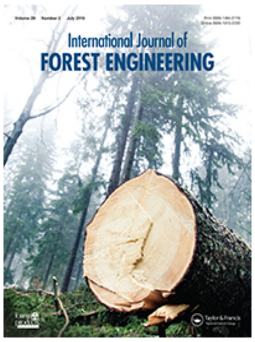

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Coppicing evaluation in the Southern USA to determine harvesting methods for bioenergy production

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ABSTRACT

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 to their fast growth and ability to coppice. There are uncertainties related to the feasibility of harvesting multiple-stem coppice trees with current technology. In this study, we investigated the physical attributes of two SRWC species, 2 years after harvest. A logistic regression was fit in an attempt to determine whether the number of surviving stems per stump (2 or fewer; 3 or more) had a relationship with the 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. Stem crowding and clump dimension was also collected from the coppice trees 2 years after harvest. In addition, the re-sprouting patterns from different seasons of the year (summer and winter) were compared. Results from both species showed that stump diameter is positively related with stem crowding. A minimal percentage of the clump dimensions exceeded the established threshold that would put these multi-stem trees in a challenging spot for subsequent harvesting operations with small-scale machinery.

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Short rotation woody crops; biomass harvesting; stem crowding; coppice; eucalyptus; cottonwood

Introduction

Renewable energy resources are an important topic today. Population growth combined with the depletion of limited oil deposits reinforces the need to develop alternative renewable sources of energy (David 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.

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. 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. None of the most promising alternative sources of energy from biomass (e.g. corn, switchgrass, and wood) in the USA have proven to be as efficient as fossil fuels in terms of energy output and cost of production (Pimentel and Patzek 2005). 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 potential alternative to fossil fuels.

Fast-growing tree species started to become popular and the concept of short rotation woody crops (SRWC) was further addressed during the 1960s and 1970s (Tuskan 1998). SRWC are intensively managed tree species that can be harvested in relatively short periods of time. Rotations can vary from 3-year-cycles up to 10-year-cycles (Kauter et al. 2003; Hauk et al. 2015). SRWC are typically harvested 3–5 times before replanting (Langholtz et al. 2007). 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. planting) while increasing the final yield of biomass (Ferm and Kauppi 1990). 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; Dougherty and Wright 2012). Seasonal harvesting has been widely discussed and many 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 (Ceulemans et al. 1996; Strong and Zavitkovskj 1983; De Souza et al. 2016). Previous studies have shown that winter harvesting ensures better growth rates and stump survival (Hytönen 1994; Oppong et al. 2002), but little is known

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about potential effects of seasonality of harvesting on the physical formation and development of the coppiced stems.

Felling coppice SRWC with current machinery is generally time consuming due to the unfavorable harvesting conditions caused by the conglomeration of stems (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 at the harvesting phase including stump diameter, stump height and season of harvest (Hytönen 1994). Because most timber 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). Moreover, 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 smaller cutting heads, and lower capital cost when compared to purpose built feller-bunchers. Some studies have explored the complications of harvesting coppice 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 conglomeration. Moreover, even small-scale feller-bunchers showed difficulties in penetrating clumps without damaging adjacent stems, which consequently affected productivity (Schweier et al. 2015). Due to the scattered formation of stems growing from the stumps, a considerable amount of biomass could be either left behind or grabbed by the machine operator in a second attempt by performing two cutting cycles on the same tree. In either case, there would be a negative impact on productivity.

Few studies have explored the physical attributes of stem crowding in coppice SRWC as potential hindrances for felling. This is especially true for the particular species used in this study; *Eucalyptus urograndis* and *Populus deltoides* and for the locations where the trials took place, Florida and Arkansas. This study examined the growth behavior of the first rotation coppice through data collected on clump dimension, stem crowding, and stem mortality following 2 years of growth. The dimensions of the clumps were evaluated in order to postulate effects on subsequent mechanized harvesting operations. Additionally, potential impacts caused by seasonality of harvesting on stem crowding and clump dimension of coppiced stems were examined, as many authors have demonstrated that seasonality of harvesting might affect the re-sprouting response, but little is known about its impacts on the physical characteristics of these trees.

