Biomass production of Black Willow (Salix nigra Marsh.) and Eastern Cottonwood (Populus deltoides Bartr. Ex Marsh.) in the Lower Mississippi Alluvial Valley

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Biomass production of Black Willow (*Salix nigra* Marsh.) and Eastern Cottonwood (*Populus deltoides* Bartr. Ex Marsh.) in the Lower Mississippi Alluvial Valley

By

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A Thesis
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Master of Science
in Forestry
in the Department of Forestry

Mississippi State, Mississippi

August 2021
This study aimed at developing allometric equations for the estimation of aboveground biomass of black willow and eastern cottonwood and determine biomass production by these species under several planting spacing and harvest frequency combinations. Logarithmic model with dbh and tree height was the best fitting model for individual tree aboveground biomass estimation of both species. At area level, logarithmic models with stand age, dominant height, and planting density produced the best results. Mixed-effects modeling showed statistically significant effects of harvest frequency for eastern cottonwood but not for black willow. Overall, we conclude that, biomass production of black willow and eastern cottonwood would play a critical role in the fulfillment of the wood energy demands and biomass yields can be enhanced by considering management factors during plantation. These findings will be useful to forest owners in Lower Mississippi Alluvial Valley for estimating biomass without destructive sampling and have optimal biomass production.
Keywords: short rotation woody crops, biomass estimation, allometric equation, biomass production potential, LMAV.
ACKNOWLEDGEMENTS

First and foremost, I would like to thank my major professor, Dr. Krishna P. Poudel for his constant support and guidance during my MS degree. I would also like to extend my gratitude to my committee members, Drs. Heidi J. Renninger and Joshua J. Granger for all their incredible help and suggestions. I would like to thank Drs. Theodor D. Leininger, Emile S. Gardiner, Ray A. Souter, and Charles O. Sabatia for establishing field sites and providing me with the research data. Special thanks to Chris Kirk for his help throughout the project. I would also like to thank Center for Bottomland Hardwoods Research for funding this research and providing me an opportunity to work on this project. Last but not the least, I will forever be indebted to my friends (Bikram and Gaurav) and family for their continued love and support.
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CHAPTER I
BACKGROUND

Accurate estimates of biomass are required to account for carbon sequestration rates, evaluate environmental impacts of climate change, locate bioenergy processing plants, and make sustainable forest management decisions (Temesgen et al. 2015). Forest biomass is an integral part of the global carbon cycle but degradation by fire and deforestation can disrupt a forest’s ability to store carbon (Poudel et al. 2019). Global land use change caused by such disturbances release around 1-1.3 petagrams of carbon per year back to the environment increasing the atmospheric carbon level (Pan et al. 2007; Baccini et al. 2012). Therefore, the estimate of present and future biomass is critical to determine the carbon fluxes (Houghton et al. 2009). Although both above and belowground biomass are equally important, most biomass studies focus on estimation of the aboveground biomass (AGB) because of the difficulty in measuring the belowground components (Lu 2006).

Biomass is a renewable source of energy and serves as an industrial raw material for bioenergy production (Hinchee et al. 2009). Perlack et al. (2005), in their “Billion Ton Report,” mentioned that biomass was gaining attention, being the only renewable resource that can be used to make liquid fuel for transportation. They identify both forest (e.g., fuelwood, logging residues, and wood mill residues) and agricultural crops (e.g., crops residues, shrubs, perennial woody crops, animal manures) as potential energy sources to reducing petroleum use by 30% by 2030. In this report, short rotational woody crops grown for bioenergy production were
categorized under perennial woody crops and were expected to contribute 377 million dry tons per year with increased crop yield and technology advancement.

Biomass estimates are also inputs to national greenhouse gas inventories and are required for understanding the potential contributions of the forestry sector in mitigating climate change impacts. Biomass estimation by harvesting trees/plants is difficult, expensive, and time consuming. Therefore, allometric equations are used to estimate the biomass based on easily measurable tree attributes such as diameter at breast height (dbh) and height. These equations are derived using regression techniques and can also be used to quantify the carbon fluxes in the forests. Biomass models, however, have some limitations such as models developed for one location may not be appropriate for another location; models for young stands may not work for mature ones; and models developed for one species may not work well for other species. Consequently, many site and species specific models have been developed to obtain more reliable estimation of the biomass (Ravindranath and Ostwald 2008).

Biomass yield potential of a species and/or varietal is the most important consideration for the plantation of short rotation woody crops (Sims et al. 2001). Although, several biomass equations, with varying degrees of complexity, have been developed for traditionally commercial tree species (Sileshi 2014), only a handful of studies have been conducted for the biomass estimation of short rotation woody crops (Huber et al. 2017). Plantation of short rotation woody crops (SRWC) will be favored by private landowners only if sustainable periodic income can be demonstrated.

The increasing demand for renewable energy has accelerated the planting of short rotation woody crops (SRWC) plantations in the United States and Canada (Kopp et al. 1997). SRWC such as *Populus* spp., *Salix* spp., and *Eucalyptus* spp. are significant source of biomass
for bioenergy and biofuels production because of their fast growth, compatibility for coppicing, short rotation (usually 3-4 years), low maintenance, and cost-efficient harvest (Sims and Venturi 2004). To meet the present and future wood energy demand and to ensure the sustainable supply of feedstocks, enhancing the biomass production of these species is essential.

Biomass production of a species is influenced by numerous biotic and abiotic factors such as soil texture and water content, atmospheric humidity and temperature, irrigation, nutrient availability, growth competition, and pest and diseases (Chatzistathis and Therios 2013; Whittaker and Shield 2016). These factors influence root growth and photosynthesis in plants, thus affecting their overall growth and development (Chatzistathis and Therios 2013). However, with different species and clonal types, the response to these factors in terms of biomass production also differs. For example, *Populus nigra* performed better in high fertility and less acidic soil however, their hybrid clones (*Populus maximowiczii × Populus trichocarpa*) had greater growth in areas with low nutrient and high moisture content (Benetka et al. 2002). Similarly, hybrid clones have greater biomass yield because of their better resistance against pest and disease and improved photosynthesis (Wilkinson et al. 2007). Apart from that, harvest frequency and spacing or planting density are the primary management factors affecting the establishment and biomass production of SRWC (Nassi O Di Nasso et al. 2010). Therefore, optimal rotation age and spacing need to be considered before the establishment of the SRWC plantation (Pérez-Cruzado et al. 2011). However, there has been limited research on the effects of harvest frequency and spacing in biomass production of SRWC.

A sustainable bioenergy production system is dependent upon the choice of species as well as the crop management system (Scholz et al. 1998). Additionally, to establish higher energy efficiency and low environmental input, a sustainable energy crop should have the
characteristics of low input requirement along with high production. Willow (*Salix* spp.) and poplar (*Populus* spp.) are two of the most common SRWC grown widely in the US for energy production (Walsh et al. 2000; Wilkinson et al. 2007). Some studies have shown that maximum yield is obtained in plantations with higher planting density (narrow spacing) and harvesting at 3-4 years to be more beneficial than annual or biennial harvest (Kopp et al. 1997, Nassi O Di Nasso et al. 2010) but more research is needed to verify these findings.
**LITERATURES CITED**


CHAPTER II
ABOVEGROUND BIOMASS EQUATIONS FOR BLACK WILLOW AND EASTERN COTTONWOOD

INTRODUCTION

Estimation of aboveground biomass (AGB) is crucial for determining the forest ecosystem productivity and sustainability (Vashum and Jayakumar 2012). This estimation is also linked with atmospheric carbon sequestration as plants serve as the reservoir of carbon, storing it in its tissues, leaves, roots, and soil. Accurate estimation of biomass is important in understanding the impact of forest degradation and deforestation in climate change (Kumar and Mutanga 2017). Forests store about 86% of aboveground carbon and 73% of the soil carbon globally (Sedjo 1993). Although carbon stored in forests can be released to the atmosphere due to deforestation and forest degradation, it is again utilized by the plants for their growth and development thus, maintaining the global carbon cycle (Houghton et al. 2009).

The issue of global warming, greenhouse gas emissions, and climate change has increased interest in the use of woody biomass for energy production because of the environmental benefits associated with it (Kopp et al. 2001). Several studies have shown that the use of bioenergy can help to mitigate climate change if a cost efficient and sustainable supply of these resources is ensured (Johansson et al. 1996; Berndes 2011; Creutzig et al. 2015). Biomass is produced by plants during the photosynthesis process when it utilizes atmospheric carbon converting it into carbohydrate and releasing oxygen to the environment (Vashum and
Jayakumar 2012). Biomass is therefore considered as a renewable and environmentally friendly source of energy (Rončević et al. 2013). Thus, the estimation of AGB is important and gaining attention from both an energy production and environmental perspective.

