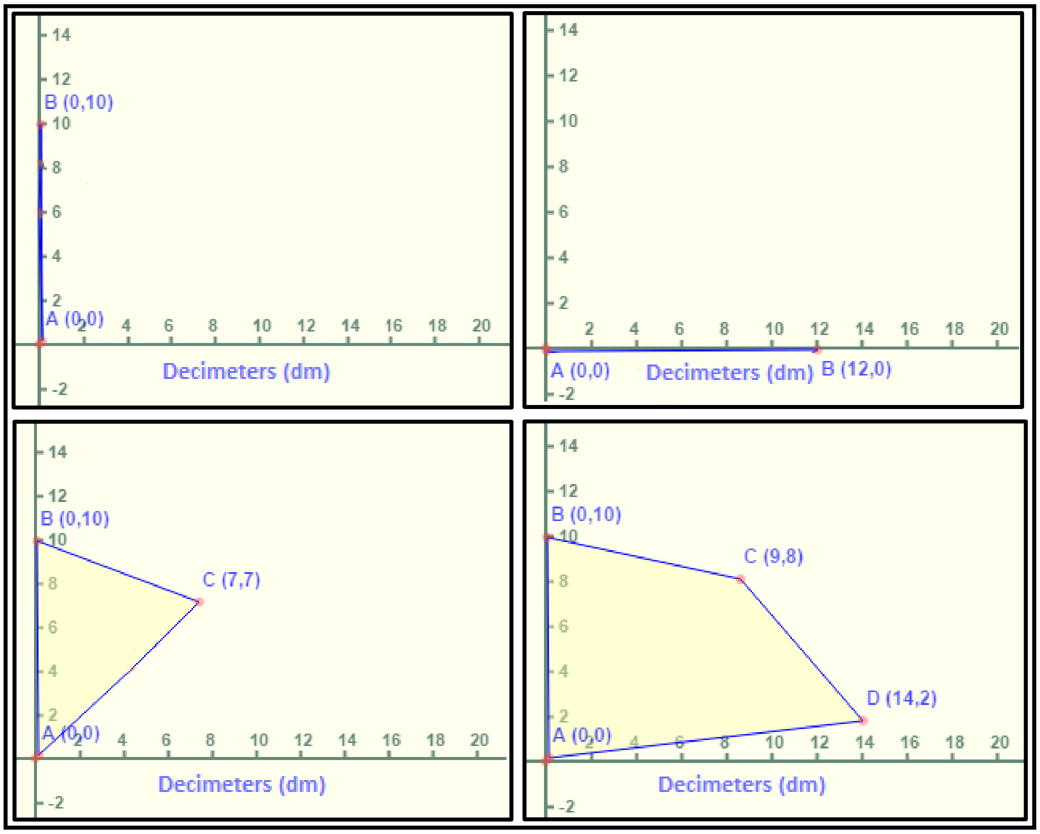

Figure 7: Clump geometry: each graphic simulates a coppiced stump; each dot simulates a stem.

We identified the longest distance between stems in the same stump. Since the purpose of this analysis was to verify whether the spatial arrangement of stems were within the collecting perimeter of a felling machine, the measurements of arrangement were taken at DBH level, which is approximately the same height where grabbing arms are usually mounted on felling heads. Most small scale feller-bunchers manufactured in the U.S. have their grabbing arms set at a height of approximately 1.5 meters above the ground, and are approximately 76 cm long. For this project, two common manufacturers of small scale feller-buncher cutting heads in North America were used as references (FECON and DFM), and all equipment information was collected through online specification sheets provided by each of these companies.

The movement executed by the grabbing arm was also taken into account. The arm opens and closes creating an angle of approximately 100 degrees. This movement allows for the grasping of multiple stems that are spread within the length of the grabbing arm (76 cm). When opened, the movement of 100 degrees displays an approaching interface (i.e. cutting head frame + grabbing arm) that is a few cm longer than the actual arm (90 cm) (Figure 8). Theoretically, this range should allow for the grabbing arm to grasp stems that are further than 76 cm apart, however, the closing movement could cause potential damage to these stems when reaching and grasping all stems at once. Thus, a threshold of 76 cm will be used as an assumption for a limiting distance between stems that could potentially hinder the operability of the machine.

Figure 8: Fecon shear head with opened grabbing arm.

3.4 Coppice Development & Yield

Two evaluations in each plot were conducted on different dates in accordance with the schedule of growing degree days (Table 1) for coppice development analysis. The first assessment was conducted by Souza et al. (2016) for his Master's thesis. The purpose of the initial assessment was to analyze stump survival, stem crowding (i.e. number of stems per stump), and stem height. Each stump was individually analyzed, and, if the stump presented any sprouting regeneration, it was recorded as a live stump. Since the number of sprouts per stump was substantially large and the sprouts were somewhat small, only the dominant heights were recorded. The dominant sprout was considered the tallest individual among all the sprouts in the same stump.

During the second assessment completed for this thesis, the number of stems per stump were counted, and measurements of height and DBH of all stems were recorded for each stump. The height of stems was measured with a clinometer, taking the ground level as the base, and the top of the trees as the tip. Stump mortality was determined by the absence of any regeneration response.

The volume formula for the eucalyptus was chosen from a study with similar site characteristics that modeled volume production of 3-year-old eucalyptus clone U6. The site is located in South China with annual average temperature of 23^{o} c, ranging from 16^{o} c to 28^{o} c. The trees ranged within an acceptable spectrum of DBH (9-16 cm), average height of 14 m, and spacing of 1.3 x 2.7 m. In total, approximately 180 trees were used for developing this model (Yang et al. 2009):

$$V = 0.00004\ D^2\ H$$

Where:

V: Volume outside bark (cubic meters m^3)

D: Diameter at breast height (cm)

H: Tree height (m)

The equation for cubic-foot volume for *P. deltoides* was re-introduced by Krinard (1988), but it was originally developed by the same author in 1971 in a 4-year-old plantation of cottonwood (*Populus deltoides*).This equation is applicable to most commercial spacings of the U.S. eastern cottonwood plantations that present DBH classes ranging from 5 to 23 cm. Therefore, this formula is considered appropriate for young cottonwood trees:

$$\text{TVOB} = 0.06 + 0.002221\, D^2H$$

Where:

TVOB = Total tree volume outside bark in cubic feet.
D = Diameter at breast height (dbh) in inches.
H = Total height in feet.

3.5 Regression Analysis

Since fewer stems growing in a stump favors mechanized harvesting (Schweier et al. 2015; McEwan et al. 2016), we assumed that 1 or 2 stems per stump would be preferable over 3 or more in order to ensure adequate harvesting conditions. The data analysis for this project used statistical tools to determine the effects that the independent variables stump *damage* and *stump diameter* (collected during first assessment) have on the dependent variable, *stem crowding* (number of stems per stump). The *stem crowding* variable was reflected as a binary variable: desired (stumps with 2 or fewer stems) or undesired (stumps with 3 or more). Two independent variables were chosen as estimators of a potential effect upon the response variable. The independent variable *stump damage* is categorical with 2 levels (0 or 1), each representing the damage caused on the stump at harvesting time. The stumps that suffered none, or minimal damage caused by either the skidder or skid-steer during initial harvesting were classified as 0. Stumps that showed signs of damage on the bark and stump (i.e. barber chair, missing chunk(s), split, fiber pull, and shattered stump) were classified as 1. The second variable used was *stump diameter*. All stumps from both seasonal plots were included in this analysis. The Statistical Analysis System (SAS, 9.4 for windows) was used to perform the analysis. A logistic regression was used to estimate the probability of having 1 or 2 stems growing from the same stump at age 2. The logistic procedure is appropriate when handling binary outcomes (i.e. yes or no), or ordinal outcomes (i.e. normal, mild and severe).

