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Determining the effects of felling method and season of year on the regeneration of short rotation coppice

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There is increasing interest in plantations with the objective of producing biomass for energy and fuel. These types of plantations are called Short Rotation Woody Crops (SRWC). Popular SRWC species are Eucalypt (*Eucalyptus* spp.), Cottonwood (*Populus deltoides*) and Willow (*Salix* spp.). These species have in common strong growth rates, the ability to coppice, and rotations of 2–10 years. SRWC have generated interest for many forest products' companies (seeking for diversification or energy self-sufficiency) and private landowners, and although they might help with the supply for the expected growth on the bioenergy and biofuels market, there are still several concerns about how and when to harvest SRWC to maximize their ability to coppice. SRWC have elevated establishment and maintenance costs if compared to other type of plantations, but due to the coppicing ability, the same plantation may be harvested up to 5 times without the need of establishing a new one. Study plots were installed at six locations in Florida, Mississippi and Arkansas, and were cut with a chainsaw and a shear head during summer and winter, to determine the effects of felling method and season on coppice regeneration. Thus, plots were divided into areas of four different treatments: shear-winter, saw-winter, shear-summer, saw-summer. Harvesting eucalypt and cottonwood trees during winter resulted in better survival rates than harvesting during summer; however, there was no effect of felling method on coppice regeneration. Finally, no statistically significant difference was found on coppice regeneration of black willow when harvested during winter or summer with a chainsaw or a shear head.

Keywords: short rotation woody crops; woody biomass harvest; eucalypt; cottonwood; willow; bioenergy

Introduction

The increasing necessity of finding new alternatives to produce fuel and energy has never been so evident in the United States. Issues like the increasing population, dependence on foreign oil, and the declining availability of fossil fuels have made renewable energy sources, such as biomass, become a plausible and promising option to address these issues. Moreover, researchers and politicians have developed some ideas, where a major part of the nation's energy needs will be sourced from renewable fuels. One of these ideas is the 25′x25 Alliance (25 by 25), in which the goal is to replace 25% of the nation's fuel and energy consumption by some type of clean energy produced from renewables by the year 2025. Several states in the US are joining alliances similar to the 25′x25, and as a result of that, a great amount of biomass will be required to produce clean energy and accomplish the goals. A considerable amount of that biomass will be allocated to woody biomass from harvest and forest products mill residues, but also from new plantations intended to supply new biofuel and bioenergy mills (25′×25: America's Energy Future. Available from: http://www.25by25.org/).

The woody biomass supply is currently coming from logging operations and mill residues; however, they are not sufficient to meet the expected increase in market demand. Recently, several companies and institutions have ventured into the short rotation woody crops (SRWC) supply system. According to the US Department of Energy (2011), a SRWC is an intensively-managed plantation of a fast-growing tree

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species that produces large amounts of biomass over a short period of time, usually less than 10 years, that can be shortened to as little as 3 years when coppiced, depending on the species and production method. In other words, a SRWC is defined as a plantation established to grow lignocellulosic material (wood) and biomass, often with the purpose of producing biofuel and bioenergy. However, besides the potential to produce energy and fuel, SRWC may also be used for pulp and paper production and sawtimber (Rinebolt 1996; Stanton et al. 2002). The characteristics that define the SRWC are the ability to coppice, rotations between 2 and 10 years, and an impressive fast growth. It is also important to highlight that SRWC generally have very high costs if compared to traditional pine plantations in the US, due to the intensive labor involved with its implementation. Tuskan (1998) specifies that SRWC involve appropriate site selection and preparation, use of improved clonal planting, extensive weed control (mechanical and chemical), fertilization as required, pest control, and efficient harvesting and post-harvest processing. For this reason, to maximize the utilization of the plantation through the coppicing ability is fundamental. Coppicing is the regeneration of new stems from the stump after the harvest is performed (Hinchee et al. 2009). Depending on genetics, species, and other factors, the same plantation can be harvested up to five times (Langholtz et al. 2007) due to the coppicing ability, thus reducing the costs and increasing the feasibility of the system.

The concept of SRWC became popular in US in the early 1970s, when the US Department of Energy (DOE) embraced this system as a way of supplying biomass feedstock for the conversion to liquid transportation fuels (Ranney et al. 1987; Tuskan 1998). Since the SRWC supply systems came into existence in the US, many studies have been implemented or undertaken to determine potential regions to establish SRWC, suitable species for each region, and silvicultural practices. Also, genetic and biotechnological improvements have been performed (Tuskan 1998).

The popular and most promising species at that time (1970s) were poplar (*Populus sp.*), sycamore (*Platanus occidentalis* L.), silver maple (*Acer saccharum* Marsh), and hybrid willow (*Salix* sp.), with poplar being the principal candidate through most of the defined regions (Tuskan 1998). Although research projects and genetic improvements have been performed with poplar, there are some exotic SRWC species that can be used in the US territory, potentially producing better results than those obtained to date. One of these species, already being introduced in plantations in the US is the Eucalypt (*Eucalyptus* sp.). The United States Department of Energy (2011) states that poplar, southern pine, willow, and eucalypt, are the most likely woody energy crop species to be developed for bioenergy production today, with productivities reaching 6 m^3/year, 5.5 m^3/year, 5.1 m^3/year, and 6 m^3/year, respectively.

The short rotations may be attractive to landowners looking for a quicker return on investment (rotations between 2 and 10 years if compared to ~30+ year rotations when growing lumber) and/or looking to diversify their land use (not only lumber or agriculture). The wider variety of species, combined with all the research and genetic improvement made to those species, are making SRWC productions more viable (Alig et al., 2000), giving the landowners more options to venture on this "unknown" system. According to Alig et al. (2000), approximately 70 millions of hectares are potentially suitable for planting poplar in the US region. However there is no certainty about the current acreage planted in SRWC in the US (White 2010).

Although the establishment of SRWC is becoming popular in the SE region of the United States, and the introduction of new species with better and promising results have been proved possible, the biofuel and bioenergy markets are not yet completely developed. Furthermore, the absence of a solid bioenergy market has discouraged the development of a system specialized in harvesting SRWC, thus making the investment in a foreign and costly machine not feasible. Currently, some SRWC are harvested with agricultural harvesters adapted to harvest woody material; however, traditional forest harvest systems are still more common in the SE region, even in SRWC.