AGB is the aggregation of all components of plants above soil, which includes the stem wood, stem bark, leaves/needles, branches, and seeds (Ravindranath and Ostwald 2008), and accounts for 70-90% of the total forest biomass (Cairns et al. 1997). The estimation of these components is important as they serve different objectives of forest management e.g., stem and crown biomass are related to timber sale and fire management, respectively (Lambert et al. 2005), and bark content can be important for bioenergy (Nosek et al. 2016). The AGB of a forest can be estimated by field measurements, remote sensing techniques and GIS methods (Brown et al. 1989; Brown and Gaston 1995; Houghton et al. 2001; Lu 2005) but field measurements are considered to be more reliable and accurate to develop biomass estimation models (Lu 2006).

Field measurement of biomass can be done through either a destructive or non-destructive method. In the destructive method, trees are harvested, and their components such as leaves, branches, and stems are weighed. Although biomass estimates are accurate, this method is tedious, expensive, and therefore, not applicable for larger areas (Kumar and Mutanga 2017). Additionally, destructive sampling also results in biomass loss during harvest (Telenius and Verwijst 1995). The destructive method is mostly used to develop biomass equations which are then used for biomass estimation of larger areas (Vashum and Jayakumar 2012). On the other hand, non-destructive methods estimate biomass using allometric equations or models and are useful in plantations with similar aged stands (Kumar and Mutanga 2017). This method is considered more appropriate than the destructive sampling and is useful in areas with endangered plant species. Although, biomass estimation using allometric equations is a non-destructive
method, the model development and validation requires trees to be harvested and weighed (Vashum and Jayakumar 2012).

The increasing population and demand for renewable energy has created a challenge in the development of a sustainable approach for bioenergy production. SRWC have the potential of high biomass production in a short period of time thus fulfilling the energy demand as well as providing ecological services and rural development opportunities (Ruark 2006). Despite the increased interest and attention on bioenergy and biofuels production in the US, there is still a lack of biomass estimation equations for short rotation woody crops (Henderson and Jose 2010). Biomass estimation models for small diameter species are few (Singh et al. 2011) and studies focusing on black willow and eastern cottonwood, in particular, are very limited. Poplar and willow are SRWC that can grow rapidly and have the ability to produce about 10 oven dry ton per hectare (ha) per year in short rotations (Anderson et al. 1983) and are used for commercial bioenergy production (Volk et al. 2018). In this context, this research focuses on developing allometric equations to predict the AGB of two SRWC: black willow and eastern cottonwood.
LITERATURE REVIEW

Forest biomass estimation is critical for evaluating the changes in a forest ecosystem and carbon sink over a period of time (Houghton 2005). Over past decades, the estimation of AGB has received significant attention because of its role in carbon sequestration and in mitigating greenhouse gas emissions (Kumar and Mutanga 2017). Several SRWC have been planted for the production of biofuels, bioenergy and bioproducts (Volk et al. 2018). In addition to serving as a raw material for renewable energy production, biomass has numerous other environmental benefits such as an increase of biodiversity and species richness across landscape (Campbell et al. 2014; Dhondt et al. 2007), decrease in soil nutrient leaching by establishing riparian buffers (Volk et al. 2006), improvement of water quality (Bressler et al. 2017), and reduction of greenhouse gas emissions (Djomo et al. 2011; Dubuisson and Sintzoff 1998). Apart from the environmental benefits, biomass also contributes to the economic growth of a nation (Bildirici 2013). Various studies have indicated the existence of the long term relationship between biomass and economic growth where the countries with higher biomass production had higher gross domestic product (GDP) (Wolde-Rufael 2005; Bildirici 2013). The increase in biomass consumption simultaneously increases the demand and supply of the biomass generating employment opportunities for people to earn and improve their living standard (Madlener and Myles 2000).

In short rotation forestry, biomass estimation has various objectives such as determining the aboveground matter at an area level, quantifying the merchantable stem bole, and estimating root or leaf biomass. In addition to the biomass model forms used, there are other aspects involved in the estimation process such as converting single tree biomass to plot level, green
weight to dry weight conversion, and standing plants to merchantable biomass (Verwijst and Telenius 1999).

The accelerating use of wood energy and growing concern about the environment has attracted attention in SRWC (Dudley and Fownes 1992). As the plantation of SRWC is mainly for a commercial purpose, it is important to have an accurate and precise estimation of biomass. A reliable, accurate and non-destructive means for estimating AGB has been of significant importance with increasing interest in SRWC (Byrd et al. 2015). This also helps landowners make appropriate decisions for sustainable management of their forest land (He et al. 2013).

The common approach of biomass estimation includes destructive sampling of sample trees and measurement of their components which is later used to develop regression models thus allowing the estimation of stand level biomass (Baskerville 1971). The estimation of forest biomass involves three major steps: (1) selection of regression models for the estimation of individual tree biomass, (2) the summation of individual tree biomass to obtain plot level biomass, and (3) the calculation of average biomass across plot to estimate forest level biomass (Breugel et al. 2011). The choice of biomass estimation models can influence local, regional, and global biomass estimation. Therefore, there has been increasing efforts in the development of the biomass equations in recent years (Sileshi 2014).

Allometric equations relate easily measurable tree attributes such as diameter at breast height (dbh, 1.37 meters (m) aboveground) and/or total height with AGB through linear and nonlinear functions (Austin et al. 2003). The equations are derived from sample tree data and are mostly species specific. Species- and site-specific models provide more accurate and less biased estimates than generalized models in absence of local calibration data (Fortier et al. 2017).
Therefore, the generalized regional models should be used with caution to eliminate potential estimation bias (Montagu et al. 2005).

Selection of explanatory variable(s) is another critical factor that determines the accuracy of allometric models. The explanatory variables used for biomass estimation mainly include dbh, height, and combinations of these such as $\text{dbh}^2 \times \text{height}$. Most biomass estimation models use only dbh as the predictor variable (e.g., Jenkins et al. 2003; Arevalo et al. 2007; Fortier et al. 2017), however, recent research highlighted the significance of height for more reliable and accurate biomass estimates (Chave et al. 2005; Lima et al. 2012). Biomass estimation using only dbh is sufficient for small area whereas, both dbh and height are required for larger area applications (Zhou and Hemstrom 2009). Montagu et al. (2005) tested five different independent variables including dbh, stem volume, $\text{dbh}^2 \times \text{height}$, $\text{dbh} \times \text{height}$, and height to estimate AGB of *Eucalyptus pilularis* in seven different sites. Their results showed that the biomass equation with dbh as the only explanatory variable had a more stable relationship in all sites. Kebede and Soromessa (2018) found similar results for *Olea europaea* L. subsp. *cuspidata* species in southeastern Ethiopia. Their result showed that dbh was a strong indicator of AGB as it provided small bias. In contrary, Lima et al. (2012) compared six different allometric models and found that the model including height as a separate predictor had the highest coefficient of determination ($R^2$). However, precision obtained by adding height in the biomass models depends on the accuracy of recorded height as it is difficult and requires more time than dbh measurement, and has greater chances of error (Williams et al. 1994).

The accuracy of carbon flux estimates is dependent on the model form used in biomass estimation (Chave et al. 2014). New model development requires destructive sampling that can be expensive, time consuming, and labor intensive. For example, the harvest cost accounts for
about 40% of the cost of producing willow biomass (Tharakan et al. 2005). Therefore, most of this research uses previously published biomass models. Development of allometric models provides a non-destructive and efficient method for biomass estimation in short rotation forestry.

Linear regression and log transformation of variables were traditionally used for biomass estimations because of the lack of computing power and for easier estimates of biomass. Logarithmic models also correct the heterogeneity of error variance common in the biomass models. However, there has been an increase in the use of nonlinear models because of their ability to capture the relationship between the dependent and independent variables without transformations (Litton et al. 2006). There are numerous forms of biomass equations; however, the most commonly used form is the power model of the form: \( y = ax^b \) where, \( y \) is biomass, \( x \) is dbh and \( a \) and \( b \) are regression coefficients (Niklas 2006). Power models are known as simple allometry and have been suggested by various researchers to estimate tree biomass as the log transformed data, when plotted, align in a straight line (Sileshi 2014; Stevens 2009).