Two final equations were generated for each species studied in this project. The same variables were included in both regression analyses, although the significant variables differed in each case. Tables with p-values of all variables including potential interactions in the model are displayed in the results chapter for each species analyzed. The generic logistic model is represented by the classical equation:

$$p = \frac{e^{(a+bx+cy+)}}{1+e^{(a+bx+cy)}}$$

where p represents the probability of achieving "desired" (2 or fewer stems per stump), a is the intercept, b is the parameter associated with the variable *stump damage*, c is the parameter associated with *stump diameter* (cm) and e is the base of the natural logarithm. The alternative hypothesis (H_a) states that there is a relationship between the binary response (desired or undesired) and either of the independent variables *bark damage* or *stump diameter*. The null hypothesis assumes that none of the independent variables mentioned above have an impact on stem crowding.

IV. Results and Discussions

4.1 Stem crowding analysis

4.1.1 Eucalyptus site

At approximately 2 years after harvesting, the overall average number of stems per live stump was 2.6, with a minimum of 1 and maximum of 6. Descriptive statistics are listed by season and age of evaluation in Table 2. The decreasing standard deviations from age 0.5 to 2 is a consequence of self-thinning in each stump.

Table 2: Key statistics of stem crowding per individual stump of eucalyptus in Florida (α = 0.05).

		N Stems	Mean Stems/stump	Max Stems/stump	Min Stems/stump	Standard Deviation
Summer						
Age	0.5	1515	4.58 ± 0.20	12	1	1.86
	2	835	2.54 ± 0.01	5	1	0.91
Winter						
Age	0.5	1673	4.24 ± 0.19	13	1	1.92
	2	1042	2.65 ± 0.09	6	1	0.95
Overall total at age 2		1877	2.6	6	1	

Figure 9 displays the number of stems per stump for each age group and harvesting season. The distributions have a pattern in which the number of stems per stump are more evenly distributed from 2 to 6 stems from the first data collection (6 months after harvest). This distribution changed during the second evaluation (2 years after harvest). Due to the competition for resources from the same stump, self-thinning is the most likely cause for the decrease in number of stems from age 0.5 to 2 (Ceulemans et al. 1996; Cacau et al. 2008). The mode at age 2 is 2 or 3 stems per stump in both harvesting seasons.

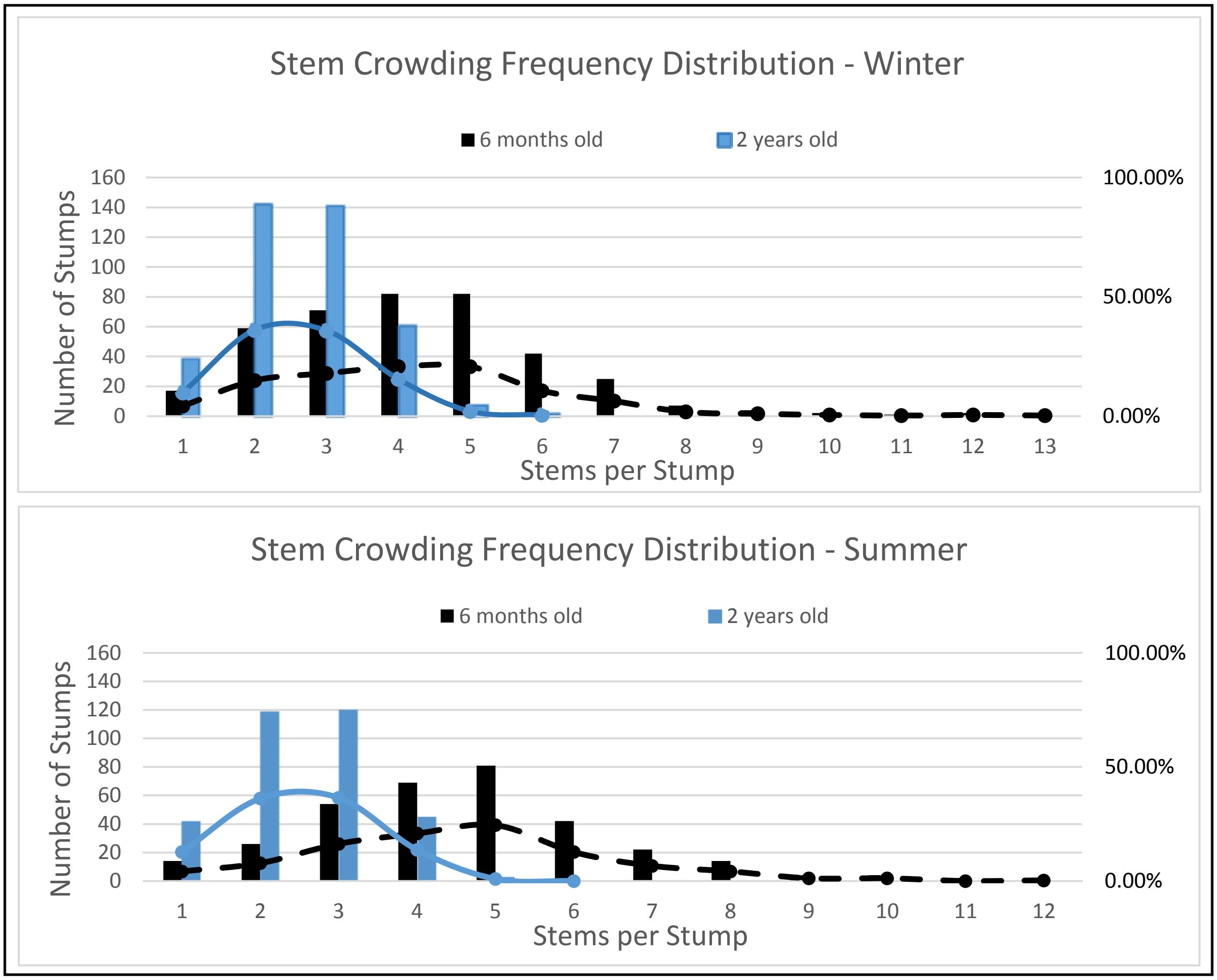

Figure 9: Distribution of stem crowding frequency at 2 different ages: (a) Winter harvest distribution; (b) Summer harvest distribution.

Both summer and winter plots showed similar configurations for stem crowding 2 years after harvest. Figure 10 indicates that among the stumps that exhibited coppicing activity, only 10% were single-stem while approximately 90% consisted of 2 or more stems per stump in both seasonal plots.