The conventional whole-tree harvesting system, currently used to harvest Eucalypt plantations in southern Florida, where a feller-buncher with a circular saw head fells and bunches the trees and a rubber-tired grapple skidder drags the trees to the loading deck, is the most common system used in the Southeast in forest stands (Wilkerson et al., 2009). This system processes the trees at the loading deck.

However, SRWC stands are planted with high density spacing (1200–1400 stems ha^{-1}, according to Tuskan 1998) and managed under 3–10 year rotations, which mean that large pieces of equipment, such as those used in whole-tree systems, may not be feasible or productive, since they are designed to harvest large trees planted in larger spacing. SRWC trees are small in diameter, possibly with more than one stem per stump (if coppice is used as management). Besides, SRWC trees can be processed at the stump to avoid dirt accumulation, which could cause problems on the quality of the final product (depending on the product).

The utilization of smaller equipment, with low capital cost, such as a skid steer with a shear head, may be a temporary option, while specialized machinery is being developed. However, it was demonstrated (Spinelli et al. 2014) that this equipment may cause damage to the stump's structure and bark, which could cause possible effects on the desired coppice regeneration.

On the other hand, little is known about the optimal harvest scheduling in SRWC in the Southeast. The effect of the season of the harvest has always been a subject of interest. Theories and previous studies (Strong & Zavitovski 1983; Hytönen 1994; Oppong et al. 2002; Xue et al. 2013; Masaka et al. 2015) state that harvesting during winter ensures maximum stump survival and yield, thus limiting the harvest to the winter season, regardless of the species and region. If these theories are also confirmed in the SE region of the United States, the impact on the developing SRWC supply systems in US would be tremendous, with elevated economic challenges, requiring the development of a system to replace the SRWC feedstock during the other seasons; however, this theory has not been proven nor tested yet in this region.

It is evident that further research in SRWC harvesting techniques and machinery is needed. This study will compare the effects of harvesting SRWC in the Southeast region with a small shear head and with a chainsaw. Theoretically a possible difference in cutting quality between these felling methods may affect the coppicing ability. Additionally, also the potential difference in coppice response between harvesting during winter and summer seasons will be examined, with the theory that summer harvest hinders coppice regeneration.

Materials and methods

Study design

Six first rotation sites (Table 1) were selected to determine the effect of the felling method and the season of year on coppice regeneration. Three sites located in Florida (study sites 1, 2, and 3) were planted with Eucalypt (two with clonal *E. urograndis* and one with *E. grandis* from seedlings). Two sites, in Arkansas and Mississippi (study sites 4 and 5), were planted with clonal Cottonwood (*Populus deltoides*), and one in Mississippi (study site 6) was planted with clonal Black Willow (*Salix* spp.).

A systematic block design was the experimental design used to install the treatments at each study site (Figure 1), which were composed by a study plot divided into four treatments: saw-summer harvest, shear-summer harvest, saw-winter harvest, and shear-winter harvest. The study plots in all sites were ~0.5 hectares in size. The specific areas of the study plots were chosen in concordance with the landowners, seeking for good tree growth, and avoiding wet and marginal growing sites.

Harvesting methodology

Two felling methods were compared to determine the different effects they may have on coppice regeneration. They were a small shear head, attached to a skid steer, and a chainsaw. The harvests took place at each study site in two different seasons of year: summer and winter.

The shear head used for the harvests in this study was a single knife bunching shear head manufactured by Fecon®, model FBS1400EXC with a cutting capacity of 35.5 centimeters (cm) and a bunching capacity of 5.7^{-3} cm^2. This head is equipped with an accumulator arm, which gives the ability to bunch several trees before dumping, one grabbing arm, one adjustable and moving knife, and one fixed knife. For the chainsaw harvesting method, no specific equipment was used, using any chainsaw model/brand available at the time of harvest. Generally, 2–3 people were necessary to perform this operation, where one operated the chainsaw while the other(s) directed the felling direction of the tree to facilitate the skidding operation after the harvest. The operator of the shear head, and the chainsaw, was the same in all harvests and sites, which ensured more homogenous cuts (i.e. damage to bark and stump), and height, although this

Table 1. Description of the sites harvested during the project.

Site	Location	Species	Age at harvest	Avg. DBH (cm)	Plantation spacing (trees/ha)	Trees felled
1	Florida	*E. urograndis*	2	12,2	1.994	828
2	Florida	*E. urograndis*	2	11,7	3.512	867
3	Florida	*E. grandis*	8	18,8	Unknown	105
4	Arkansas	*P. deltoides*	3	4,3	Unknown	803
5	Mississippi	*P. deltoides*	5	11,9	4.745	301
6	Mississippi	*S. nigra*	5	7,6	4.745	583