Arevalo et al. (2007) used dbh based biomass models for willow clones and found the power model to have the highest and most consistent \( R^2 \) values followed by the lowest root mean square error (RMSE) for both training and testing data sets although it had higher bias. Hauk et al. (2015) found that the power model using dbh as the predictor was able to estimate the biomass within the preferred degree of accuracy. Therefore, biomass estimation of SRWC using power models is considered be precise and accurate (Verwijst and Telenius 1999). In contrast, Picard et al. (2015b) investigated different model forms for forest biomass estimation and found complex allometry performed better than the power model.

Arevalo et al. (2007) developed diameter-based biomass models for four willow species (*Salix discolor, Salix alba, Salix dasyclados, Salix sachalinensis*) growing on two different sites.
Models were fitted using ordinary least squares regression on log transformed variables, weighted least squares regression on log transformed variables, and nonlinear regression at three different levels – intermediate (clone and age specific), specific (clone, age, and site specific), and general (clone specific). They found significant effects of site, clone, and age on the biomass of the species and the ordinary least squares regression model developed with these variables had the most accurate prediction. However, because the measurement of such variables is expensive and time consuming, the intermediate models with slightly lower accuracy than specific models were recommended. In a study of *Salix viminalis* and *Salix dasyclados* in Sweden, Telenius and Verwijst (1995) concluded that the generalized equation that accounted for age provided better estimates than the clone- and species-specific models.

Fortier et al. (2017) used dbh as the only predictor for the biomass of hybrid poplar because of the strong correlation between tree height and dbh. Additionally, they found dbh to be a strong predictor of poplar AGB in both general and site-specific equations. The site-specific models had lower AIC values, but the generalized model was reliable when the objective was to estimate the AGB rather than component biomass.
METHODOLOGY

Study Site and Data

Washington County (33.3001° N, 90.9438°W) lies in the west-central of Mississippi State (Morris 1961). It has an area of about 200,000 hectare (ha) with an elevation between 27.5 meters (m) and 43 m above sea level (Gunn et al. 1980). The climate is characterized as humid, warm with the average temperature ranging from 8°C in January to 24°C in July. High intensity rainfall is distributed from November to April with an average annual precipitation of 55 inches (in). The study area has five main soil associations including poor, moderate and highly drained soil (Morris 1961). The soils found are alluvial soil, silt loams, sandy loams, clayey, and silty clay loams. The county is dominated by agriculture with major cultivation of cotton, corn, soybeans, and rice.

Figure 2.1 shows the study site located in Washington County, MS on the U.S. Army Corps of Engineers’ land situated near the eastern boundary of Leroy Percy State Park. The area consists of dowling clay and sharkey clay soil with 0-2 % and 0-0.5 % slope respectively. On the study site, the area with dowling clay (very poor drainage) is occasionally flooded and the one with sharkey clay is rarely flooded (poor drainage). The plantation was established in 2012 on an agricultural field which was previously in rice cultivation. Transline® herbicide with the surfactant Cide-Kick was sprayed on the site in the first year with backpack sprayers and with a tractor in later years for weed control. Furthermore, SEVIN® was aerially sprayed to protect eastern cottonwood from leaf beetle.
Figure 2.1  Study site in US Army Corps of Engineers Land, Hollandale, MS
The experimental design used for the study was a split-split plot experiment in randomized complete block design with three replications of 0.2 ha blocks. Each block was divided into 8 plots and 28 subplots. The plots were divided by species and spacing, and subplots were the harvest frequencies. The spacing levels were 0.9 x 0.9 m (3 x 3 feet (ft)), 2.1 x 0.8 m (7 x 2.5 ft), 2.7 x 1.8 m (9 x 6 ft), and 3.7 x 3.7 m (12 x 12 ft) and harvest frequency levels were 1 (harvest every 6 years), 2 (harvest every 3 years), and 3 (harvest every 2 years). Spacing 0.9 x 0.9 m consists of four double rows leaving outer two double rows as buffer. Similarly spacing 2.1 x 0.8 m, 2.7 x 1.8 m, and 3.7 x 3.7 m consist of five, four, and three single rows leaving two outer rows as buffers. In each row of the subplots, first two plants were harvested, then three were skipped, and again two plants were harvested. This cycle was repeated for all the blocks. The cumulative weight of all skipped plants was also measured although their dbh and height were not recorded.

Field measurements were conducted during the winter season from December to February every year from 2013 to 2018. During the non-harvest years, dbh and height of all plants were measured however, during the harvest year, dbh centimeters (cm), height (m) and biomass of only the sample trees were measured (Table 2.1). Tree height and dbh measurements were done before harvesting the plants. Plants were cut at the ground level (3-4 inch stump height) with brush saw for smaller plants and with chain saw for bigger plants and then the total biomass was measured in the field. Some of the plants with extremely small biomass were brought to the laboratory for measurement. Diameters were not recorded for plants with height <1.3 m because they did not meet the minimum required height for dbh measurement. Therefore, for the development of individual stem biomass estimation models, only the plants with height ≥ 1.3 m were used so that both predictor (dbh and height) could be used in the model. As both
black willow and eastern cottonwood produce multiple stems, the dbh and height of the
dominant stem was measured. Area level biomass estimation was also carried out for which
biomass of measurement trees (dbh, height and AGB measured), and non-measurements trees
(only AGB measured) were added and the total AGB per ha was calculated.

Table 2.1  Harvest schedule for different spacing levels and subplots in the study site. Year in
which a subplot is harvested is represented by x.

<table>
<thead>
<tr>
<th>Spacing (m)</th>
<th>Subplot</th>
<th>Harvest year. Numbers in parenthesis indicate age.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2014 (2) 2015 (3) 2016 (4) 2017 (5) 2018 (6)</td>
</tr>
<tr>
<td>0.9 x 0.9</td>
<td>1</td>
<td>x x x x</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>x x x x</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>x x x x</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>x x x x</td>
</tr>
<tr>
<td>2.1 x 0.8</td>
<td>1</td>
<td>x x x x</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>x x x x</td>
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<tr>
<td>2.7 x 1.8</td>
<td>1</td>
<td>x x x x</td>
</tr>
<tr>
<td>3.7 x 3.7</td>
<td>1</td>
<td>x x x x</td>
</tr>
</tbody>
</table>

**Allometric Model Development**

Several linear and log transformed models were tested to estimate individual tree and
area level AGB of eastern cottonwood and black willow (Table 2.2). The dependent variable for
individual tree models were total AGB or its logarithm whereas the independent variables were
dbh, height, and their combinations or transformations. For area level estimation, the predictors
for the above ground biomass per ha (AGBPH) were dominant height (HD in m), stand age (SA),
and trees per hectare (TPH) (Equation 2.1). Dominant height for the area level was determined
by averaging the height of 10 tallest plants from each plot.
This equation was later log transformed based on the heterogeneous distribution of the residuals. The equation 2.1 will be referred to as model S1 and its log transformation as S2.

Byrd et al. (2015) found a strong relationship between the logarithm of \((\text{dbh}^2 \times \text{height})\) and logarithm of AGB for black willow and eastern cottonwood. Huber et al. (2017) also used log transformed dbh and height separately as predictors for the biomass estimation of various SRWC in agroforestry systems including poplar and willow clones. Other models used in this study have traditionally been used in the estimation of AGB of several species.

Table 2.2 Regression models for the estimation of individual tree AGB of black willow and eastern cottonwood used in this study.

<table>
<thead>
<tr>
<th>Model</th>
<th>Prediction Equation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>(Y = \beta_0 + \beta_1 X_1)</td>
<td>Djomo et al. 2010</td>
</tr>
<tr>
<td>M2</td>
<td>(\ln(Y) = \ln(\beta_0) + \beta_1 \ln(X_1))</td>
<td>Jenkins et al. 2003</td>
</tr>
<tr>
<td>M3</td>
<td>(Y = \beta_0 + \beta_1 X_2)</td>
<td>Huy et al. 2019, Brown et al. 1989</td>
</tr>
<tr>
<td>M4</td>
<td>(\ln(Y) = \ln(\beta_0) + \beta_1 \ln(X_2))</td>
<td>Huber et al. 2017, Arevalo et al. 2007</td>
</tr>
<tr>
<td>M5</td>
<td>(Y = \beta_0 + \beta_1 X_3)</td>
<td>Montagu et al. 2005, Brown et al. 1989</td>
</tr>
<tr>
<td>M6</td>
<td>(\ln(Y) = \ln(\beta_0) + \beta_1 \ln(X_3))</td>
<td>Byrd et al. 2015, Silesi 2014, Brown et al. 1989</td>
</tr>
<tr>
<td>M7</td>
<td>(Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2)</td>
<td>Eker et al. 2017</td>
</tr>
<tr>
<td>M8</td>
<td>(\ln(Y) = \ln(\beta_0) + \beta_1 \ln(X_1) + \beta_2 \ln(X_2))</td>
<td>Huber et al. 2017, Silesi 2014, Schumacher and Hall 1933</td>
</tr>
</tbody>
</table>

Note: \(Y\) = total AGB (kg), \(X_1\) = total height (m), \(X_2\) = diameter at breast height (cm), \(X_3 = X_1 \times X_2^2\) i.e., product of diameter squared and height, \(\ln(\cdot)\) = natural log.
Models M2, M4, M6 and M8 use logarithmic transformations to linearize the apparent nonlinear relationship between the dependent and independent variables. When the dependent variable is log transformed, the predicted values are biased. Therefore, the log-transformation bias correction factor (CF) suggested by Baskerville (1971) was used in this study (Equation 2.2).

\[
CF = \exp\left(\frac{\text{MSE}}{2}\right)
\]

where, MSE is the mean square error of the log-transformed model. The predicted values were then multiplied by CF to back transform the data.