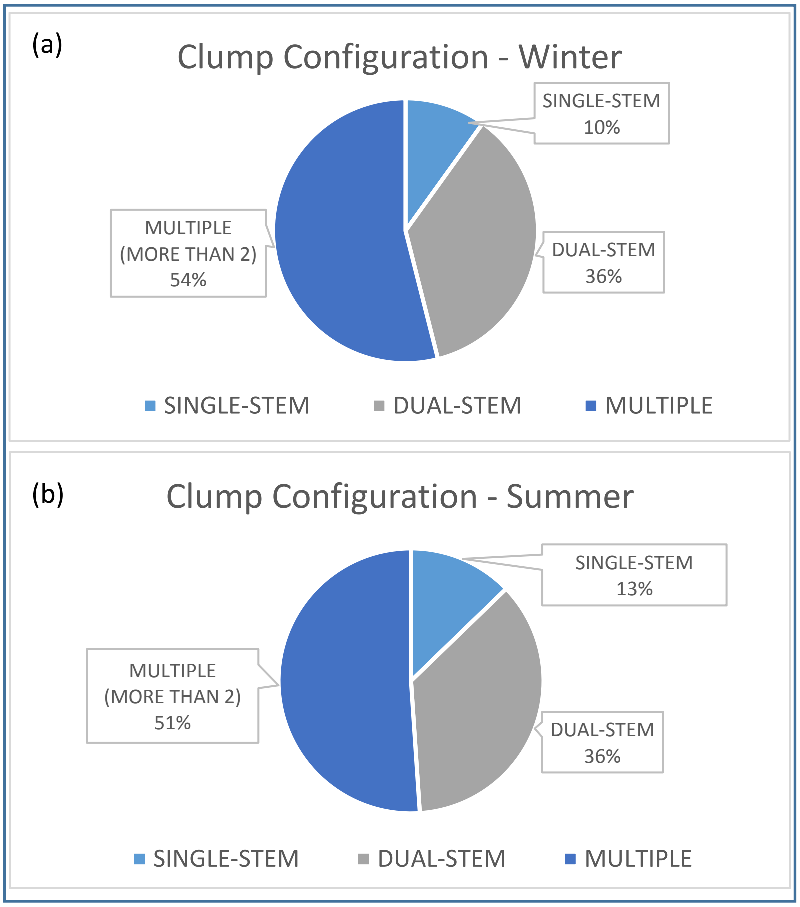

Figure 10: Clump configuration by seasons of harvest at age 2: (a) Winter harvest stumps; (b) Summer harvest stumps.

From a standpoint of mechanized harvesting, a stand with approximately 90% of the stumps being multi-stemmed is a result that is often not desired. Multiple stems are likely to cause various challenges during the cutting process. These challenges involve grasping, accumulating and cutting multiple stems at the same time which might increase the cycle-time and decrease productivity (Schweier et al. 2015; McEwan et al. 2016).

It is important to point out that stump survival was not included in Figures 8 and 9. Although stem crowding was not affected by season of harvest, the winter plot presented a higher stump survival, which resulted in a better regeneration response compared to the summer cutting (Table 3).

Table 3: Stump survival of eucalyptus over time by harvesting seasons.

Winter Harvest				Summer Harvest			
Timeline	Live Stumps	Live Stems	Stump Survival	Timeline	Live Stumps	Live Stems	Stump Survival
Harvesting	431	431	-	Harvesting	435	435	-
0.5 year	395	1673	90 %	6 months	331	1515	75 %
2 years	393	1042	89 %	2 years	329	835	74 %

Stump survival results from the first evaluation (6 months after harvest) showed that coppice response is affected by season of harvest as already found in similar studies where harvesting trees during the summer reflected a reduced coppicing response (Strong and Zavitkovskj 1983; Hytönen 1994). When stump mortality was evaluated for the second time (2 years after harvest), we noted that only 2 stumps died from both treatments which represented approximately 1 % of stump mortality from age 0.5 to 2 (Table 3).

4.1.2 Cottonwood site

At approximately 2 years after harvesting, the overall average of number of stems per stump was 1.35, with a minimum of 1 and maximum of 5. The total number of stems found in the summer plot was nearly half the total number of stems found in the winter plot at both ages. Similar to the eucalyptus trees, the decreasing standard deviation from ages 0.5 to 2 is a consequence of self-thinning occurring in each stump. Descriptive statistics are listed by season and age in Table 4. The frequency distribution of stem crowding of the cottonwood trees was somewhat different from the eucalyptus, especially at age 2 where single-stem stumps were clearly predominant (Figure 11).

Table 4: Key statistics of stem crowding per individual stump of cottonwood in Arkansas (α = 0.05).

		N Stems	Mean Stems/stump	Max Stems/stump	Min Stems/stump	Standard Deviation
Summer						
Age	0.5	566	2.7 ± 0.30	11	1	2.2
	2	288	1.4 ± 0.10	5	1	0.74
Winter						
Age	0.5	1047	2.7 ± 0.17	13	1	1.75
	2	497	1.3 ± 0.06	4	1	0.61
Overall total at age 2		785	1.35	5	1	