Materials and methods

Study design

Two second rotation coppice sites were selected for this study, Florida and Arkansas. The sites were established during a previous study (Souza et al. 2016) with split plot designs of season of harvest and felling method treatments in each study site. The site located in Florida was planted with clonal Eucalypt (*Eucalyptus urograndis*). At the time of harvest, the trees were approximately 2 years old, with an average DBH of 12 cm, and density of approximately 1800/hectare. The site located in Arkansas was planted with clonal Cottonwood (*Populus deltoides*) and the trees were harvested at the age of 3, with an average DBH of 4.6 cm. The study sites in both locations were approximately 0.5 hectares in size. Two seasonal treatments were installed dividing each site into two equal sized plots (0.25 ha each) of summer and winter harvest.

Each plot was visited twice for data collection. For accuracy purposes, the schedule for the evaluations in each seasonal plot for subsequent comparisons was set based on the number of growing degree days. After harvesting, the assessments in summer and winter plots occurred at approximately 6 months (1st evaluation) and 2 years (2nd evaluation) (Table 1). The assessments made during the first evaluation for both species were reported from a similar study where different cutting methods were tested on first rotation single-stem SRWC stands, and calendar-days was the only system used for defining the schedule of the visits (Souza et al. 2016).

Clump dimension analysis

The dispersion of the stems in the clumps was collected during the second evaluations (i.e. after 2 years of coppice growth) in both sites: Florida – June 2016; Arkansas – May 2016. Few studies have explored the dimension of clumps as potential hindrances of harvesting productivity. Schweier et al. (2015) measured total clump circumference at breast height and found that while stump crowding would impact productivity, the circumference of the clump had no significant impact on time consumption. It is important to point out that the latter study consisted of trees varying from 14 to 20 cm in DBH and 2 to 13 stems per stump among trials.

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

This section of the study aimed to provide details regarding spatial stem distribution (here also referred as stem-dispersion) and the associated limitation of these trees to be harvested by current small-scale 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 "x" and "y" axis relative to stem A. For instance, 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). 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 1).

The longest distance between stems in the same stump was identified. 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 USA have their grabbing arms set at a height of approximately 1.5 meters above the ground, and are approximately 76- cm long. Two common manufacturers of small-scale feller-buncher cutting heads in the USA were used as references (FECON and DFM) for this study and all equipment information was collected through online specification sheets provided by the 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) (Figure 2).Thus, a threshold of 76 cm was used as an assumption for a limiting distance between stems that could potentially hindrances the operability of the machine.

Data analysis

Two evaluations in each plot were conducted on different dates in accordance with the schedule of growing degree days (Table 1) for the coppice development analysis. The purpose of the first 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 (Souza et al. 2016).

During the second assessment (1.5 years after the first assessment), the stems were re-counted in each stump for determining stem mortality, stump mortality, clump dimension, height, and DBH of all stems. 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. Stem mortality was determined by subtracting the number of shoots from the first assessment by the number of stems found during the second assessment in each individual stump. In order to be more accurate and fairly divide the period of evaluations by growing seasons for winter and summer plots, a system of growing degree days was used to schedule subsequent visits to each plot. The degree days of each site were calculated by dividing the