Four evaluation statistics, namely bias, bias percent, RMSE, and RMSE percent were used to evaluate the prediction accuracy of the models (Equations 2.3, 2.4, 2.5, and 2.6). Note that, strictly speaking, bias represents the difference between the true value of an unknown parameter and the expected value of its estimator. However, in forestry literature (and in this study) it is used to represent the mean difference between the measured or observed value of a variable of interest and its predicted value.

\[
\text{Bias} = \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)}{n}
\]

\[
\text{Bias\%} = \frac{\text{Bias}}{\bar{y}} \times 100
\]

\[
\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{n}}
\]

\[
\text{RMSE\%} = \frac{\text{RMSE}}{\bar{y}} \times 100
\]
where, $y_i$ is the observed biomass and $\hat{y}_i$ is the predicted biomass of the $i^{th}$ tree and $\bar{y}$ is the average tree biomass.

The models with lower bias and RMSE values were chosen to be the best models. All models were validated by randomly splitting data into a model training set (75%) and validation set (25%). Models were fitted using the training dataset and goodness of fit statistics were computed for both the training and validation sets. If the bias and RMSE values did not change drastically, then the model was considered to have good predictive ability, thus a good model.
RESULTS AND DISCUSSION

Graphical analysis showed nonlinear relationships of dbh and height with AGB for both species (Figure 2.2 & 2.3). Consistent with our outcome, Jenkins et al. (2003) found a similar result where dbh and height had a non-linear relationship with the predicted biomass of black willow and eastern cottonwood.

Figure 2.2  Scatterplot showing relationship between dbh and green weight of eastern cottonwood and black willow at the study site in Hollandale, MS
Summary statistics for diameter, height, and biomass for each species are given in Table 2.3. Eastern cottonwood stems were taller and had larger diameter than willow but also had more variation than black willow justified by higher standard deviation (SD). Stem height ranged from 0.21 m to 9.88 m for black willow with a mean of 1.87 m and from 0.24 m to 11.10 m for eastern cottonwood with a mean of 3.94 m. The maximum diameter was 30.48 cm and 15.24 cm with the mean of 1.47 cm and 2.15 cm for black willow and eastern cottonwood, respectively. The biomass production in kilogram (kg) ranged from 0.002 kg to 57.417 kg for black willow and 0.005 kg to 64.674 kg for eastern cottonwood. This results aligns with Colbert et al. (2002)
where average height and dbh of eastern cottonwood were higher than of black willow.

Similarly, Fernandes et al. (2015) found that for both treated (24 hour soaked in imidacloprid solution to prevent leaf beetle) and untreated cuttings, eastern cottonwood growth was higher than black willow. Average tree height and plot level total basal area of treated cuttings increased for eastern cottonwood however, decreased for black willow. The better growth response of eastern cottonwood as shown in Table 2.3 can be correlated to the use of SEVIN® in the study site to protect eastern cottonwood from leaf beetle.

Table 2.3 Summary statistics of variables used in regression models by species at the study site in Hollandale, MS

<table>
<thead>
<tr>
<th>Species</th>
<th>Variables</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Black willow</strong></td>
<td>Height (m)</td>
<td>1.20</td>
<td>9.90</td>
<td>2.39</td>
<td>1.34</td>
</tr>
<tr>
<td></td>
<td>dbh (cm)</td>
<td>0.25</td>
<td>10.67</td>
<td>0.87</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td>Biomass (kg)</td>
<td>0.009</td>
<td>43.183</td>
<td>1.15</td>
<td>3.38</td>
</tr>
<tr>
<td><strong>Eastern cottonwood</strong></td>
<td>Height (m)</td>
<td>1.40</td>
<td>11.10</td>
<td>4.49</td>
<td>2.24</td>
</tr>
<tr>
<td></td>
<td>dbh (cm)</td>
<td>0.25</td>
<td>15.24</td>
<td>2.75</td>
<td>2.31</td>
</tr>
<tr>
<td></td>
<td>Biomass (kg)</td>
<td>0.027</td>
<td>64.674</td>
<td>4.884</td>
<td>8.08</td>
</tr>
</tbody>
</table>

Notes: SD = standard deviation

Parameter estimates, standard error (SE), and R² for eight models used in this study are given in Table 2.4. All model parameters were positive and statistically significant at 0.05 level of significance except for model M7 which was significant but had negative effect in the biomass of both species. Linear model M5 (D2H as predictor) had the highest R² of 0.9507 and 0.9280 for black willow and eastern cottonwood respectively along with lower SE.
Tree height and dbh are correlated with one another and therefore, to avoid the collinearity problem, combined predictor D2H is used for the biomass estimation because of the relationship between mass and volume (Dutca et al. 2019). However, for the biomass estimation of SRWC this combined predictor has been rarely used. Byrd et al. (2015) found a strong relationship between log transformed biomass and log transformed D2H which accounted for more than 80% variation in both black willow and eastern cottonwood. Contrary to these results, Dutca et al. (2019) found dbh and height as a separate predictor produced more accurate predictions of biomass than the combined predictors. The prediction efficiency was based on Q-ratios and with its increase the mean absolute percentage residual (MAPR), and the sum of squares of log accuracy ratios (SLAR) increased for the combined variables predictor.
Table 2.4  Parameter estimates of regression equations used to predict aboveground biomass of individual trees by species at the study site in Hollandale, MS

<table>
<thead>
<tr>
<th>Species</th>
<th>Models</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>R²</th>
<th>CF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Black willow</strong></td>
<td>M1</td>
<td>-3.8474</td>
<td>2.0860</td>
<td>-</td>
<td>0.6771</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.1469)</td>
<td>(0.0536)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M2</td>
<td>-2.8477</td>
<td>2.5646</td>
<td>-</td>
<td>0.7002</td>
<td>1.3793</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0544)</td>
<td>(0.0624)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M3</td>
<td>-0.8911</td>
<td>2.3574</td>
<td>-</td>
<td>0.8217</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0638)</td>
<td>(0.0408)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M4</td>
<td>-0.1103</td>
<td>1.1093</td>
<td>-</td>
<td>0.7025</td>
<td>1.2144</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0296)</td>
<td>(0.0269)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M5</td>
<td>0.5342</td>
<td>0.03675</td>
<td>-</td>
<td>0.9507</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0284)</td>
<td>(0.0003)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M6</td>
<td>-0.5912</td>
<td>0.4669</td>
<td>-</td>
<td>0.7189</td>
<td>1.3654</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0239)</td>
<td>(0.0109)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M7</td>
<td>0.3757</td>
<td>3.1471</td>
<td>-0.8141</td>
<td>0.8326</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.1944)</td>
<td>(0.1215)</td>
<td>(0.1184)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M8</td>
<td>-1.4787</td>
<td>0.5886</td>
<td>1.3104</td>
<td>0.7305</td>
<td>1.3568</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.1604)</td>
<td>(0.0653)</td>
<td>(0.1512)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Eastern cottonwood</strong></td>
<td>M1</td>
<td>-7.7636</td>
<td>2.8123</td>
<td>-</td>
<td>0.6059</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.2789)</td>
<td>(0.0555)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M2</td>
<td>-3.2754</td>
<td>2.7671</td>
<td>-</td>
<td>0.8469</td>
<td>1.3414</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0423)</td>
<td>(0.0288)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M3</td>
<td>-4.0449</td>
<td>3.2529</td>
<td>-</td>
<td>0.8635</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.1136)</td>
<td>(0.0317)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M4</td>
<td>-0.4524</td>
<td>1.5586</td>
<td>-</td>
<td>0.9138</td>
<td>1.2466</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0132)</td>
<td>(0.0117)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M5</td>
<td>1.2889</td>
<td>0.0376</td>
<td>-</td>
<td>0.928</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0585)</td>
<td>(0.0003)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M6</td>
<td>-1.1069</td>
<td>0.6209</td>
<td>-</td>
<td>0.9181</td>
<td>1.2397</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0160)</td>
<td>(0.0045)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M7</td>
<td>-1.3783</td>
<td>4.3738</td>
<td>-1.2771</td>
<td>0.8859</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.1803)</td>
<td>(0.0684)</td>
<td>(0.0706)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M8</td>
<td>-1.0601</td>
<td>1.2653</td>
<td>0.5761</td>
<td>0.9181</td>
<td>1.2397</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0659)</td>
<td>(0.0332)</td>
<td>(0.0613)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: R²= coefficient of determination, CF= correction factor (’-‘)= model was fitted without log transformation of the dependent variable, ( )= number in parenthesis includes standard error
Residual vs. fitted plots were also evaluated for all models. In black willow, models M2 and M8 showed a better residuals distribution both below and above the zero line (Figure 2.4). The residual plots for models M1, M3, and M7 showed a curvilinear pattern. Residual distributions for M4 and M6 showed heteroscedastic errors common in biomass data as residuals were increasing with the increase in fitted values. Model M5 also had homogeneous distribution with only a few large residual values.