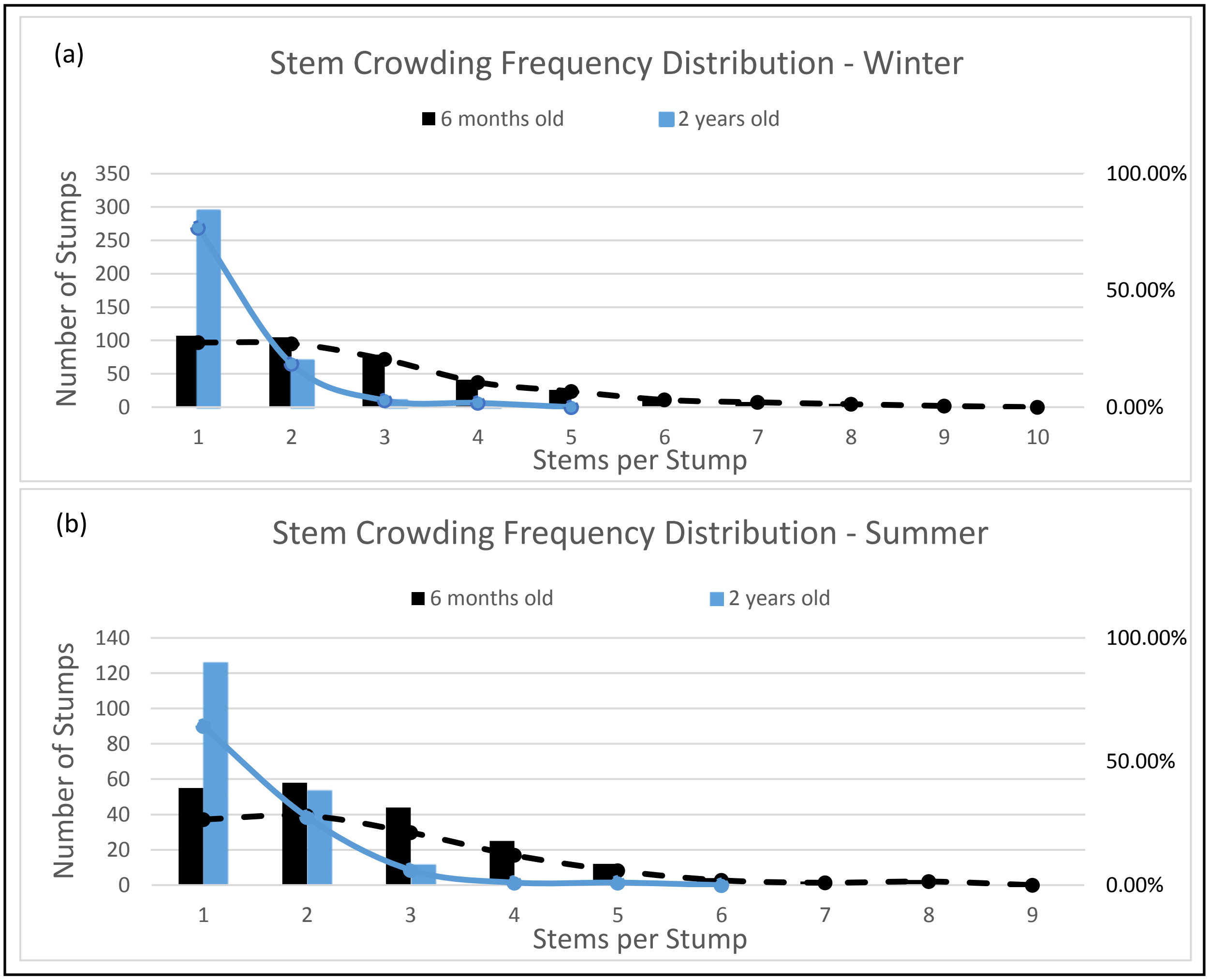

Figure 11: Distribution of stem crowding frequency at 2 different ages: (a) Winter harvest distribution; (b) Summer harvest distribution.

Unlike the eucalyptus trees, more than 60% of the stumps were single stem. An outcome like this facilitates mechanized harvesting. However, from a biomass production standpoint, this result may not be beneficial since the final volume achieved from multiple-stem stumps may be greater. A more detailed analysis of volume and final yield is explained in the *Yield* section of this document. Figure 12 illustrates the proportion of single, dual, and multiple-stem stumps of the cottonwood trees at age 2.

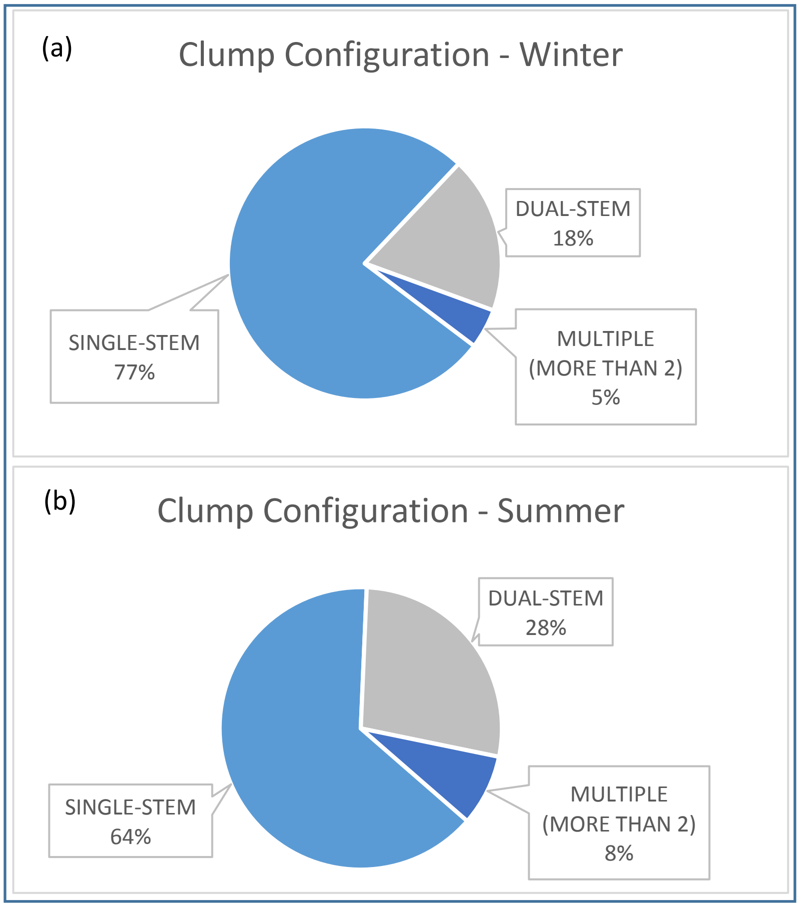

Figure 12: Clump configuration by seasons of harvest at age 2: (a) Winter harvest stumps; (b) Summer harvest stumps.

Similar to the eucalyptus, stump mortality was also minimal from age 0.5 to 2, indicating that once successfully re-sprouted, the stumps are likely to remain alive (Table 5). As reported in Souza et al. (2016), season of harvest had an even greater impact on the cottonwood trees (summer survival less than 50%). The lower survival of cottonwood stumps compared to the eucalyptus can be explained by the fact that cottonwood trees are deciduous, and therefore their re-sprouting ability is more responsive to seasonality of harvesting (Oppong et al. 2002). In addition, another likely reason for the high stump mortality of the cottonwood stumps (summer treatment) could be explained by the presence of grass in the summer plot of the cottonwood trees, which probably reinforced this outcome by increasing vegetative competition for local resources.

Table 5: Stump survival of cottonwood over time in 2 different seasons of harvest.

Winter Harvest				**Summer Harvest**			
Timeline	**Live Stumps**	**Live Stems**	**Stump Survival**	**Timeline**	**Live Stumps**	**Live Stems**	**Stump Survival**
Harvesting	401	401	-	Harvesting	425	425	-
0.5 year	386	1047	96 %	6 months	207	566	49 %
2 years	383	497	95 %	2 years	196	288	46%

4.2 Clump dimension

The results from this analysis indicate that the dispersion of multi-stem stumps would not affect machine operability when using a small-scale cutting head. At age 2, both seasonal plots exhibited that 99 % of stems on all coppiced trees had a dispersion of less than the threshold (76 cm) for the eucalyptus trees, and thus could be harvested in one cutting cycle (Table 6). The cottonwood trees presented a similar result where none of the stumps of the winter plot exceeded the cut-off, and only 1 % of the summer harvest trees exceeded it.

Table 6: Clump dimension analysis of eucalyptus and cottonwood. Dispersion of stems within each stump in different harvesting seasons at age 2.

Species	Winter Harvest			Summer Harvest		
	Operation	Distance apart (cm)	Frequency of stumps	Operation	Distance apart (cm)	Frequency of stumps
Ecalyptus urograndis	Max	135	-	Max	118	-
	Mean	35	-	Mean	34	-
	Mode	25	-	Mode	25	-
	>76 cm	-	4 ≈ 1%	>76 cm	-	4 ≈ 1%
Populus deltoides	Max	69	-	Max	116	-
	Mean	27	-	Mean	32	-
	Mode	23	-	Mode	30	-
	>76 cm	-	0 ≈ 0%	>76 cm	-	2 ≈ 1%

These results identify that clump dimension should not have a limiting effect on mechanized harvesting, however, it does not prove that the frequency of re-sprouting (stem crowding) is not a limiting factor for mechanized harvesting operations. For instance, similar studies have shown that stem crowding negatively affected machine productivity. Schweier et al. (2015) investigated machine productivity of new small-scale feller-bunchers on plantations of poplar coppice. The number of stems per stump as well as clump circumferences were examined and tested as potential hindrances towards machine performance. Results showed that while clump circumference did not present a significant impact on machine efficiency, the productivity achieved on single-stem trees was approximately 10 times greater than the productivity found in the coppiced trials. However, it is important to point out that the feller-buncher used to harvest the coppice trees did not have an accumulator arm, which probably affected machine performance on multi-stem trees. The poplar trees analyzed in the aforementioned study were approximately 7 years old, which indicates that clump circumference, or "clump dimension", should not be an issue at 7, nor at age 2, as our results indicate.