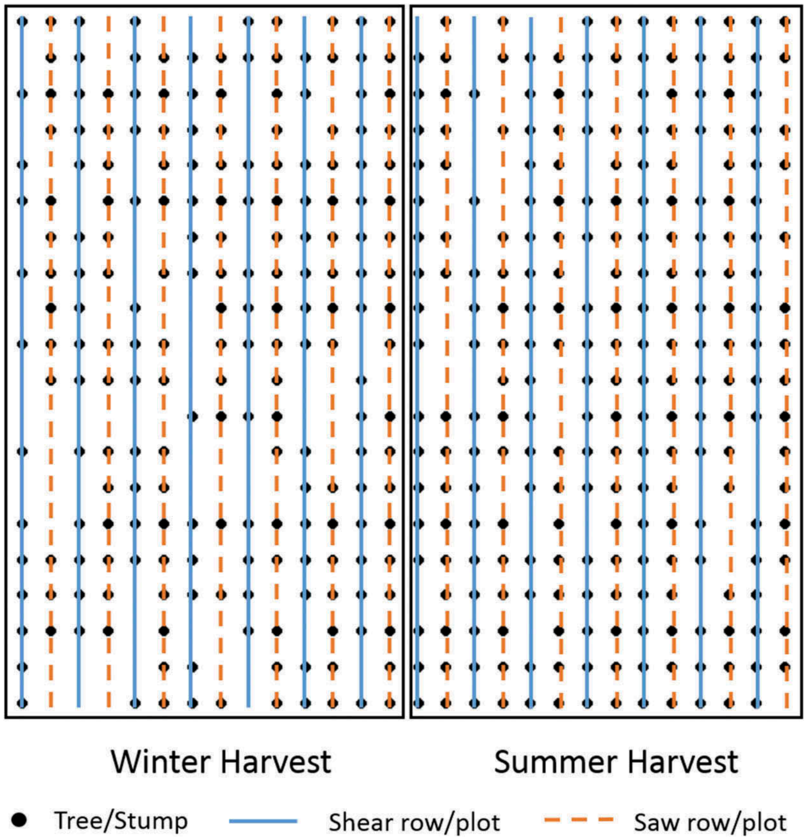

Figure 1. Design of all study plots, using as an example the black willow site located in study site 6. The dots represent the number of trees per row. Each dot represents a harvested tree.

variable was not measured nor taken into consideration in the study.

The layout or design of the plantations was fundamental to the selection of the harvesting treatment. The ideal methodology was the completely randomized design, randomly cutting each tree, and controlling the effect of extraneous variables. However, due to physical and spatial limitations, and to facilitate the felling operation, it was not possible to implement the random design. As a consequence, a systematic design alternating the felling equipment between rows, harvesting one row with the chainsaw and the adjacent row with the shear head was the selected experimental design. At the study sites 1 and 3, alternating the felling equipment was not possible due the layout of the plantation; consequently, instead of alternating the equipment every row, it was alternated every 5 rows, thus creating blocks of 5 rows for each equipment. Number of rows, number of trees per row, and length of rows were variable, depending on the site and the spacing of the plantation.

No information about the amount of harvested wood was collected, since the harvested areas were considerably small (~0.5 hectares), and the harvested material was left in an area designated by the landowner. Additionally, no weather or site (soils or understory vegetation) complications were present.

Coppice evaluation

The field evaluation of the coppice response occurred 5 months after the winter harvest and 6 months after the summer harvest. Each stump was individually analyzed, and if the stump presented regeneration of new stems, it was recorded as a live stump; however, if it had no new stems it was recorded as a "dead" stump. The number of new stems regenerated was counted at each stump.

Finally, an evaluation of bark damage and damage caused to the stumps was performed after the harvests. Five bark damage classes were specified, each representing the percentage of the bark of the stump that was damaged: 0 (0%), 1 (1–25%), 2 (26–50%), 3 (51–75%), and 4 (>75%). The types of harvest damage observed on stumps were: barber chair, missing chunk(s), fiber pull, split, and shattered stump, which were related to damages observed in similar studies (Spinelli et al. 2007; Schweier et al. 2014). Different from the bark damage, the harvest damage was caused to the structural part of the stump, or to the wood, and not to the exterior part. Additionally, the diameter of the stump's cut surface (DGL) was measured for each stump, with a caliper, to account for the effect that diameter may have on the coppice regeneration. Depending on the cylindrical form of the stumps, two measurements, perpendicular to each other, were taken and averaged to get the stumps DGL.

Data analysis

The data analysis for this project used statistical tools, charts and tables to determine the effects that the independent variables (felling equipment, season, and bark and stump damage) have on the dependent variable (coppice response), which was classified as the coppicing ability (or stump survival) and the number of new stems regenerated per stump. Additionally, stumps' DGL and skidder damage (when existing) were considered, since they could be related to coppicing ability of the cut trees. It is relevant to mention that the DGL followed a similar distribution for both felling methods and seasons, giving no reason to individually analyze it by equipment or season. Response variables followed Binomial and Poisson distribution, violating the statistical assumption. Hence, the Generalized Linear Mixed Model (GLMM) analysis was used to compare the coppicing response of the stumps, since normality of the response variable is not required to run this analysis. The results presented at this study are supported by the appropriate statistical tests resulted from the "glmer" function of package "lme4" from R. The supporting statistics consist of z-values with the associated *p*-values, obtained from Wald Z tests, which are appropriate for analysis of this type (Bates 2006; Bolker et al. 2008; Berridge & Crouchley 2011; Bolker 2015).

Although each stump was individually evaluated, due to the experimental design, the harvesting methodology, and the layout of the study plots, a random effect of rows nested into plot was accounted for the study sites 1 and 3, while a random effect of rows was accounted for all the other sites. As a consequence, plots (for study sites 1 and 3) and rows (for the other sites) were considered as the experimental unit, and not the stump. Ignoring these random effects causes attenuation and inconsistence in the estimation, generally overestimating the treatment effect (Wampold & Serlin 2000; Demidenko 2013). Each study site was individually analyzed, with the utilization of a full model (Table 2). The variables included in the models were: season, felling equipment, DGL, bark damage, harvest damage, skidder damage (if a skidder was used), an interaction between season and felling equipment, and an interaction between felling method and bark damage. The significance of the factors were determined at $\alpha = 0.05$. Additionally, an ANOVA was performed for each model to determine their significance, at $\alpha = 0.05$.

Although all models included all the variables studied in this project, only the effects of variables that resulted in statistically significant values are explained and addressed in the results section. If a variable was not significant, it will not be mentioned further.

Results

After the coppice evaluation, it was decided that due to technical issues, study sites 2 and 3 would not be included in the analysis. For an unknown reason the stumps' survival at study site 2 was extremely low (below 20%), which led to the exclusion of the site in the final results. On the other hand, the size of trees

Table 2. Models used to determine the felling effects on coppice regeneration.