![Figure 2.4](image)

**Figure 2.4** Residual vs. fitted plot for individual stem biomass models for black willow at the study site in Hollandale, MS

Similar to black willow, models fitted without log transformation (M1, M3, and M7) showed curvilinear residual patterns for eastern cottonwood (Figure 2.5). The residual distribution was homogeneous for model M2 indicating a good model. Models M6 and M8 had
similar residual plots, however model M5 had few increasing residuals with the increase in fitted values.

![Figure 2.5 Residual vs. fitted plot for individual tree biomass models for eastern cottonwood at the study site in Hollandale, MS](image)

Table 2.5 shows the goodness of fit statistics for the fitted models obtained from model cross-validation. The log transformed models provided a better fit for both species except for model M6. Among the eight models, only four models (M2, M4, M5, and M8) were chosen for cross validation for both species based on the residual distribution, $R^2$, and SE values. Model M5 had the lowest RMSE and bias for both species however, this model overestimated the biomass by 2.69% and 1.77% for black willow and eastern cottonwood, respectively. RMSE percent was higher for black willow than eastern cottonwood.
The accuracy of a model depends on the variables and factors considered. The general model (clone specific) was found to have higher RMSE percent ranging from 25% - 83% between different clones than the intermediate (age and clone) or specific (age, site, and clone) models (Arevalo et al. 2007). Therefore, to have more precise and accurate biomass estimation there might be the need of considering other factors such as age, soil nutrient content, average temperature and so on.

Table 2.5 Cross validation result of the individual stem models for black willow and eastern cottonwood

<table>
<thead>
<tr>
<th>Species</th>
<th>Models</th>
<th>Bias</th>
<th>Bias%</th>
<th>RMSE</th>
<th>RMSE%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black willow</td>
<td>M2</td>
<td>-0.137</td>
<td>-11.92</td>
<td>0.989</td>
<td>86.33</td>
</tr>
<tr>
<td></td>
<td>M4</td>
<td>0.108</td>
<td>9.39</td>
<td>1.57</td>
<td>136.9</td>
</tr>
<tr>
<td></td>
<td>M5</td>
<td>-0.0308</td>
<td>-2.69</td>
<td>0.705</td>
<td>61.53</td>
</tr>
<tr>
<td></td>
<td>M8</td>
<td>-0.0325</td>
<td>-2.84</td>
<td>0.858</td>
<td>74.88</td>
</tr>
<tr>
<td>Eastern Cottonwood</td>
<td>M2</td>
<td>0.373</td>
<td>6.99</td>
<td>4.75</td>
<td>88.99</td>
</tr>
<tr>
<td></td>
<td>M4</td>
<td>0.615</td>
<td>11.52</td>
<td>3.1</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>M5</td>
<td>-0.0946</td>
<td>-1.77</td>
<td>2.29</td>
<td>42.87</td>
</tr>
<tr>
<td></td>
<td>M8</td>
<td>0.117</td>
<td>2.20</td>
<td>2.58</td>
<td>48.23</td>
</tr>
</tbody>
</table>

Summary statistics for dominant height, trees per hectare, stand age, and biomass for area level calibration are given in Table 2.6. The height of the willow ranged from 1.15 m to 9.51 m while for eastern cottonwood it ranged from 1.76 m to 10.48 m. The mean AGB production for eastern cottonwood was approximately 4 times higher than that of black willow.
Table 2.6  Descriptive statistics of the variables used for area level calibration at the study site in Hollandale, MS

<table>
<thead>
<tr>
<th>Species</th>
<th>Variables</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Black Willow</strong></td>
<td>Dominant Height (m)</td>
<td>1.15</td>
<td>9.51</td>
<td>2.89</td>
<td>1.46</td>
</tr>
<tr>
<td></td>
<td>Trees per ha</td>
<td>830</td>
<td>10477</td>
<td>7636</td>
<td>2999.25</td>
</tr>
<tr>
<td></td>
<td>Stand Age (years)</td>
<td>2</td>
<td>6</td>
<td>4.63</td>
<td>1.51</td>
</tr>
<tr>
<td></td>
<td>Cumulative AGB (Mg/ha)</td>
<td>0.29</td>
<td>42.79</td>
<td>6.64</td>
<td>7.73</td>
</tr>
<tr>
<td><strong>Eastern Cottonwood</strong></td>
<td>Dominant Height (m)</td>
<td>1.76</td>
<td>10.48</td>
<td>5.57</td>
<td>2.23</td>
</tr>
<tr>
<td></td>
<td>Trees per ha</td>
<td>830</td>
<td>10477</td>
<td>7636</td>
<td>2999.25</td>
</tr>
<tr>
<td></td>
<td>Stand Age (years)</td>
<td>2</td>
<td>6</td>
<td>4.63</td>
<td>1.51</td>
</tr>
<tr>
<td></td>
<td>Cumulative AGB (Mg/ha)</td>
<td>1.83</td>
<td>75.85</td>
<td>24.62</td>
<td>18.87</td>
</tr>
</tbody>
</table>

Table 2.7 shows the parameter estimates of the four models used for the area level calibration. All parameters were statistically significant except stand age for eastern cottonwood. However, stand age was significant at 0.05 level when the variables were log transformed. With the log transformation of the models, there was an increase in $R^2$ and decrease in standard error indicating that the log transformed models better fit to the dataset.
Table 2.7  Parameter estimates of the regression models for area level calibration by species at the study site in Hollandle, MS

<table>
<thead>
<tr>
<th>Species</th>
<th>Models</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>R²</th>
<th>CF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Willow</td>
<td>S1</td>
<td>-14.7000</td>
<td>0.0006</td>
<td>4.3670</td>
<td>0.9005</td>
<td>0.7602</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2.8590)</td>
<td>(0.0002)</td>
<td>(0.4100)</td>
<td>(0.4057)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>-7.3766</td>
<td>0.6509</td>
<td>2.0287</td>
<td>0.7300</td>
<td>0.8258</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.0607)</td>
<td>(0.1070)</td>
<td>(0.1726)</td>
<td>(0.1939)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eastern Cottonwood</td>
<td>S1</td>
<td>-38.2000</td>
<td>0.0021</td>
<td>8.7550</td>
<td>-0.4857</td>
<td>0.7905</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(6.4650)</td>
<td>(0.0005)</td>
<td>(0.9467)</td>
<td>(0.1283)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>-4.5618</td>
<td>0.4239</td>
<td>2.0198</td>
<td>0.2824</td>
<td>0.9457</td>
<td>1.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.5310)</td>
<td>(0.0523)</td>
<td>(0.1370)</td>
<td>(0.1409)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: R²= coefficient of determination, CF= correction factor (‘-‘= model was fitted without log transformation of the dependent variable, ( )= number in parenthesis includes standard error

Residual vs. fitted plots (Figure 2.6 and 2.7) show the residual distribution for both species. In black willow, the residuals are seen increasing with the increase in fitted values for model S1 while the same model for eastern cottonwood indicates a curvilinear relationship. For both species, model S2 shows a homogeneous distribution of residuals with a few large residuals for the black willow.
Figure 2.6  Residual vs. fitted plot for black willow (area level) at the study site in Hollandale, MS

Figure 2.7  Residual vs. fitted plot for eastern cottonwood (area level) at the study site in Hollandale, MS
CONCLUSIONS

Estimates of accurate biomass are necessary for understanding the role of forestry in carbon sequestration. There are several studies related to traditional forest biomass estimation. However, allometric equations for SRWC are scarce. Allometric equations that relate dbh and height or their combination to biomass are used for the estimation. Therefore, it is important to choose the model that best fits the given dataset (Chave et al. 2004; Picard et al. 2015a).