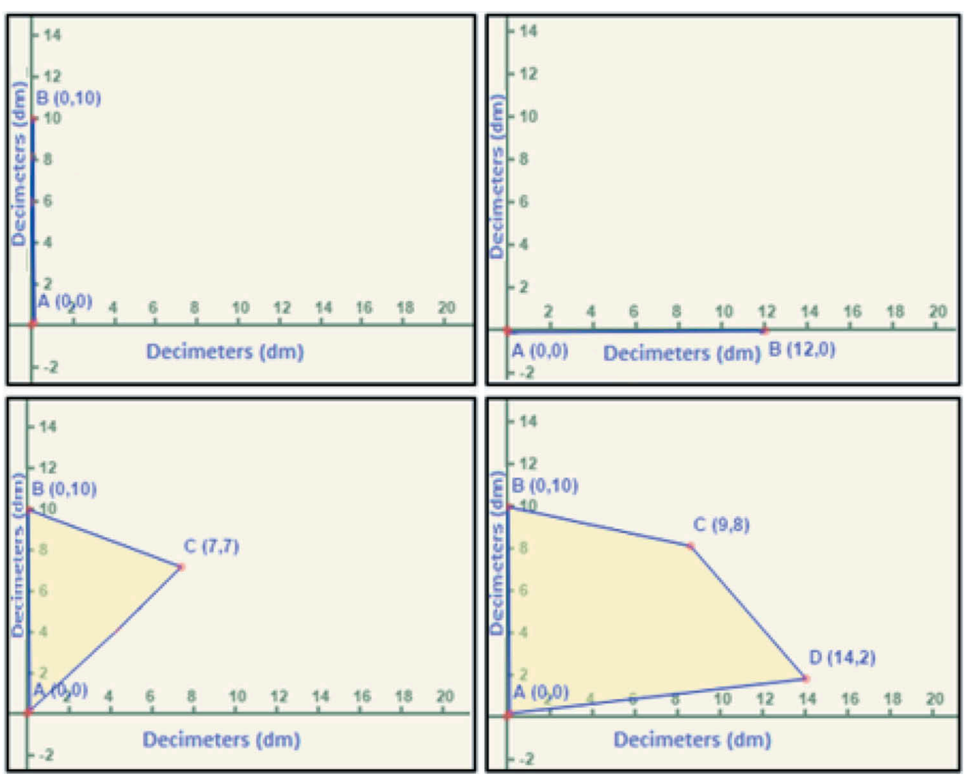

Figure 1. Clump geometry for stumps with 1, 2, 3 and 4 stems: each chart simulates a clump; each dot represents a stem.

Figure 2. Fecon shear head with opened grabbing arm.

average temperature of each day (i.e. the sum of maximum temperature and minimum temperature divided by two), and subtracting the "temperature base". The temperature base is the temperature below which plant development stops. The temperature at which growth starts for woody plants in the USA is approximately 45°–55° Fahrenheit; to standardize the calculations for determining a growing degree day, the temperature base has been set at 50°F (Miller et al. 2001; Siegert et al. 2015).

Since fewer stems growing in a single stump favors mechanized harvesting (Schweier et al. 2015; McEwan et al. 2016), it was 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* had on the dependent variable, *stem crowding* (number of stems per stump). The data representing both independent variables data were collected by Souza et al. (2016) during the harvesting stage. The variable *stem crowding* was reflected as a binary response: desired (stumps with 2 or fewer stems) or undesired (stumps with 3 or more). The independent variable *stump damage* was defined as 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 data for the variable *stump diameter* were collected at the height of the stump surface where the cut was performed. 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 (here labeled as desired) growing from the same stump at age 2.

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 for each species analyzed. The generic 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 "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 *stump damage* or *stump diameter*. The null hypothesis is based on the assumption that none of the independent variables mentioned above have an impact on stem crowding.

Results

Clump dimension

Results from the clump dimension study indicate that the dispersion of stems on clumps would not affect machine operability when using a small-scale cutting head. At age 2, both seasonal plots exhibited that 99% of all coppice clumps had a stem-dispersion of less than the threshold (76 cm) for the eucalyptus trees, and thus could be harvested in one cutting cycle (Table 2). The cottonwood trees presented a similar result where none of the clumps of the winter plot exceeded the cut-off, and only 1% of the summer harvest trees exceeded it. In total, 722 eucalyptus and 671 cottonwood trees were evaluated for this analysis.

Stem crowding analysis on E urograndis coppice

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 3. The decreasing standard deviation from the age 0.5 to 2 years is a consequence of the competition among stems for resources in the same stump otherwise known as self-thinning (Ceulemans et al. 1996; Cacau et al. 2008).

Figure 3 displays the number of stems per stump for each age group and harvesting season for *E. urograndis*. The stem crowding charts from the first data collection (6 months after harvest) show a pattern in which a majority number of stems per stump are more evenly distributed from classes 2 to 6. This distribution pattern changed during the second evaluation (2 years after harvest) where the vast majority of the clumps transitioned into two or three stems per stump.

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

	Winter Harvest			Summer Harvest		
Species	Operation	Dispersion (cm)	Frequency	Operation	Dispersion (cm)	Frequency
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%

Table 3. 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
Total at age 2		1877	2.6	6	1	

The pattern of stem mortality from age 0.5 to 2 as well as the configuration of the clumps (percentage of single, dual and multiple stems) at age 2 was very similar between summer and winter plots. Figure 3 illustrates that among the stumps that exhibited coppicing activity, only 10% were single-stem while approximately 90% consisted of two or more stems per stump in both seasonal plots.

It is important to point out that stump survival was not included in Figure 3. Although stem crowding did not seem to be 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 4). Only two stumps died from age 0.5 to 2 in both seasonal plots, which represents an indication that the stumps that successfully regenerate new shoots tend to remain alive regardless of the season of harvest.