Site	Model no.	Model
1	1	$CR \sim FM/S + Dam + FM : Dam + DGL + HD + SD + (1\|Plot/Row)$
1	2	$NS \sim FM/S + Dam + FM : Dam + DGL + HD + SD + (1\|Plot/Row)$
3	3	$CR \sim FM + Dam + FM : Dam + DGL + HD + SD + (1\|Plot/Row)$
3	4	$NS \sim FM + Dam + FM : Dam + DGL + HD + SD + (1\|Plot/Row)$
4	5	$CR \sim FM/S + Dam + FM : Dam + DGL + HD + (1\|Row)$
4	6	$NS \sim FM/S + Dam + FM : Dam + DGL + HD + (1\|Row)$
5, 6	7	$CR \sim FM/S + Dam + FM : Dam + DGL + HD + (1\|Row)$
5, 6	8	$NS \sim FM/S + Dam + FM : Dam + DGL + HD + (1\|Row)$

Note: *CR*, Coppice regeneration; *S*, Season (winter and summer); *FM*, Felling method (shear and chainsaw); *Dam*, Bark damage class; *DGL*, Diameter at ground level (cm); *HD*, Harvest damage type; *SD*, Skidder damage; *NS*, Number of new stems; :, Interaction between; ~, "As a function of" at study site 3 was a concerning factor after the winter harvest (in some cases the DBH of the trees reached, and even exceeded, the 36 cm opening capacity of the felling head), leading to the decision of not performing a summer harvest at that site.

Additionally, although the effect of season on coppice regeneration was calculated for all study sites, and the results are reported, the experimental design of the plots was not ideal. Hence, it can be inferred that the results presented for the effects of season on coppice regeneration can be suggested but not considered definitive.

Effects of harvesting on eucalypt coppice regeneration

At the study site 1, a significant season effect was observed (*p*-value: 0.00398), in which 96% of the trees felled during winter regenerated coppice, while only 79% of the trees felled during summer regenerated new stems (Figure 2). According to the GLMM analysis, tress cut during winter were 21.3 (19.1–23.6; 95% C.L) times as likely to regenerate coppice as trees cut during summer (Table 3). No significant difference was observed between felling with the shear head or chainsaw.

On the other hand, higher damage to the bark of the stumps resulted in a statistically significant value (*p*-value: 0.00419), negatively affecting the ability to coppice the eucalypts at study site 1. In total, 55 trees felled were classified under the bark damage class 0, and 52 (95%) of those trees successfully regenerated coppice while 151 of the trees felled were classified under the bark damage class 4 and only 125 (83%) of those trees were successful in regenerating coppice (Figure 2). According to the GLMM procedure, stumps without bark damage were 0.54 (0.11–0.96; 95% C.L.) times as likely to coppice as stumps with bark damage (Table 3).

In addition to the bark damage, a significant effect (*p*-value: 0.00541) of an interaction between the shear head and the bark damage was detected at study site 1 (Figure 2). For trees cut with the shear head, not causing damage to the bark resulted in 100% of coppice regeneration. However, when bark damage was present at higher levels (class 4) the stumps' survival rate was higher than when damage was moderate (classes 2 and 3) and as much as when damage was low (class 1). On the other hand, for stumps cut with the chainsaw, stumps with bark damage class 4 had lower survival rates than the stumps with the other damage classes or no damage.

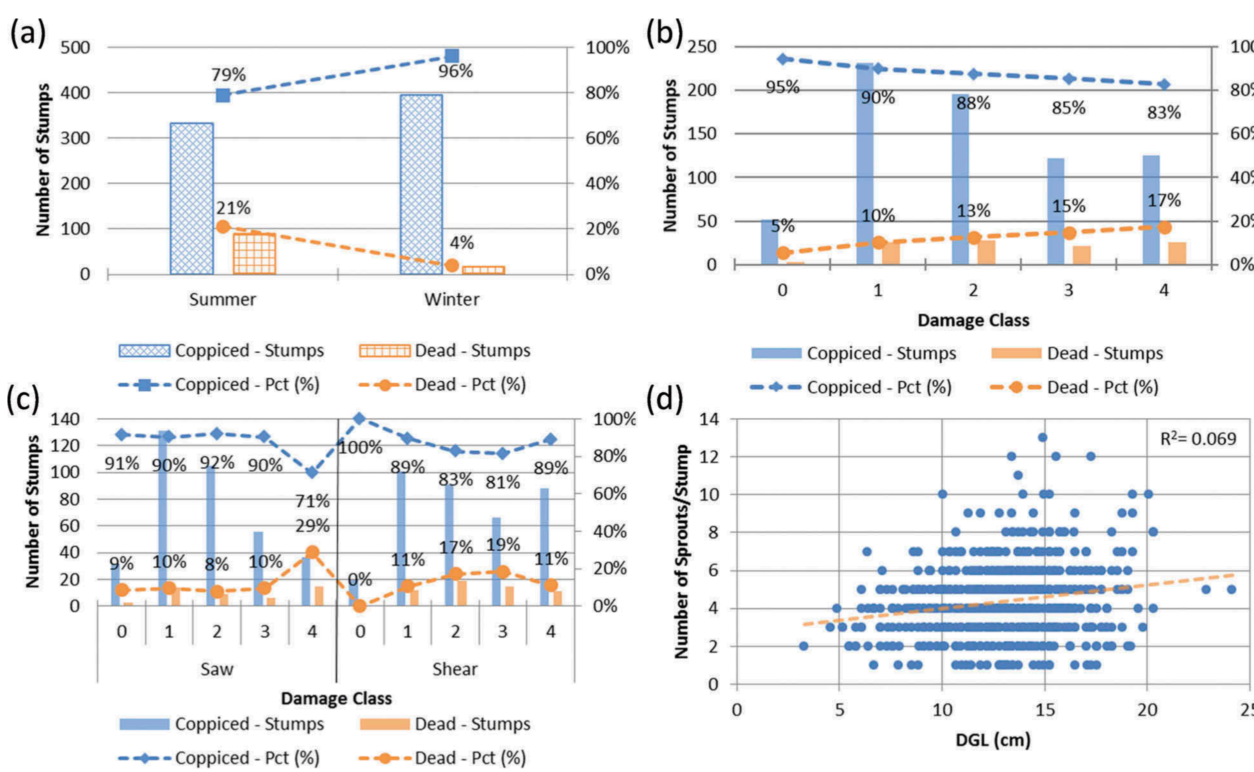

Figure 2. Charts of the effects of harvesting on coppice regeneration of eucalypt at study site 1: (a) Effects of season on the stumps' survival. (b) Bark damage negative effect on stumps' survival. (c) Interaction between shear head and bark damage on stumps' survival. (d) Effect of the diameter of the stumps on the number of stems regenerated.