The AGB estimation for short rotational woody crops, especially black willow and eastern cottonwood, using both height and dbh as predictor variables is scarce. Some allometric equations have been developed, however they are based only on the dbh of the stem (Nordh and Verwijst 2004; Berner et al. 2015; Arevalo et al. 2007). In this study, both height and dbh and a combined variable (D2H) were used as predictors of black willow and eastern cottonwood biomass and eight different regression models were fitted. Models using only one variable (dbh or height) were also fitted to evaluate their accuracy. This study found that log transformed models were a better fit for both the individual stem and area level biomass estimations of black willow and eastern cottonwood.

The equation by Montagu et al. (2005), M5 in this study, was fitted using the combination of predictor variables as D2H. Log transformation in this equation, however, decreased the $R^2$. The model using only height (M1) of the stem as the predictor was also fitted. For the log transformed model of M1 (M2), residuals were evenly distributed both below and above the zero line however, RMSE was higher than that of other models used in this study. Model M2 also performed slightly better for eastern cottonwood than black willow with around 84 % of variation explained for eastern cottonwood and around 70 % for black willow.
Therefore, this study concludes that Model M5 (D2H as predictor) was the best fitting model for the individual stem biomass estimation for both species. This conclusion is based on the lower values of RMSE and bias, better residual distribution, higher $R^2$, and lower standard error. As model M5 used the combined variables D2H, it may have performed better due to the relationship between mass and volume. For area level biomass estimation, model S2 (log transformed) was the better fit than linear models for both black willow and eastern cottonwood because of higher $R^2$, lower SE and homogeneous residuals distribution.

The results from this study will be beneficial for forest landowners in the aboveground biomass estimation of short rotation woody crops without having to harvest it. The cost benefits from harvest of SRWC is about 40% which is the largest contributor (Tharakan et al. 2005) and therefore accurate biomass estimation is of critical importance. Height based models will serve the development of remote sensed based models for predicting aboveground biomass for two important short rotation woody crops in the Lower Mississippi Alluvial Valley.
LITERATURES CITED


CHAPTER III
RESPONSE OF BLACK WILLOW AND EASTERN COTTONWOOD TO DIFFERENT MANAGEMENT REGIMES

INTRODUCTION

In the U.S., 2018 was the year with the highest energy consumption of 101.3 quadrillion British Thermal units (BTU) (McFarland 2019). The world energy consumption is projected to increase by 50% by 2050 with renewable energy such as bioenergy, wind, and solar being the most used energy source (Capuano 2020). In this scenario, biomass as a renewable source is one of the sustainable solutions to solve the future global energy demand (Dincer 2000). Biomass derived from forests and agricultural lands has been used for biofuels and electricity production. In rural and developing countries, woody biomass has significant contribution to the reduction of greenhouse gas emissions and economic development (Sadrul Islam and Ahiduzzaman 2012). The most common form of biomass use in those countries is fuelwood for cooking and heat generation which is expected to escalate with the increasing global population. Other renewable resources such as wind, water, and solar are also used for energy, however biomass accounts for the maximum utilization (Stolarski et al. 2008). This increasing interest in the use of biomass is expected to result in a shortage of raw materials for wood-based industries. Therefore, the sustainable production and supply of the biomass feedstock for bioenergy industries is critical to displace fossil fuel: a major source of increasing carbon dioxide in the atmosphere.

The selection of energy crops is influenced by these crops’ ability to produce high yields with low input (McKendry 2002). Pest resistance, water and nutrient requirements, and
establishment costs are the other factors that need to be considered. The short rotation woody crops (SRWC) are ideal bioenergy crops as well as they contribute to the enhancement of ecosystem, reduction of soil erosion, water quality improvement, nutrient recycling, and carbon sequestration (Zalesny et al. 2011).

Southeastern states have high potential for woody biomass production (Caldwell et al. 2018) as forest covers about 46% of the total land area (Oswalt et al. 2014) and accounts for 60% of U.S. timber production (Wear and Greis 2013). The favorable soil and climatic conditions for woody crops plantation in the southeastern U.S. makes this region a potential biomass hotspot (Walsh et al. 2000). Willow, poplars, sweetgum, sycamore, and Eucalyptus spp. are some of the SRWC preferred for biomass in the southeastern U.S. However, forest degradation and deforestation combined with global population increase has created a serious need for the improvement and maximization of SRWC biomass yield (Zalesny et al. 2011).

Previous studies have often linked biomass yield improvement of SRWC with the use of genetically improved clones (Bailey et al. 2014; Larsen et al. 2014), consideration of the un-rooted cuttings length for planting (Schuler and McCarthy 2015; Rousseau et al. 2012), increased soil fertility (Stolariski et al. 2015; Larsen et al. 2014), and weed control on the plantation site (Ledin and Willebrand 1996). In addition, Dimitriou and Aronsson (2004) found that irrigating a willow plantation by nitrogen rich waste water improved biomass yield and reduced the need for fertilization. However, little is known about the effects of harvesting frequency and initial planting density in the biomass yield of SRWC in the southeastern U.S. In this context, this study evaluated the biomass yield of black willow and eastern cottonwood under four different spacing and three different harvest frequencies to determine the most effective management regime for maximum biomass yield for these species.
LITERATURE REVIEW

Harvest frequency and planting density are the primary management factors that influence biomass production of a species. Therefore, characteristics of the species to be planted need to be considered while deciding the appropriate spacing and rotation length (Willebrand et al. 1993). The selection of spacing and clones to be planted are important initial steps as they determine the effective utilization of the plantation site, choice of harvesting options, and rotation lengths (Fang et al. 2007; Smith and Brennan 2006). A common rotation length for bioenergy crops is around 5 years (Fortier et al. 2017) but the choice of harvest frequency/rotation lengths is also dependent on the objective of the plantation. Nassi O Di Nasso et al. (2010) evaluated the yield of the _Populus deltoides_ Bartr. under three different harvest frequencies – annual (harvest every year), biennial (harvest every two year), and triennial (harvest every two year) harvest. The results showed that in an annual harvest scheme, the biomass production of poplar increased until the third year and declined thereafter. However, in biennial and triennial harvest schemes, the biomass production decreased after the first harvest. Triennial harvest followed by biennial were more productive than the cumulative yield from annual harvests.

Sustainable biomass yield of willow requires undivided attention to the choice of clone, rotation years, and planting spacing (Bergkvist and Ledin 1998). Kopp et al. (1997) compared biomass yields of three willow clones under three different planting densities harvested annually, biennially, and triennially. Among the three clones, two of them were eliminated because of the low survival rate, pest, and rabbit damage. They found the surviving clone (SV1) had the highest biomass yield in 0.3 x 0.9 meters (m) spacing and triennial harvest. In addition, the 0.3 x 0.9 m spacing had higher biomass production than other spacing (0.3 x 0.3 m, and 0.6 x 1.1 m)
regardless of rotation years. Stolarski et al. (2008) studied biomass production of seven willow clones under several harvesting schemes. Their results showed that the quadrennial harvest (harvest every four year) resulted in higher biomass production than annual harvest for all clones except the one with a low survival rate. Mola-Yudego and Aronsson (2008) found increased biomass production for willow plantations under short rotation management with rotation length of 6 years having significantly lower biomass than a rotation year of 4.5 and 4.2 years.

The environmental benefits of biofuels is another factor motivating people to substitute fossils fuels for electricity production (Kopp et al. 2001). However, transitioning from fossil fuels to bioenergy will require sustainable supply of a bioenergy feedstock. Kopp et al. (2001) compared the difference in biomass production of willow over 10 years by clones and fertilization in Tully, New York and found fertilized clones achieved maximum biomass a year earlier than the non-fertilized clones although fertilization was not statistically significant. In addition, the study revealed a significant effect of annual temperature where the warmest season had the maximum biomass production with sharply decreased biomass production during the coolest season. Similar temperature effects were reported by Willebrand et al. (1993) on several Salix species which showed significantly lower biomass yield during the year with low annual temperature. They also concluded that Salix species performs best in 4-6 years of rotation than 1-2 years.