4.3 Logistic regression

4.3.1 Eucalyptus

We combined trees from both treatments, generating a total population of 722 stumps for further analysis. *Stump diameter* ranged from 3.3 to 24.13 cm with an average of 13 cm. The majority of the stumps (66%) were not damaged during harvesting while the remaining 33% presented clear signs of damage (Souza et al. 2016). Interactions among the predictor variables were tested by adding the factor *stump damage*stump diameter*. The significance of the factors was determined at α = 0.05. No significant interactions were found among the variables tested (p-value = 0.41). The p-values for the model validation were also significant at α = 0.05 (Wald = <.0001; Likelihood Ratio = <.0001). By combining these variables, the hypothesized stem crowding logistic model is represented by the equation:

$$p = \frac{e^{(a+bx+cy)}}{1+e^{(a+bx+cy)}}$$

where *p* represents the probability of achieving the "desired" condition for harvesting (2 or fewer stems per stump), *a* is the intercept, *b* represents the parameter estimate for the variable *bark damage*, *c* is the parameter for *stump diameter* (cm), and *e* is the base of the natural logarithm. Both variables are significant indicators of stem crowding on eucalyptus coppice (Table 7).

Table 7: P-values, odds estimates, and estimated parameters for effects of stump diameter and damage on stem crowding.

Variables	P-value	Parameter Estimators	Odds Point Estimates	Odds Ratio Confidence Limits	
Stump Diameter (cm)	0.0002	-0.0972	0.907	0.862	0.955
Bark Damage	0.0010	0.2589	1.697	1.239	2.325
Intercept	0.0052	0.9713	-	-	-

The odds point estimates will increase or decrease the odds of success (desired) by each change in unit of the variables. For instance, the odds of success for *stump diameter* would decrease by approximately 10 % if moving from diameter 5 to 6 cm (i.e. $\text{odds}_{5\text{ cm}} = \text{odds}_{6\text{ cm}} * 0.097$). The same is valid for the variable *bark damage*, though the odds of success would increase from damage categories 0 to 1.

The positive relationship between *stump damage* and the probability of *desired* (2 or fewer stems) indicates that the damage caused on the stumps at harvesting will decrease the chances of having a greater numbers of shoots per stump. This result can be explained by the fact that the axillary buds that regenerate sprouts in eucalyptus trees are embedded in the bark (Ceulemans et al. 1996), and the damage caused during harvesting probably compromised those buds. Our data suggests that *stump damage* favors mechanized harvesting by reducing the likelihood of a larger number of shoots per stump. However, this is a delicate inference as the damage caused during harvesting on the stumps can also result in very high stump mortality rates preventing any regeneration whatsoever (Hytönen 1994). In addition, further analysis is needed in order to determine whether there is a relationship between stump damage and tree age at the time of harvesting. For instance, depending on the age, stump diameters will vary, and it is possible that larger stumps would have a greater likelihood of being damaged.

On the other hand, the variable *stump diameter* showed a negative relationship with *desired*, indicating that larger stumps are more likely to regenerate more shoots. Figure 13 displays the estimated relationship among the variables tested. Residuals tests were performed in order to confirm that the assumption of homoscedasticity was not violated.

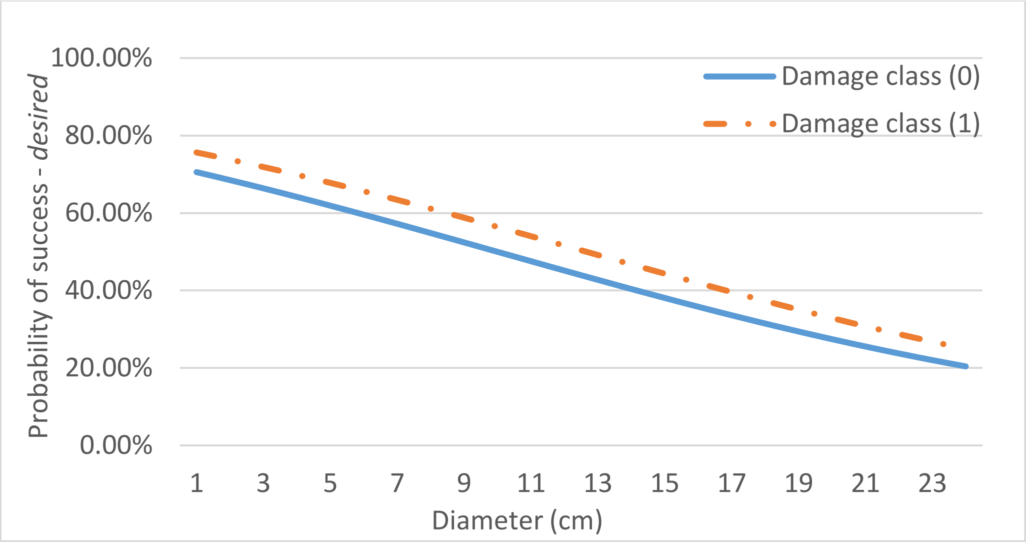

Figure 13: Logistic regression curves predicting the probability of achieving desired: 2 or fewer stems per stump

4.3.2 Cottonwood

The variable *stump diameter* ranged from 1.0 to 12.1 cm with an average of approximately 5.0 cm. In total, 550 stumps from both summer and winter plots were individually evaluated. Only 32 stumps fell into the category *undesired* as 518 stumps were categorized as *desired*. No significant interactions among the 2 variables tested was found (p-value = 0.2). Unlike the model developed for the eucalyptus trees, the variable *stump damage* did not achieve significance (p-value = 0.09) at α = 0.05. The p-values for the model validation were also significant at α = 0.05 (Wald = <.0001; Likelihood Ratio = <.0001). The majority of the stumps (90%) did not have signs of damage while the remaining 10% were damaged. This result could be explained by the fact that the harvested cottonwood trees were considerably smaller in diameter than the eucalyptus, allowing for smoother and faster cuts, and preventing damage. Thus, the stem crowding logistic model is represented by the equation:

$$p = \frac{e^{(a+bx)}}{1 + e^{(a+bx)}}$$

where *p* is the probability of achieving *desired, a* is the intercept, *b* represents the parameter estimator of *stump diameter* and *e* is the base of the natural logarithm. Table 8 displays the estimated parameter values with its respective p-values for the variables tested, and odds ratio estimates. The parameter estimates for both factors was significant at α = 0.05.

Table 8: P-values, odds estimates and estimated parameters for effects of stump diameter on stem crowding.

Variables	P-value	Parameter Estimators	Odds Point Estimates	Odds Ratio Confidence Limits	
Stump Diameter (cm)	<.0001	-0.4876	0.614	0.513	0.735
Intercept	<.0001	5.49	-	-	-

Figure 14 displays the relationship between *stump diameter* and the probability of *desired* (2 or fewer stems per stump). Similar to the eucalyptus trees*, stump diameter* showed a negative relationship with the response (2 or fewer stems), indicating that cottonwood trees with large stump diameters are likely to generate more shoots after cutting.