Stem crowding analysis on P. deltoides coppice

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 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 at the stump level. Descriptive statistics are listed by season and age in Table 5.

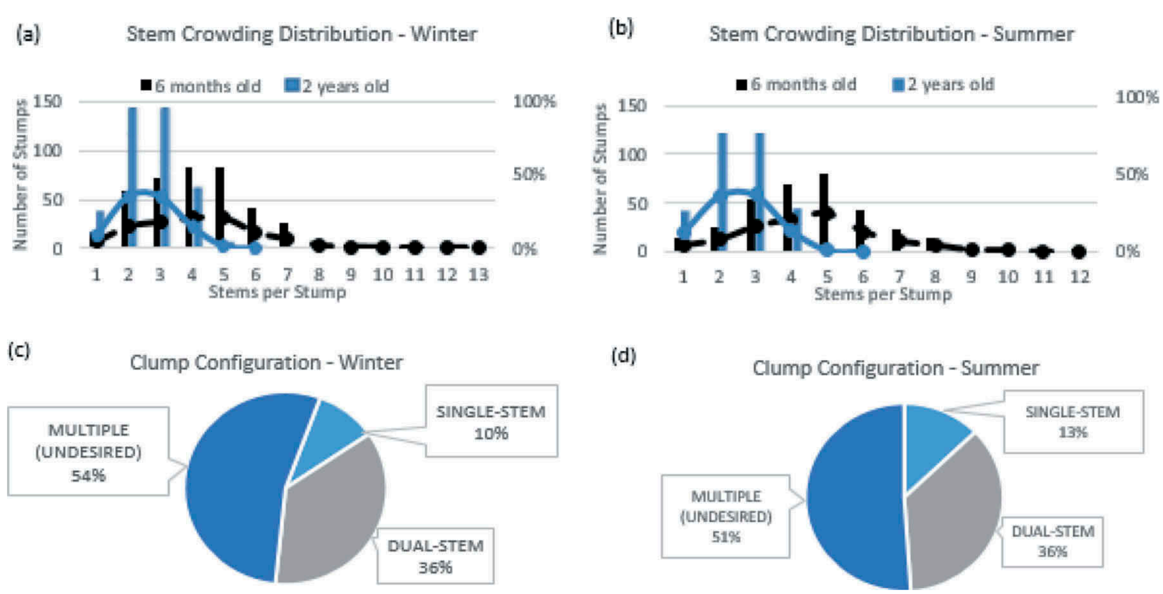

Figure 3. Charts of stem crowding from coppice regeneration of eucalypt: (a) Stem crowding distribution of winter harvest at different ages. (b) Stem crowding distribution of summer harvest at different ages (c) Clump configuration of winter harvest at age 2. (d) Clump configuration of summer harvest at age 2.

Table 4. Stump survival of eucalypts stumps following different harvest 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%

Table 5. 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
Total at age 2		785	1.35	5	1	

Stem crowding distribution from age 0.5 to 2 was again fairly similar among winter and summer plots. However, when compared with the eucalyptus trees, the cottonwood stem crowding showed a different pattern. At age 0.5, most of the stumps consisted of 1, 2 or 3 stems. This configuration had a more dramatic change at age 2 when the large majority of the stumps became single-stemmed. Figure 4 illustrates this difference, and also the proportion of single, dual, and multiple-stem stumps of cottonwood coppice at age 2.

Similar to the eucalyptus, stump mortality was also minimal from age 0.5 to 2 indicating that once successfully re-sprouted, stumps are likely to remain alive regardless of the season of cut (Table 6). As reported in McEwan et al. (2016), season of harvest had an even greater impact on stump survival of the cottonwood trees compared to the eucalyptus (90% in winter; 75% in summer). Less than 50% of the summer harvesting stumps survived while 96% of the stumps from cottonwood winter harvesting showed a positive regeneration response.

Regression analysis of E. urograndis stem crowding

For developing the logistic model, both seasonal treatments were combined, generating a total population of 722 stumps of which 380 fell into the category *undesired* and 342 stumps were categorized as *desired*. *Stump diameter* ranged from 3.3 to 24.13 cm with an average of 13 cm. The majority of the stumps (66.3%) were not damaged during harvesting while the remaining 33.3% 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 a *desired* condition for harvesting (2 or fewer stems per stump), *a* is the intercept, *b* represents the parameter estimate for the variable *stump damage, c* is the parameter for *stump diameter* (cm), and *e* is the base of the natural logarithm. Both variables were found to be significant indicators of stem crowding on eucalyptus coppice (Table 7).