Several studies have shown wider spacing to be effective in the stem diameter, height growth, and volume of poplar (Johnstone 2008; DeBell et al. 1996; Tun et al. 2018). For example, the diameter and height growth in wider spacing (4.5 x 4.5 m) were, respectively, 89% and 30% greater than in the narrower spacing (1.5 x 1.5 m) (Johnstone 2008). Tun et al. (2018) also observed similar results with the mean dbh of 21.8 cm for wider spacing (12% greater) than
that of narrow spacing. On the contrary, some studies reported higher planting density to have significant effect in greater biomass yield of poplar. Rončević et al. (2013) found that, narrower spacing resulted in higher biomass yield of eastern cottonwood under two-year rotation. In addition, regeneration from coppice had significantly higher growth and biomass production than from the initial plantation established from cuttings. Studies have also shown differences in diameter and height growth pattern of poplars due to planting density. Fang et al. (1999), found high correlation between diameter growth and planting density in poplar. However, the diameter growth rate decreased slowly after the third growing season, whereas the tree height continued to increase at the same rate. Francis and Baker (1981), on the other hand, found similar growth pattern between height and diameter in the Mississippi Delta, where growth gradually decreased after the second growing season. This discrepancy may be attributed to differences in soil types, soil fertility, climate, air humidity and other factors.
METHODS

Original Study Plan (2012-2024)

1) A 2 x 2 x 5 factorial split-split plot experiment in randomized complete blocks with species as whole-plot of 2 levels, spacing as subplot of 2 levels and a biomass harvesting frequency sub-sub plot of 5 levels (single harvest to 5 harvests); and

2) A 2 x 2 x 2 factorial split-split plot experiment in randomized complete blocks with species as whole plot of 2 levels and spacing as subplot of 2 levels, and a biomass harvesting frequency sub-sub plot of 2 levels.

Revised Study Plan (2012-2018)

The individual plant biomass was summed to obtain average biomass per hectare for all spacing and harvest frequency combinations. The method used for the measurement is described in Chapter 2. During harvest years, dbh, height, and green weight of individual trees from each subplot were measured. There are four different harvest frequencies and four different spacing. However, one of the harvest frequencies (harvest at year 4), the harvest was done in 2017 while the rest had their final harvest in 2018 (Table 2.1). In this scenario, comparison between these harvest frequencies would not be valid and therefore, the subplots which had their final harvest in year 6 (2018) were only used for the experiment. The effects of these treatments in above ground biomass (AGB) production of both species is evaluated in this Chapter. The AGB (megagram (Mg)/ha) ranged from 14.519 to 56.323 for eastern cottonwood and from 2.393 to 18.167 for black willow across all the treatment levels. Only the plots that were harvested in year 2018 were used in this analysis.
Experimental Design

Among the four spacing, 0.9 x 0.9 m and 2.1 x 0.8 m had three levels of harvest frequency (1, 2, and 3) however, 2.7 x 1.8 m and 3.7 x 3.7 m had only one harvest frequency level. Therefore, two experimental designs were created for the analysis.

The two experimental designs used in this study are:

Design 1:

1. A 2 x 2 x 3 split-split plot experiment in randomized complete blocks with species as whole plot factor of 2 levels, spacing as sub-plot factor of 2 levels, and biomass harvesting frequency as sub-sub plot factor of 3 levels (single to 3 harvests) (Equation 3.1), and

\[ y_{ijkl} = \mu + b_i + \alpha_j + \beta_k + \alpha \beta_{jk} + \gamma_{ij} + \alpha \gamma_{ij} + \beta \gamma_{jk} + \alpha \beta \gamma_{jkl} + \epsilon_{ijkl} \]  

(Equation 3.1)

Where,

- \( b_i \) = random block effect,
- \( \alpha_j \), \( \beta_k \), \( \gamma_{ij} \) = fixed effect of species, spacing, and harvest frequency, respectively
- \( \alpha \beta \gamma_{jkl} \) = interaction effect, and

\( \epsilon_{ijkl} \) = random error term

Design 2:

2. A 2 x 2 factorial experiment in randomized complete block design. Two factors were species and spacing with two levels each (Equation 3.2).

\[ y_{ijk} = \mu + b_i + \alpha_j + \beta_k + \alpha \beta_{jk} + \epsilon_{ijk} \]  

(Equation 3.2)

Where,

- \( b_i \) = random block effect,
- \( \alpha_j \), \( \beta_k \) = fixed effect of species, and spacing respectively
\[ \alpha_\beta_{jk} = \text{interaction effect, and} \]

\[ \epsilon_{ijk} = \text{random error term} \]

Statistical analysis was performed in R 4.0.5 (R Core Team, 2021). To perform the split-split plot experiment, agricolae package was used. The differences among the treatments were also evaluated by pairwise comparison using emmeans package for both experimental designs. This comparison determined the treatments statistically significant in the biomass production of black willow and eastern cottonwood. In addition, interaction plot was also developed to evaluate the interaction between species, harvest frequency and biomass.
RESULTS AND DISCUSSION

The average biomass production over the six-year rotation of eastern cottonwood and black willow was 35.686 Mg/ha and 9.322 Mg/ha respectively. AGB distribution pattern of black willow and eastern cottonwood are presented in Figures 3.1 and 3.2, respectively. The overall biomass distribution of eastern cottonwood was higher than that of black willow. Biomass distribution by spacing and harvest frequency were also evaluated. In all treatment combinations, eastern cottonwood had higher biomass production than black willow. In each spacing level, eastern cottonwood had higher biomass production with a single harvest at age 6; however, for black willow harvesting two times (every three years) resulted in higher biomass yield. In Southern Quebec, Labrecque and Teodorescu (2005) found better diameter, height, and biomass growth of poplar clones compared to willow. Poplar had higher growth and biomass production in all growing season. It was reported that poplar had two times greater biomass yield than willow during the third growing season. These results align with the finding in this study.

![Figure 3.1](image.png)

Figure 3.1 Overall biomass distribution range of eastern cottonwood and black willow in the study site at Hollandale, MS
Figure 3.2  Biomass distribution of black willow and eastern cottonwood in different spacing and harvest frequency combinations at the study site in Hollandale, MS

The average biomass (Mg/ha) productions by both species under different harvest frequency and spacing levels are shown in Table 3.1. The increase in harvest frequency lowered the biomass production of eastern cottonwood in all spacing levels indicating that a single harvest at age 6 yielded greater biomass followed by triennial and biennial harvest. This result aligns with Nassi O Di Nasso et al. (2010) as poplar yielded higher biomass in triennial harvest than biennial and annual harvesting schemes. Similarly, wider spacing decreased the biomass yield for single harvest in all spacings, however increased the production for biennial and triennial harvest. This indicates that the greater the number of crops per ha, the greater the
biomass yield. Rončević et al. (2013) found similar response of eastern cottonwood with biomass yield and spacing having a reciprocal relationship.

The response of black willow to spacing and harvest frequency were opposite. For spacing 0.9 x 0.9 m, the biomass production increased with the increase in harvest frequency showing that biennial harvest resulted in a higher biomass yield than a triennial and single harvest. However, triennial harvest had the highest biomass followed by single and biennial harvest in spacing 2.1 x 0.8 m.

Both species produced the lowest biomass in spacing 3.7 x 3.7 m followed by spacing 2.7 x 1.8 m for black willow and 0.9 x 0.9 m with biennial harvest for eastern cottonwood. The best biomass productivity of black willow was obtained from spacing 2.1 x 0.8 m with triennial harvest of 18.167 Mg/ha. However, for eastern cottonwood spacing 0.9 x 0.9 m with single harvest had the highest biomass yield of 56.323 Mg/ha. A similar outcome was observed by Fang et al. (1999) in China with narrow spacing and rotation length of six year resulting in highest biomass yield in poplar.

A study of willow by Bullard et al. (2002) showed higher biomass yield with narrower planting density which supports our results as spacing 0.9 x 0.9 m and 2.1 x 0.8 m had higher production of biomass than 2.7 x 1.8 m and 3.7 x 3.7 m spacing. Similarly, Kopp et al. (1997) found triennial harvest to produce higher biomass than annual and biennial harvest. Although eastern cottonwood showed better biomass production than black willow, it also requires more inputs. For example, eastern cottonwood had to be sprayed by insecticides for protection from leaf beetle; however, for black willow no special treatment was required. Similarly, with higher growth the harvest cost also increases as it is difficult to harvest bigger
trees and requires more labor. Therefore, these financial factors need to be considered in order to have clear vision on the capital gains.