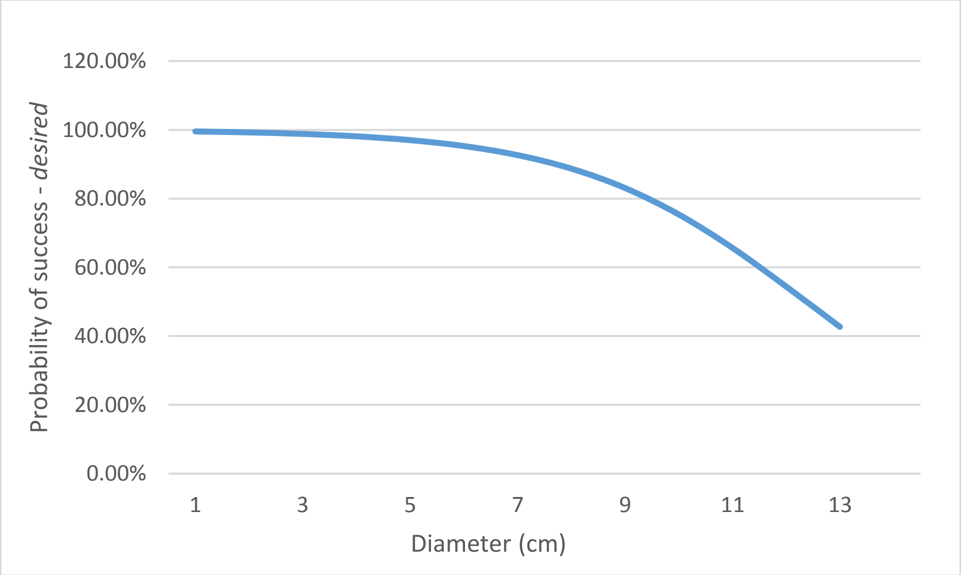

Figure 14: Logistic regression curves predicting the probability of achieving the outcome ‘’desired’’: 2 or fewer stems per stump

The variable *stump diameter* was more important with the cottonwood trees than with the eucalyptus. The steepest decline was observed when *stump diameter* ranged from 7-13 cm. The value found for the parameter estimate of *stump diameter* (-0.4876) is the primary cause of this occurrence. In the eucalyptus trees, the parameter estimate of *stump diameter* was much closer to zero (-0.097), thus it generated a curve that was almost linear. Although these results indicate that stump diameter is more responsive to stem crowding in cottonwood trees than with the eucalyptus, it is also important to consider the range of stump diameters analyzed in each species, as the models developed may or may not present similar estimators at different stump diameter ranges.

4.4 Yield

After 2 growing seasons, the differences regarding DBH and tree height between the summer and winter plot trees were already noticeable in both species studied. Not surprisingly, the winter trees showed greater averages for both DBH and height (Table 9). This can be explained by the fact that regrowth is maximized by harvests performed during winter and minimized by harvests that occur during summer (Blake 1983). However, these differences in DBH and height were less evident between the seasonal plots of eucalyptus than with the cottonwood trees in Arkansas.

Table 9: DBH and height averages and respective standard deviations of stems by harvesting seasons at age 2.

Species	Harvesting season	Total nº stems	DBH (cm)	Height (m)	DBH (SD)	Height (SD)
E. urograndis	**Summer**	835	5.50	10.94	2.40	2.85
	Winter	1042	5.73	12.7	2.20	3.16
P. deltoides	**Summer**	288	2.01	3.70	1.27	1.23
	Winter	497	3.03	5.27	1.24	1.38

In general, the winter plot trees yielded a larger volume per acre in both species tested. The high stump mortality found in the summer plots was a major reason for this outcome – this is especially true for the cottonwood trees where stump mortality was nearly 50%. On the other hand, this difference was less distinguishable at a per stem volume basis. The average volume per stem of each seasonal plot allows for comparison of wood production without the stump mortality factor. Nevertheless, individual stem comparisons between seasonal plots showed that the winter plot stems were still yielding larger volumes. Table 10 displays the mean volumes found per stem, stump, and total volume per hectare.

Table 10: Yield results by species and season of harvest at age 2. CI of means generated at α = 0.05.

Species	Harvesting season	Final yield (m^3/hectare)	Mean (m^3/stem)	Mean (m^3/stump)
E. urograndis	**Summer**	32.82	0.0159 ± 0.0009	0.0403 ± 0.0029
	Winter	48.19	0.0187 ± 0.0008	0.0496 ± 0.0026
P. deltoides	**Summer**	1.68	0.0025 ± 0.0001	0.0036 ± 0.0003
	Winter	4.67	0.0037 ± 0.0001	0.0049 ± 0.0002

4.4.1 Yield per stump

4.4.1.1 Eucalyptus

The volume produced at the stump level (sum of volumes of all stems in each stump) was also calculated and compared among 5 classes of stem crowding (i.e. 1, 2, 3, 4, and 5 stems per stump) for the eucalyptus trees. There were only 2 cases that there was 6 stems growing from the same stump, therefore stumps from class 6 were considered as class 5. For this analysis, the winter and summer plots were combined into one single dataset. In this fashion, the total sample size represents all individuals (stumps) from winter and summer plots. The purpose of this analysis is to compare the yields generated from each class of stump and thus detect significant differences among classes. The Generalized Linear Model (GLM) was used to analyze yield of different stump classes. The pairwise comparisons were obtained from the Tukey-Kramer method of adjustment, which is suggested for analysis of unbalanced data such as this (Stoline 1981; Ludbrook 1998). For the eucalyptus trees (Figure 15), significant differences among means of the 5 classes of stem crowding were significant (α = 0.05). All means were found to be significantly different from each other except for classes 4 and 5 (Table 11).

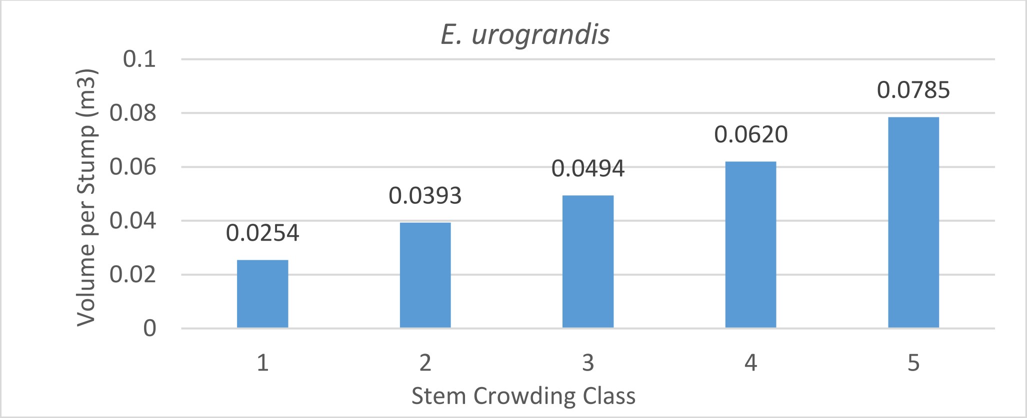

Figure 15: Average of stump volume per stem crowding class.

Table 11: P-values (α = 0.05) generated from pairwise comparisons among 5 classes of eucalyptus stem crowding.

Least Squares Means for effect stems_stump Pr > |t| for H0: LSMean(i)=LSMean(j) Dependent Variable: Volume/stump					
i/j	**1**	**2**	**3**	**4**	**5**
1		0.0002	<.0001	<.0001	<.0001
2	0.0002		<.0001	<.0001	<.0001
3	<.0001	<.0001		0.0001	0.0005
4	<.0001	<.0001	0.0001		0.1678
5	<.0001	<.0001	0.0005	0.1678	

*The p-values found at the encounter of columns *i* and *j* represent the significance of the means being compared. That is, if p-value > 0.05, the means from the classes in each column being compared are not statistically different.