Table 3. Models and results obtained from the GLMM procedure to determine felling effects on coppice regeneration. Significant variables were determined at α = 0.05.

Site (Species)	Model no.	Variable	Estimates[a] (odds ratios)	Std. Error	z-value	p-value
1 (Eucalypt)	1	Intercept	18.0113	1.0879	2.706	0.0068
		Season[1]	21.3270	1.1134	2.879	0.0039
		Bark damage[2]	0.5357	0.2179	−2.863	0.0042
		Shear:Damage[3]	2.1346	0.2726	2.781	0.0054
1 (Eucalypt)	2	Intercept	3.0529	0.1192	9.362	0.0000
		DGL[4]	1.0956	0.0184	4.950	<0.001
4 (Cottonwood)	5	Intercept	3.6371	0.5812	2.222	0.0263
		Season	15.4947	0.7699	3.559	0.0004
		Winter:Shear[5]	33.7236	1.4759	2.384	0.0171
		Shear:Damage[6]	0.4039	0.4223	−2.147	0.0318
4 (Cottonwood)	6	Intercept	0.8679	0.1200	−1.180	0.2380
		DGL	1.6583	0.0344	14.686	0.0001
5 (Cottonwood)	7	Intercept	5.8334^{-13}	79.45	0.000	0.9997
		DGL	2.2639	0.3046	2.683	0.0073
5 (Cottonwood)	8	Intercept	2.5255	0.0999	9.269	0.0001
		Felling type[7]	1.2194	0.0941	2.108	0.0350
		DGL	1.1612	0.0142	10.495	0.0001
6 (Willow)	7	Intercept	12.146	1.022	2.444	0.0145
		DGL	2.0049	0.2962	2.349	0.0188
6 (Willow)	8	Intercept	3.6439	0.0628	20.608	0.0001
		Season	1.5949	0.0623	−7.499	0.0001
		DGL	1.2212	0.0153	13.001	0.0001

Note: [1]Winter versus summer. [2]Bark damage classes. [3]Interaction between shear head and bark damage. [4]Diameter of the stump at cut level, in cm. [5]Interaction between winter and shear head. [6]Interaction between shear head and bark damage. [7]Shear head versus chainsaw. [a]Odds ratios obtained from e^x.

This infers that when cutting with the chainsaw, higher bark damage affects the stump survival, while when cutting with the shear head higher bark damage may have similar effects that when damage is low. After analyzing the model with the GLMM procedure, the conclusion was that stumps harvested with the shear head were 2.13 (1.60–2.67;95% C.L.) times as likely to coppice as stumps cut with the chainsaw when bark damage was severe (Table 3).

The number of stems regenerated per stump was significantly affected by the DGL at study site 1 (p-value: <0.0001). Stumps with larger diameters generally regenerated a larger number of stems. Smaller stumps, with DGL range between 0 and 2 cm, regenerated an average of 3 stems per stump, and larger stumps, with DGL in the range 20–25 cm, averaged 6.7 stems per stump regenerated (Figure 2). The GLMM procedure indicates that for each 1 cm increase in DGL, stumps regenerated 1.09 (1.06–1.13; 95% C.L.) times as many new stems (Table 3).

Effects of harvesting on cottonwood coppice regeneration

The season variable showed a significant effect on the stumps' survival at study site 4 (p-value: 0.000372), where 98% of trees harvested during the winter were successful in regenerating coppice, while only 49% of trees harvested during summer regenerated coppice (Figure 3). According to the GLMM procedure performed on the effect of season on coppicing ability, trees cut during the winter harvest were 15.49 (13.99–17.00; 95% C.L.) times as likely to regenerate coppice after the harvest as trees cut during the summer harvest (Table 3). However, this large difference can also be explained by a significant interaction between the season and the felling method (p-value: 0.017135). It was noted that the larger mortality rate observed after the summer harvest (51%), is majorly attributed to the stumps cut with the shear head. Stumps cut with the shear head during winter presented a survival rate of 99%, while it was observed that the survival rate was 26% for the stumps cut with the shear head during summer (Figure 3). As indicated by the GLMM procedure, the stumps cut with the shear head during the winter were 33.7 (30.83–36.62; 95% C.L.) times as likely to regenerate coppice as stumps cut with the shear head during the summer (Table 3). Therefore, although there is a significant season effect, the larger difference observed is explained by the interaction between the season and the shear head.

An interaction between the shear head and the bark damage was determined to be significant (p-value: 0.031821) on the survival of cottonwood