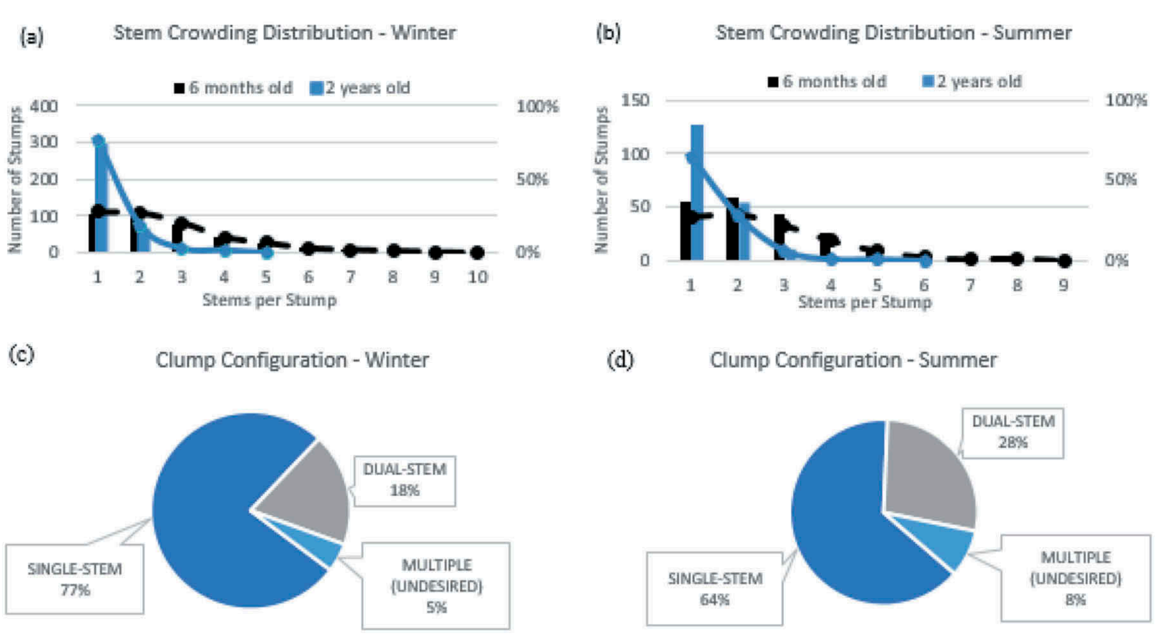

Figure 4. Charts of stem crowding from coppice regeneration of cottonwood: (a) Stem crowding distribution of winter harvest at different ages. (b) Stem crowding distribution of summer harvest at different ages (c) Clump configuration of winter harvest at age 2. (d) Clump configuration of summer harvest at age 2.

Table 6. Stump survival of cottonwood stumps following different harvest seasons.

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%

Table 7. P-values, odds estimates, and estimated parameters for effects of stump diameter and damage on eucalyptus 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 positive relationship between *stump damage* and the probability of *desired* (2 or fewer stems) indicates that the damage caused on the stumps at the harvesting stage will decrease the chances of having a greater numbers of shoots per stump. 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 5 displays the estimated relationship among the variables tested.

Regression analysis of P. deltoides stem crowding

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 were 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. Most stumps (90%) did not have signs of damage while the remaining 10% were damaged. The p-values for the model validation were also significant at α = 0.05 (Wald = < .0001; Likelihood Ratio = < .0001). 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.

Figure 6 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 variable, indicating that cottonwood trees with large stump diameters are likely to generate more shoots after harvesting.

Discussion

Postulate effects of clump dimension coppice

It was hypothesized that the dimension of the clumps would hindrance felling operations. The results of this analysis suggest that clump dimension should not have a limiting impact on mechanized harvesting with a small-scale cutting head nor should the cutting season affect the dimension of the clumps in both species tested. However, these results cannot ensure that the frequency of re-sprouting (stem crowding) is not a limiting factor for mechanized harvesting operations and further research is needed.