These results indicate that the final volume per stump will increase as more stems grow from each stump until class 4. The volume gained from class 4 to 5 was minimal, probably due to the competition for resources among an excessive number of stems. This behavior is expected to continue for any stem crowding class greater than 5, although the data from this research is limited to classes 1 - 5.

4.4.1.2 Cottonwood

The total volume per stump of the cottonwood trees increased with higher classes of stem crowding (Figure 16). The mean comparisons of the cottonwood trees were also very similar to the eucalyptus. All classes were significantly different from each other, although there were only 4 classes of stem crowding analyzed (Table 12).

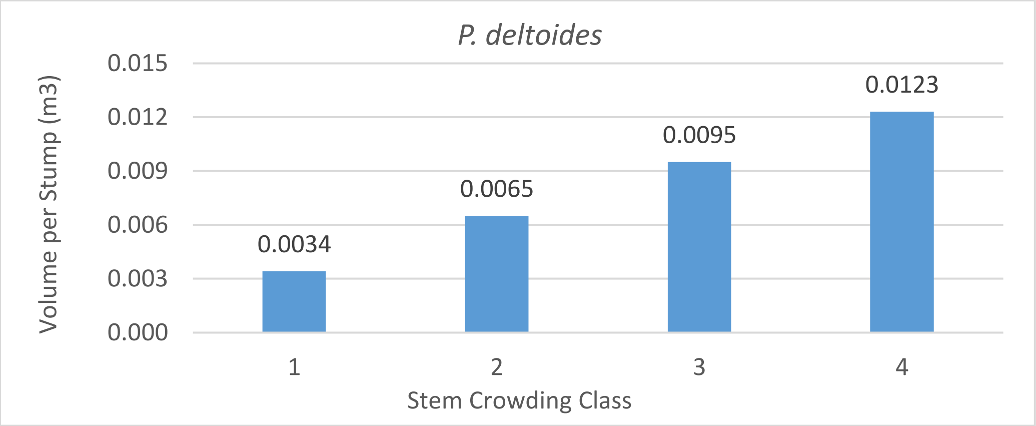

Figure 16: Average of stump volume per stem crowding class.

Table 12: P-values (α = 0.05) generated from pairwise comparisons among 4 classes of cottonwood stem crowding.

Least Squares Means for effect Stems_stump Pr > |t| for H0: LSMean(i)=LSMean(j) Dependent Variable: Volume/stump				
i/j	1	2	3	4
1		<.0001	<.0001	<.0001
2	<.0001		<.0001	<.0001
3	<.0001	<.0001		0.0015
4	<.0001	<.0001	0.0015	

*The p-values found at the encounter of columns *i* and *j* represent the significance of the means being compared. That is, if p-value > 0.05, the means from the classes in each column being compared are not statistically different.

None of the p-values from (Table12) achieved significance among the 4 classes of stem crowding analyzed. This result indicates that all means from each stem crowding class are significantly different from each other, meaning that the overall volume per stump increases as more trees grow from a single stump. However, further considerations need to be taken into account, for instance, the bark ratio of multiple stems growing from the same stump is likely to be greater when compared to single-stem coppiced trees. Multiple-stem trees are expected to have smaller dimensions due to a more intense competition for nutrients from the same source (stump). Thus, the clump formation will consequently produce a greater bark content and lower white wood content, which is typically undesired for bioenergy production. Compared to white wood, bark has higher concentrations of nutrients, ash, and other heavy metals that will negatively affect the quality of biofuels (Kauter et al. 2003).

4.4.2 Yield per stem

4.4.2.1 Eucalyptus

The average volume per stem in each class was analyzed in an attempt to visualize the effects caused on each individual stem when growing in clumps. Thus, the volume found in each individual stump was divided by its respective number of stems (stem crowding class) in order to calculate the average volume per stem in each class of stem crowding. Figure 17 illustrates the differences between means of volume generated per stem among 5 classes of stem crowding of the eucalyptus trees. This comparison will tell us if and at what class the crowding effect starts or stops affecting individual stem volume production. A pairwise comparison using Tukey-Kramer method of adjustments was used to identify significant differences among the means ($\alpha = 0.05$). The p-values (Table 13) indicated no statistical differences among means of classes 3, 4, and 5. Class 1 was found statistically different from all other classes. Class 2 was also significantly different from all classes except when compared to class 5. We expected to see a decrease in per stem volume production from classes 1 to 2 because of an intensified competition for nutrients caused by the crowding effect. However, these results indicate that crowding effect becomes marginal after stem crowding class 3.

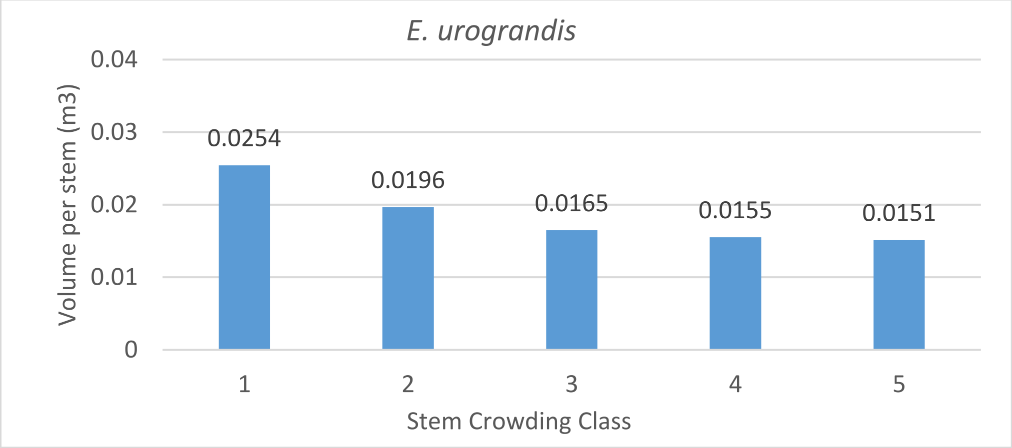

Figure 17: Average of stem volume per stem crowding class.

Table 13: P-values (α = 0.05) generated from pairwise comparisons among 5 classes of eucalyptus stem crowding.

Least Squares Means for effect stems_stump Pr > |t| for H0: LSMean(i)=LSMean(j) Dependent Variable: Volume/stem					
i/j	**1**	**2**	**3**	**4**	**5**
1		0.0002	<.0001	<.0001	0.0095
2	0.0002		0.0051	0.0058	0.5545
3	<.0001	0.0051		0.9322	0.9918
4	<.0001	0.0058	0.9322		1
5	0.0095	0.5545	0.9918	1	

*The p-values found at the encounter of columns *i* and *j* represent the significance of the means being compared. That is, if p-value > 0.05, the means from the classes in each column being compared are not statistically different.

4.4.2.2 Cottonwood

Figure 18 shows the mean volume per stem among the 4 classes of stem crowding of the cottonwood trees. None of the comparisons of means among stem crowding classes were significant (Table 14). In other words, there were no significant differences on stem volume production among the different classes of stem crowding. This result indicates that dense stumps will only add to the final volume of biomass produced per stump without diminishing volume production per stem. However, it is important to point out that these trees are still considerably young and probably have not yet achieved maximum MAI, which is usually obtained around ages 6-7 (Kauter et al. 2003). In addition, the clump configuration analysis of the cottonwood trees showed that approximately 70% of the trees were single-stem and less than 10% of the trees had 3 or more stems per stump.