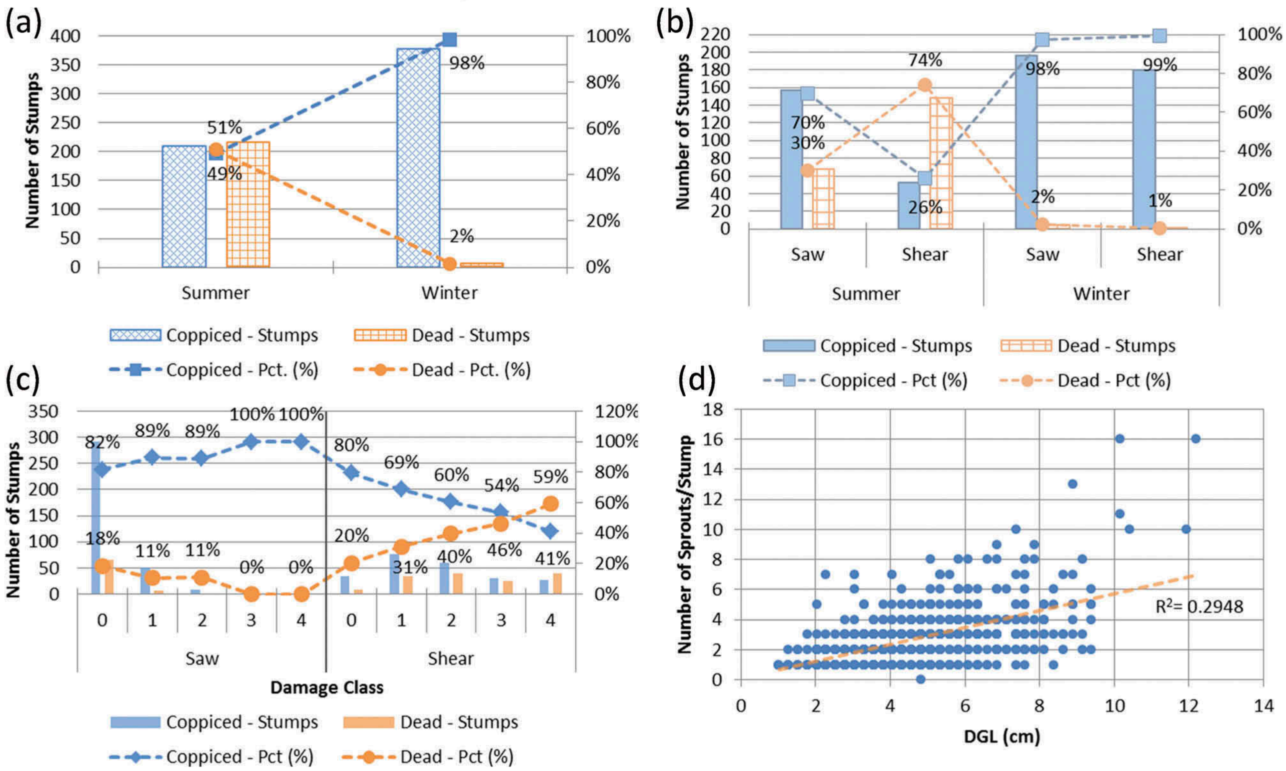

Figure 3. Charts of the effects of harvesting on coppice regeneration of cottonwood at study site 4: (a) Effects of the season on stumps' survival. (b) Interaction between season and shear head on stumps' survival. (c) Interaction between shear head and bark damage on stumps' survival. (d) Effect of the diameter of the stumps on the number of stems regenerated.

stumps at study site 4. Stumps felled with the chainsaw had less damage to their bark, when compared to stumps felled with the shear head. Additionally, the few number of stumps cut with the chainsaw that had bark damage were highly successful in coppicing, while the coppicing success of the stumps cut with the shear head had a negative linear relation with bark damage; the more severe damage, the lower the resulting survival rate (Figure 3). The GLMM procedure indicated that stumps cut with the shear head, and with bark damage, were 0.40 (−0.42–1.23; 95% C.L.) times as likely to regenerate coppice as stumps felled with the chainsaw and with bark damage present (Table 3).

The DGL of stumps also had a significant effect on the number of new stems regenerated at the study site 4 (p-value: 0.0001). It was observed that stumps with a smaller DGL regenerated less stems than stumps with a larger DGL. On average, the stumps with DGL between 0 and 3 cm regenerated 1.4 stems, while the stumps with larger DGL regenerated up to 16 stems (Figure 3). After performing the GLMM procedure, it was determined that for each 1 cm increase in stump diameter, the cottonwood stumps at study site 4 regenerated 1.66 (1.59–1.73; 95% C.L.) as many stems (Table 3).

On the other hand, the felling equipment had a significant effect on the number of new stems per stump of felled cottonwood at study site 5 (p-value: 0.0350). On average, stumps cut with the shear head regenerated 5.7 stems, while stumps cut with the chainsaw regenerated 4.7 stems (Figure 4). The GLMM procedure indicated that stumps cut with the shear head regenerated 1.22 (1.03–1.40; 95% C.L.) times as many stems as stumps cut with the chainsaw (Table 3).

The DGL of the stumps had a significant effect on the stump survival (p-value: 0.0073) and on the number of stems regenerated (p-value: 0.0001) at study site 5. Stumps with larger DGL showed better survival rates than the stumps with a smaller DGL (Figure 4). According to the GLMM procedure of the survival of the stumps at study site 5, for each 1 cm increase in the DGL, the stumps were 2.26 (1.67–2.86; 95% C.L.) times as likely to regenerate coppice (Table 3).

Additionally, stumps with a larger DGL regenerated more stems, when compared to stumps with a smaller DGL (Figure 4). On average, stumps with a lower DGL regenerated 2.7 stems, while the stumps with a larger DGL regenerated an average of 8.5 stems. The GLMM procedure for the effect of