Schweier et al. (2015) found that while clump circumference did not present a significant impact on small-scale machine efficiency, the productivity achieved on single-

Table 8. P-values, odds estimates and estimated parameters for effects of stump diameter on cottonwood 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	-	–	–

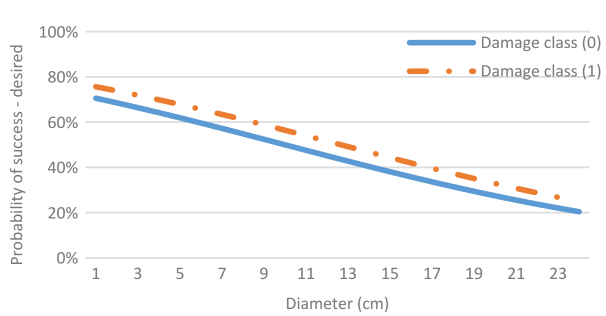

Figure 5. Logistic regression curves of eucalyptus predicting the probability of achieving the outcome *desired*: 2 or fewer stems per stump.

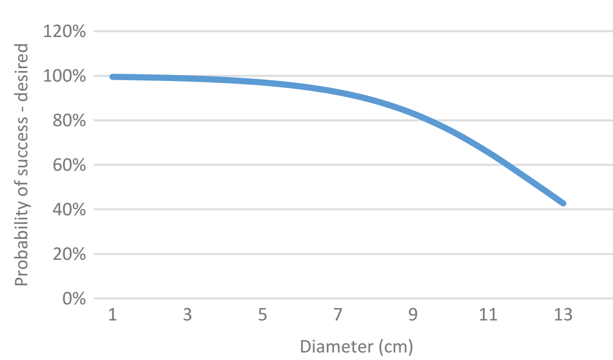

Figure 6. Logistic regression curves of cottonwood predicting the probability of achieving the outcome *desired*: 2 or fewer stems per stump.

stem trees of poplar coppice was approximately 10 times greater than the productivity found in the multi-stem 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 suggests that clump circumference should not be an issue at age 7, nor at 2, as our clump dimension results indicate.

In general, 2-year-old coppice stands are still considered immature to be harvested. 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, due to their juvenility, in many cases it is fairly difficult to identify a dominant stem among the others. Some of the stems may or may not develop a stronger dominance over the neighboring stems. In addition, the number of harvesting cycles may also alter stem-per-stump ratio. As mentioned previously, some coppice species tend to increase the number of re-sprouting stems after consecutive rotations (Laureysens et al. 2003; Nassi O Di Nasso et al. 2010). These changes could result in potential harvesting limitations including grabbing, accumulating, or even cutting multiple stems within the same cutting cycle using small-scale harvesting technology.

Stem crowding

No major differences were detected between the seasonal plots regarding stem crowding with both species used. The proportions of single, dual and multi-stem stumps were very similar among the seasonal plots, however, the summer plots in both species presented a larger mortality of stumps inhibiting regeneration after harvesting. Thus, the first assessments (Souza et al. 2016) have shown a superior re-sprouting response from the winter plots in both species. This trend has been consistent over the first 2 years of growth in both species, as expected, and, demonstrated by similar studies on seasonality of coppice of several species of both traditional coppice and SRWC (Blake 1983; Kays and Canham 1991; Hytönen 1994).

More than 90% of the eucalyptus trees from both seasonal treatments consisted of two or more stems per stump. From an operational standpoint, multi-stem trees are often not desired because they 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 as shown by similar studies (Schweier et al. 2015; McEwan et al. 2016). On the other hand, it should be noted that both species are still considerably young and many changes are yet to occur due to self-thinning. Many of the multi-stem trees did not present a clear dominance of a stem prevailing over the others, which reinforces the theory that self-thinning is still ongoing.

There have been arguments as to whether or not thinning multi-stem coppice trees would increase the final yield by eliminating the competition for resources with the other stems developing nearby. However, this theory has been ruled out by some studies with eucalyptus coppice. Cacau et al. (2008) found that thinning down to 2–3 stems per stump had no effect compared to self-thinning after 42 months, indicating 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 had no impact over self-thinning. However, these results were achieved in a tropical area (Brazil) with different site-related characteristics when compared with the southeastern climate of the USA. In addition, different ratios of stem crowding among eucalyptus coppice are expected to emerge depending on the species and clones used (Souza et al. 2012). It should be noted that many coppice species tend to increase the number of regenerating shoots per stump after consecutive rotations of harvesting (Laureysens et al. 2003; Nassi et al. 2010).