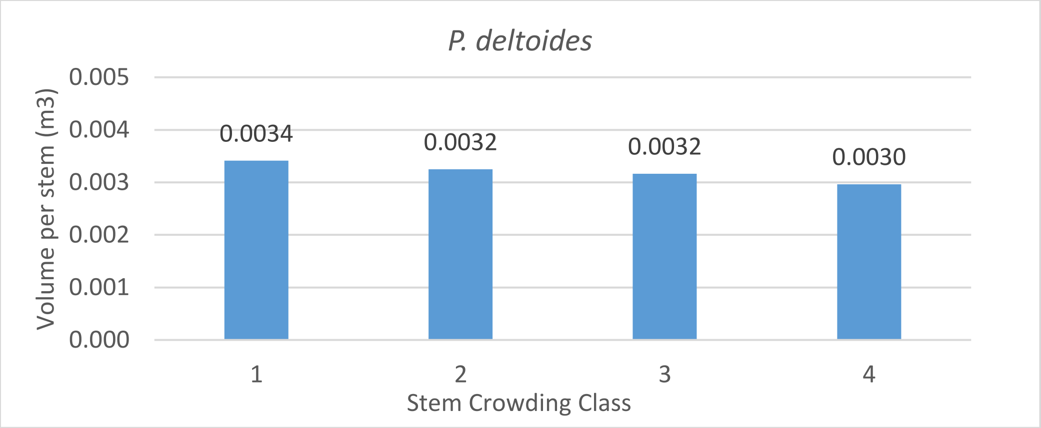

Figure 18: Average of stem volume per stem crowding class.

Table 14: P-values (α = 0.05) generated from pairwise comparisons among 4 classes of cottonwood stem crowding.

Least Squares Means for effect Stems_stump Pr > |t| for H0: LSMean(i)=LSMean(j) Dependent Variable: Volume/stump				
i/j	1	2	3	4
1		0.7595	0.8956	0.8075
2	0.7595		0.9961	0.9464
3	0.8956	0.9961		0.9871
4	0.8075	0.9464	0.9871	

*The p-values found at the encounter of columns *i* and *j* represent the significance of the means being compared. That is, if p-value > 0.05, the means from the classes in each column being compared are not statistically different.

V. Conclusions

This study investigated coppice development of eucalyptus and cottonwood trees, and the implications of harvesting multiple-stem trees with current technology. In addition, a logistic regression was fit in an attempt to predict the probability of a stump to regenerate more or fewer stems based on stump damage and stump diameter. The assessments were made 2 years after harvesting.

5.1 Stem crowding

The eucalyptus trees displayed a high occurrence of multiple-stem stumps, whereas the cottonwood stumps were mostly single-stem. The number of regenerated stems per stump at age 2 was very similar between the seasonal harvesting treatments. The proportion of single, dual, and multiple-stem stumps were nearly the same between summer and winter plot trees.

Results from both species showed that the diameter of the stump is positively related with the number of re-sprouts. The other variable analyzed for a potential impact on the response variable, *stem crowding,* was *stump damage*. Although *stem crowding* in the cottonwood trees did not respond to the damage caused to the stumps during harvest, the eucalyptus trees showed that damaged stumps tend to re-sprout at a lower frequency. A related study including both eucalyptus and cottonwood trees showed that the stump survival of coppice plantations relies on low bark damage during harvesting (Souza et al. 2016). Thus, harvesting operations with minimal impact on the stumps are highly recommended in order to ensure higher survival rates and stem crowding.

The ideal number of stems growing in a stump is often discussed. Conclusions are made based on a broad variety of plantation attributes including tree age, rotation, spacing, tree species, etc. As in any other silvicultural plantation, the ultimate goal is typically to produce high yields of volume. In a biomass plantation, however, special tree characteristics are often required. High bark content, leaves, twigs, and other non-woody components may be undesirable elements for bioenergy production. Multiple-stem trees will often present different proportions of bulk wood and other non-woody parts, therefore trees that produce the higher amount of volume will not always be the best option for biomass production. By combining all these factors together, establishing an ideal number of stems per stump can be challenging.

5.2 Yield

Higher final yields of biomass per hectare were found in the winter plots of both species. This outcome can be partially explained by the higher stump mortality found in the summer plots. Another reason for this difference is the higher volume per stem when comparing the stems from each treatment. The winter treatment trees had the advantage of an interrupted growing season, and a likely higher concentration of resources in the root system which allowed for a greater yield of wood volume than the trees from the summer treatment. The difference of final volume of wood produced between treatments was even more noticeable with the cottonwood trees.

The volume found per stump in all cases increased with the number of stems growing from each stump. More stems per stump is expected to produce more volume per stump, but less volume per stem as more stems compete for nutrients from the same source. The means of volume per stem of the eucalyptus trees in each class of stem crowding (i.e. 1, 2, 3, 4, or 5 stems per stump) showed that the volume per stem in each class decreased as the class number increased. However, in clumps with 3 stems or more, the mean volume per stem found after the third stem was statistically considered the same. The cottonwood trees displayed the same behavior in that more stems growing from the same stump would generate a larger per stump yield. However, the means for stem volume in all classes (1 – 4 stems) were statistically confirmed to be the same, which means that the volume produced per each individual stem should be similar in all classes, regardless of the number of stems growing from the same stump.

It should be noted that both species are still considerably young and not at the appropriate time to be harvested as the maximum MAI has not yet been achieved. This is especially true for the cottonwood trees since harvesting rotations can be up to 5 years long, and also because most of the trees in this study were single-stem. As for the eucalyptus trees, in many cases it was fairly difficult to identify a dominant stem among the others. These stems might eventually develop a thorough dominance over the neighboring stems, which will allow for further stem crowding and yield analysis.

5.3 Clump dimension

Two major manufactures of small-scale felling heads were consulted in order to acquire equipment specifications and establish a threshold that would tell us at what point large clumps could hinder harvesting operations. Both species and seasons of harvest showed that harvesting multi-stem coppice trees with current technology is feasible. Approximately 99% of the clumps from both species and seasonal treatments were considered to be in adequate conditions for mechanized harvesting. Only 1 % of the multiple-stem coppice trees exceeded the threshold established for the trees whose multiple-stems were substantially dispersed. Nonetheless, harvesting clumps formed by coppiced trees is still a concern for mechanized harvesting. The vast majority of the cottonwood trees consisted of single-stem stumps and should not cause any problems regarding mechanized harvesting. On the other hand, approximately 90% of the eucalyptus trees were multi-stem and considerably larger in size, which increases the chances of encountering difficulties for harvesting those trees. Many implications caused by stem crowding formation in coppice plantations are still a threat to machine productivity of harvesting operations as already reported by other researchers (Schweier et al. 2015; McEwan et al. 2016).

This study was focused only on the second rotation of 2-year-old SRWC coppice trees. Many changes may occur on stem crowding and clump dimension during subsequent rotations which could result in different research findings in the future. Thus, further investigations at different rotations and ages are needed in order to thoroughly understand and address the challenges of harvesting multi-stem coppice trees.

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