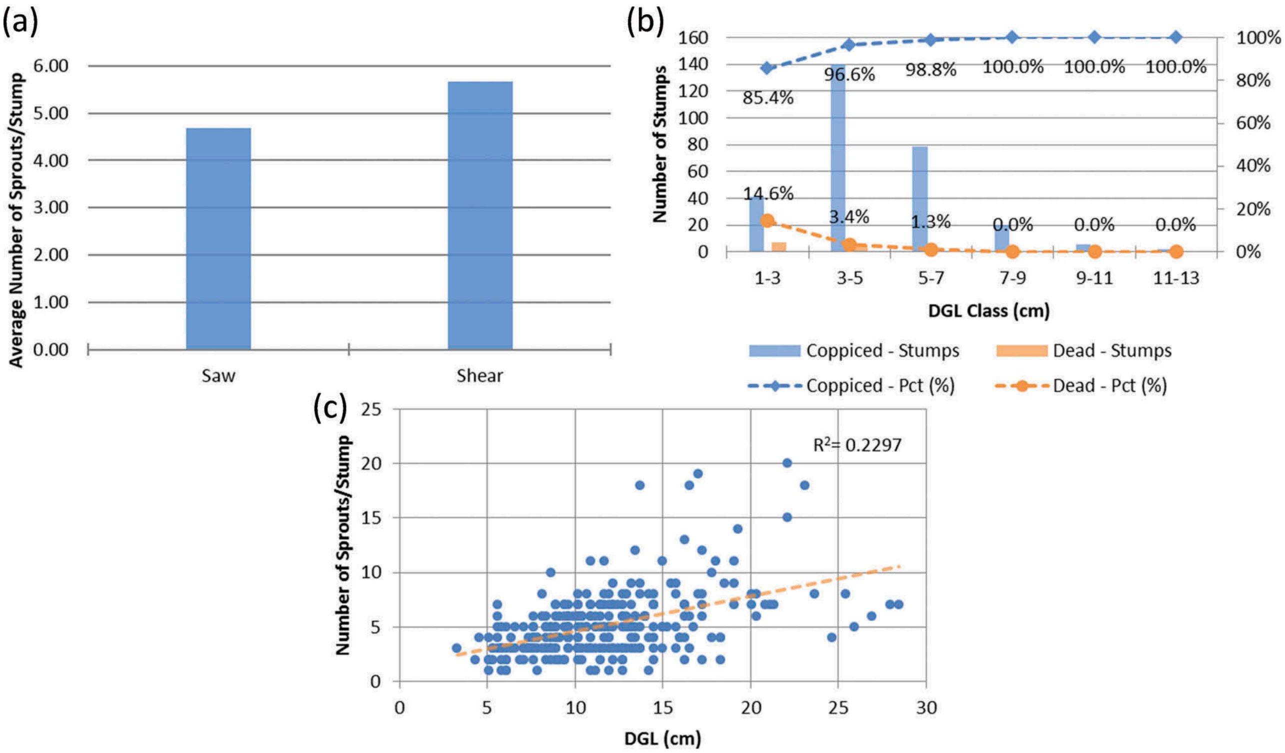

Figure 4. Charts of the effects of harvesting on coppice regeneration of cottonwood at study site 5: (a) Effects of felling method on number of stems regenerated. (b) Effects of the diameter on stumps' survival. (c) Effect of the diameter of the stumps on the number of stems regenerated.

DGL on number of stems indicated that for each 1 cm increase in a stump's diameter, stumps regenerated 1.16 (1.13–1.18; 95% C.L.) as many stems (Table 3).

Effect of harvesting on black willow coppice regeneration

It was observed that the average number of stems regenerated per stump was higher when the harvest was performed during summer than when performed during winter (p-value: 0.0001). Stumps cut during summer averaged 6.2 stems per stump while stumps cut during winter averaged 4.5 stems per stump (Figure 5). The GLMM procedure used for this analysis indicated that when trees were felled during summer they regenerated 1.60 (1.47–1.72; 95% C. L.) times as many stems as when trees were felled during winter (Table 3).

Additionally, the DGL was determined to have an effect (p-value: 0.0188) on the stump survival of black willow. The stumps with the lowest DGL class had lower survival rates when compared to the higher DGL classes (Figure 5). According to the GLMM procedure performed to the stump survival of black willow trees, for each 1 cm increase in stump DGL, the stumps were 2.00 (1.42–2.59; 95% C.L.) times as likely to regenerate coppice (Table 3).

The DGL of the black willow stumps also had a significant effect (p-value: 0.0001) on the number of new stems per stump. A positive linear relation was observed between the DGL and the number of stems per stump, where stumps with larger DGL, generally regenerated a larger number of stems. Stumps located on the smallest DGL class averaged 1.44 stems, while the stumps on the largest DGL classes averaged up to 9 stems (Figure 5). After performing the GLMM procedure, it was estimated that for each 1 cm increase in stump DGL, stumps of black willow regenerated 1.22 (1.19–1.25; 95% C.L.) as many stems (Table 3).

Discussion

The key outcome of this study was to determine if the felling equipment and the season of year could have an impact on the coppicing ability of the stumps of eucalypt, cottonwood and black willow; however, additional variables were present at the time of the harvest and could not be left out, broadening the scope of the study. Other studies have proved, with different tree species that factors such as tree diameter, bark damage, and harvest damage

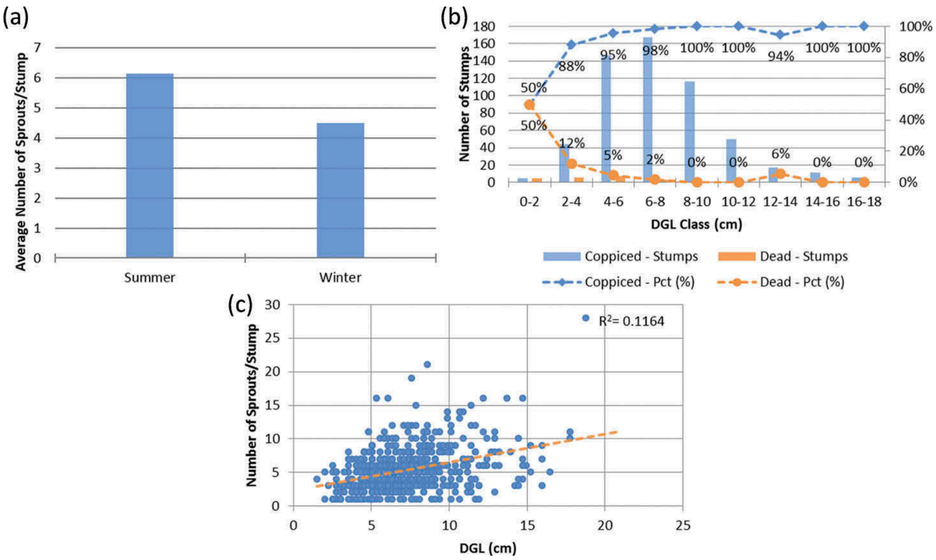

Figure 5. Charts of the effects of harvesting on coppice regeneration of black willow at study site 6: (a) Effects of season on number of stems regenerated. (b) Effects of the diameter on stumps' survival. (c) Effects of the diameter of the stumps on the number of stems regenerated.

may have impacts on the regeneration of coppice (Simões et al. 1972; Strong & Zavitovski 1983; De Souza et al. 1991; Ducrey & Turrel 1992; Hytonen, 1994, 1996, 2001).