For the cottonwood trials, seasonality of harvesting also caused little to no effects toward stem crowding. Unlike the eucalyptus, more than 60% of all cottonwood coppice trees were single-stem. An outcome like this certainly facilitates mechanized harvesting, however, these results were not expected since poplar trees are known for their abundant number of shoots when coppice occurs (Nassi et al. 2010; Verlinden et al. 2015). A possible explanation for this outcome could be associated with the heavy presence of grass in the cottonwood stands which might have increased the competition for local resources. Laureysens et al. (2003) reported an average of approximately five shoots per stump during the first rotation coppice of various clones of poplar trees. In general, the number of re-sprouting relies heavily on the species used (Ceulemans et al. 1996) and tend to increase during subsequent rotations of harvesting (Laureysens et al. 2003). Self-thinning can reduce the population of stems up to 75% within the first growing year (Verlinden et al. 2015), which indicates a moderate similarity with the results of this study where nearly 50% of the stems died over the period of 1.5 years in both seasonal plots.

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 (Kauter et al. 2003). 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 facts together, establishing an ideal number of stems per stump can be certainly challenging.

Modeling stem crowding

Stump damage had a positive relationship with the categorical variable *desired* indicating that the damage caused on the stumps during harvesting is likely to result in a smaller number of shoots per stump for the eucalyptus trees. This 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 suggest 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 diameter will vary, and it is possible that larger stumps will endure a greater likelihood of being damaged.

Around 90% of the cottonwood stumps did not present significant signs of damage after the first rotation harvest occurred. This result could be related to the fact that the harvested cottonwood trees were considerably smaller in diameter than the eucalyptus, allowing for smoother and faster cuts, and preventing damage. The parameter estimate associated with *stump diameter* from the cottonwood model generated a more dramatic response to stem crowding compared to the parameter found for the eucalyptus model. The steepest decline of the curve for the cottonwood was observed when the diameter ranged from 7cm to 13 cm. The value found for the parameter estimate of *stump diameter* (−0.4876) is the primary cause of this occurrence. In the eucalyptus model, the same parameter was much closer to zero (−0.097), thus, a change in unit of *stump diameter* would not be as responsive with the eucalyptus trees. However, it is important to point out that the range of the stump diameters assessed in this study was fairly different among the species tested, and the models developed may or may not present different estimators at different diameter ranges.

Conclusions

This study investigated coppice development of eucalyptus and cottonwood trees, and the implications of harvesting multiple-stem trees with single-stem harvesting 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 the diameter and the damage caused to the stumps during harvesting. The assessments were made 2 years after the first rotation harvesting.

In both eucalyptus and cottonwood trials, the proportion of regenerated stems per stump (single, dual or multiple-stem stumps) at age 2 was very similar between the seasonal harvesting treatments, winter and summer.

Results from both species showed that *stump diameter* was positively related with the number of re-sprouts. Although *stem crowding* in the cottonwood trees was not responsive to *stump damage*, in the eucalyptus trees the latter variable was found significant. Thus, harvesting operations with minimal impact on the stumps are recommended when the goal is to ensure an abundant stem crowding. On the other hand, *stump damage* favors mechanized harvesting by reducing the likelihood of a larger number of shoots per stump.

In addition, the dimension of the clumps formed by the coppice trees was analyzed as a potential hindrance of subsequent harvesting. Both species and seasonal treatments showed that the dispersion of the stems should not be an issue with current technology. Approximately 99% of the clumps from both species and seasonal treatments were 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 excessively dispersed.

In this study, we found that clump dimension should not compromise felling operations of coppiced cottonwood and eucalyptus at age 2. At this age, we can anticipate that no more sprouts will emerge once the existing stems have already been through the process of self-thinning and likely have established their position on the stump. From this point on, these stems are expected to expand in diameter and some may die due to late competition for local resources. Neither of these events should compromise the results of this research. In conclusion, small-scale harvesting systems such as the one used in this study are a feasible method for harvesting coppice stands of biomass woody crops.

Further research on coppice SRWC is needed as many other aspects of SRWC harvesting are still being discussed. For instance, the dispersion of stems from this study was focused in only two species whereas very few studies have investigated this same characteristic on other species of SRWC. Further harvesting techniques must be tested and studied as SRWC species present different growing patterns and harvesting technology is constantly changing. Only then we will be able to fully benefit from the potential of coppice forests for efficient biomass production.

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