Effect of season on coppice regeneration

Eucalypt and cottonwood trees presented better survival rates when the harvest was performed during winter. This pattern was expected to be observed on cottonwood and black willow trees, which are deciduous genera, however it was not expected on the eucalypt, since it is an evergreen genus without a clear dormancy phase, capable of producing new stems when felled at any time of the year (Ceulemans et al. 1996; Sims and Ventury 2004). The lower survival rate observed on the cottonwood harvested during summer may be explained by the fact that the carbohydrate reserve in the root system is lower after the onset of shoot growth during the first part of the growing season (Strong & Zavitovski 1983; Ceulemans et al. 1996). On the other hand, the higher survival rate observed on the eucalypt harvested during winter may be explained by the fact that the period of rain in south Florida occurs during summer, and although eucalypt is an evergreen species, it may store higher levels of carbohydrates during the drought period, maximizing the regeneration of coppice if harvest occurs during winter.

Although season did not affect the survival of black willow stumps, a significant effect was observed on the number of stems per stump. Stumps cut during the summer season regenerated, on average, more stems than stumps cut during winter. This pattern was not expected, however it seems to match the results of other studies (Steinbeck 1978; Hytönen 1994). According to Hytönen (1996), the reasons for differences in coppicing due to timing of the cutting are not fully understood, since the number of stems regenerated varies, presenting better results either during summer or winter.

Effect of the felling method on coppice regeneration

There were no differences observed on stump survival of eucalypt, cottonwood or black willow when harvesting with a shear head or a chainsaw, which was expected, since previous and similar studies showed similar results (Simões et al. 1972; Crist et al. 1983; Hytönen 1994; Pyttel et al. 2013). However, the effect observed on the number of stems regenerated per stump at study site 5, proved that stumps cut with the shear head regenerated, on average, more stems than stumps cut with the chainsaw, which also coincided with Hytönen (1994) results, where leaving a rougher cutting surface resulted in higher numbers of stems regenerated.

Other factors affecting coppice regeneration

Among the studied factors (bark damage, harvest damage, and DGL), the diameter of the stumps was significant in the regeneration of coppice, regardless of the species. It was observed that DGL had a positive linear relationship with the average number of stems regenerated in all sites. Stumps with a larger DGL averaged more stems than stumps with a smaller DGL. This result was expected, since the stumps with a larger DGL, theoretically, have more buds on their surface, which can develop to form new stems to replace the material removed or damaged during the harvest.

The DGL also showed significance on the survival of cottonwood and black willow stumps at study sites 5 and 6, respectively. In this case, stumps with a larger DGL presented better survival than the smaller stumps. A result that seems likely, since stumps with a larger DGL probably had larger root systems, which could have captured higher amounts of nutrients and water, suppressing the growth or regeneration of new stems by the stumps with smaller DGL.

It was also noted that bark damage caused a significant effect on the survival of eucalypt stumps at study site 1. A negative linear relationship was observed, where the more severe the bark damage was, the lower the survival rate results. This is probably because the axillary buds that regenerate new stems in eucalypt trees are located under the bark, and damaging the bark may damage or expose those buds, affecting the coppice regeneration (Opie et al. 1984; Ceulemans et al. 1996).

Additional to the factors mentioned before, interactions between felling equipment, season, and bark damage were tested. The interaction between the felling equipment and the bark damage observed at study site 1 helps to explain the bark damage effect observed at the mentioned site. Higher bark damage decreases the survival rate of the stumps; however this pattern is not entirely accurate depending on the felling equipment. At study site 1, sawn stumps with bark damage 0, 1, 2, and 3 presented similar survival rates (90–92%), differing only from stumps with bark damage 4, which have lower survival rates when compared to the others (71%); still in concordance to the literature (Crist et al. 1983; Hytönen 1994) where higher bark damage tends to affect coppice regeneration. On the other hand, when cutting with the shear head, causing more damage to the stumps, also negatively affected the survival of the stumps. However, stumps with bark damage class 4 had identical survival rates to stumps with bark damage 1; the reason for this result however could not be fully understood, and further observations will be made in the future to determine possible causes of this effect.

At study site 4, the interaction between the felling equipment and the bark damage explains how the negative linear relation between bark damage and stump survival was majorly explained by the shear head, since 85% of the sheared stumps presented damage on their bark, while 15% of the sawn stumps presented damage on their bark. This was expected, due to the cutting motion of the shear head being more harmful than the saw and to previous knowledge of damage caused to the stumps by shear heads (McNeel & Czerepinski 1987).

Finally, an interaction between the felling equipment and the season was observed at study site 4. This interaction explained how the season effect observed at this site was mainly due to the stumps cut with the shear head, which had a mortality rate higher than the survival rate when harvested during summer, and almost nonexistent when harvested during winter (74% for the summer harvest and 1% for the winter harvest).

Conclusions

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

Although a season effect was observed at two of the studied sites, the restriction of the harvest to the one season should not be yet recommended. Previous studies (e.g. Sims & Venturi 2004) have proved that a frequent harvesting system throughout the year appears to be a feasible method to reduce costs of biomass delivered to the mill in comparison to a short season harvest. Hence, a cost analysis could be performed to this study to determine the impacts that the observed season effect has on the profitability of the system.

The utilization of the shear head attached to a skid steer proved to be a good option while waiting for the development of machinery specialized on harvesting SRWC. The use of a shear head instead of a chainsaw (which implies higher danger, lower productivity, and is more labor intensive) is highly recommended.

Additionally, it was found that depending on the species, the number of stems per stump was affected by DGL, felling method, and season. Nonetheless, the importance of the number of stems regenerated per stump is not yet clear. There is no certainty about the benefits of having several stems per stump, instead of having a unique stem. Perhaps having a single large stem regenerated per stump may be more desirable, depending on the goal of implementing a coppice plantation (energy, pulpwood, fuel, etc.), even resulting in a higher yield than 10 small stems, and facilitating the harvest process.

Finally, a second phase of this study is being developed, to determine the possible long-term differences (decrease or increase on number of stems/stump, stump mortality) that could emerge after the harvest (i.e. 2–3 years) and to observe possible differences in yield between harvesting seasons and equipment.

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