Table 3.1 Average biomass production of black willow and eastern cottonwood in all treatment combinations over 6 years of plantation at the study site in Hollandale, MS

<table>
<thead>
<tr>
<th>Species</th>
<th>Spacing (m x m)</th>
<th>Harvest Frequency</th>
<th>Average Biomass (Mg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Eastern Cottonwood</strong></td>
<td>0.9 x 0.9</td>
<td>1</td>
<td>56.323</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>24.892</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>22.697</td>
</tr>
<tr>
<td></td>
<td>2.1 x 0.8</td>
<td>1</td>
<td>52.366</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>40.495</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>38.067</td>
</tr>
<tr>
<td></td>
<td>2.7 x 1.8</td>
<td>1</td>
<td>36.121</td>
</tr>
<tr>
<td></td>
<td>3.7 x 3.7</td>
<td>1</td>
<td>14.520</td>
</tr>
<tr>
<td><strong>Black Willow</strong></td>
<td>0.9 x 0.9</td>
<td>1</td>
<td>5.400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>9.624</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>10.080</td>
</tr>
<tr>
<td></td>
<td>2.1 x 0.8</td>
<td>1</td>
<td>13.783</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>18.167</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>10.038</td>
</tr>
<tr>
<td></td>
<td>2.7 x 1.8</td>
<td>1</td>
<td>4.375</td>
</tr>
<tr>
<td></td>
<td>3.7 x 3.7</td>
<td>1</td>
<td>2.393</td>
</tr>
</tbody>
</table>

The biomass yield during the second and third cutting cycle increased compared to the first cutting cycle. Therefore, plants regenerated from stump have higher biomass production than from the plantation of cuttings. This indicates that once the plants have been harvested, it
would be beneficial to let it grow from coppice rather than planting again and therefore decreases the plantation cost. Rončević et al. (2013) also reported second cutting cycle having significantly higher production than the first cutting cycle. Sleight et al. (2016) compared biomass yield between first and second rotation and found that biomass production of willow increased by 7.9% compared with the first rotation yield. When comparing the first harvest with second and third harvests in of black willow (Figure 3.3), spacing 2.1 x 0.8 m and harvest frequency 3 had biomass yield of 1.299 Mg/ha during the first harvest which later increased to 3.729 Mg/ha in second harvest, and 5.008 Mg/ha in the third harvest. For spacing 0.9 x 0.9 m, harvest frequency 3, first harvest resulted in 2.276 Mg/ha of biomass yield with 3.384 Mg/ha and 4.423 Mg/ha in second and third harvest simultaneously. For harvest frequency 2 and spacing 2.1 x 0.8 m, after the first harvest of 16.263 Mg/ha there was an increase in biomass yield by 7.325 Mg/ha in the second harvest. However, there was just a slight increase of 0.429 Mg/ha in the second cutting cycle for spacing 0.9 x 0.9 m.

When comparing between the two spacings, for harvest frequency 3, spacing 0.9 x 0.9 m had greater biomass yield during the first harvest than 2.1 x 0.8 m, however during the second and third cutting cycle, spacing 2.1 x 0.8 m yielded higher biomass. However, for harvest frequency 2, spacing 2.1 x 0.8 m black willow had higher biomass yield for both the first and second cutting cycle.
Figure 3.3  Biomass yield comparison of black willow between cutting cycles (harvest from cuttings vs. harvest from coppice regeneration)

Biomass production of eastern cottonwood in the 2.1 x 0.8 m spacing was higher for all harvest years than the 0.9 x 0.9 m spacing (Figure 3.4). When comparing between the harvest cycle in harvest frequency 3, the third harvest cycle had highest biomass yield followed by second and first harvest cycle in both the spacing. For spacing 0.9 x 0.9 m and harvest frequency 3, the first harvest yielded a biomass of 3.281 Mg/ha which later increased to 8.688 Mg/ha in the second and 10.728 Mg/ha in the third harvest. Similarly, spacing 2.1 x 0.8 m had sharp increase from 5.079 Mg/ha in the first harvest to 13.235 Mg/ha and 19.753 Mg/ha in the third harvest respectively. In harvest frequency 2, biomass yield increased by 7.929 Mg/ha in the second harvest for spacing 0.9 x 0.9 m and by 9.938 Mg/ha for 2.1 x 0.8 m spacing.
Mixed effect model results are shown in Table 3.2 with 0.9 x 0.9 m and 2.1 x 0.8 m analyzed separately from 2.7 x 1.8 m and 3.7 x 3.7 m spacing. Harvest frequency and interaction of species and harvest frequency were statistically significant for spacing 0.9 x 0.9 m and 2.1 x 0.8 m. However, there was no significant effect of spacing, and interaction of spacing and harvest frequency. This result agreed with Cañellas et al. (2012) where no significant effect of spacing was observed in the biomass productivity of poplar after three years of growth. A study by DeBell et al. (1996) showed a little effect of planting density in *Populus* after 7 years of growth although the biomass yield increased with decrease in spacing in the earlier years.

For 2.7 x 1.8 m and 3.7 x 3.7 m spacing levels, both species, spacing, and their interaction had significant effect on biomass yield. Significant effect of spacing ($p<0.01$) (3 x 3
m, 3 x 4 m, 4 x 4 m, and 4 x 5m) was reported by Fang et al. (2007) in the biomass production over 10 years of poplar with narrower spacing yielding higher biomass than wider spacing.

Table 3.2 Analysis of variance table for split-split-plot analysis (0.9 x 0.9 m and 2.1 x 0.8 m) and factorial randomized block design (2.7 x 1.8 m and 3.7 x 3.7 m)

<table>
<thead>
<tr>
<th>Experiment Variables</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>0.9 x 0.9 and 2.1 x 0.8</strong></td>
<td></td>
</tr>
<tr>
<td>Block</td>
<td>0.8619</td>
</tr>
<tr>
<td>Species</td>
<td>0.1111</td>
</tr>
<tr>
<td>Spacing</td>
<td>0.3278</td>
</tr>
<tr>
<td>Species: Spacing</td>
<td>0.8097</td>
</tr>
<tr>
<td>Harvest Frequency</td>
<td>0.0484*</td>
</tr>
<tr>
<td>Species: Harvest Frequency</td>
<td>0.0175*</td>
</tr>
<tr>
<td>Spacing: Harvest Frequency</td>
<td>0.5581</td>
</tr>
<tr>
<td>Species: Spacing: Harvest Frequency</td>
<td>0.3111</td>
</tr>
<tr>
<td><strong>2.7 x 1.8 and 3.7 x 3.7</strong></td>
<td></td>
</tr>
<tr>
<td>Species</td>
<td>0.0009***</td>
</tr>
<tr>
<td>Spacing</td>
<td>0.0171*</td>
</tr>
<tr>
<td>Species: Spacing</td>
<td>0.0347*</td>
</tr>
</tbody>
</table>

Level of significance: ***=0.001, **=0.01, and *=0.05

Differences among the treatments is shown in Figure 3.5. There is no significant difference between species and spacing however, there is a significant difference among harvest frequencies. The plot shows no variation between harvest frequency 1 and 2 and similar result is seen between harvest frequency 2 and 3. However, there is a significant difference between harvest frequency 1 and 3, which are represented by different characters in the plot. To evaluate
whether this difference was for both species or not, pairwise comparison was carried out (Table 3.3).

![Graph showing comparison between treatments](image)

**Figure 3.5**  Comparison between treatments (species, spacing, and harvest frequencies)

The pairwise comparison (Table 3.3) showed that the significant difference was only for eastern cottonwood and was between harvest frequency 1 and 2 ($p=0.05$) and harvest frequency 1 and 3 ($p=0.02$). Eastern cottonwood in single harvest produced 2.165 Mg/ha more biomass than two times harvest and 2.396 Mg/ha more biomass than three times harvest.
Table 3.3  Pairwise comparison between species and harvest frequency for spacing 0.9 x 0.9 m and 2.1 x 0.8 m

<table>
<thead>
<tr>
<th>Species</th>
<th>Harvest Frequency</th>
<th>Species</th>
<th>Harvest Frequency</th>
<th>Estimate</th>
<th>SE</th>
<th>df</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cottonwood</td>
<td>1</td>
<td>Willow</td>
<td>1</td>
<td>4.475</td>
<td>1.143</td>
<td>3.14</td>
<td>0.41</td>
</tr>
<tr>
<td>Cottonwood</td>
<td>1</td>
<td>Cottonwood</td>
<td>2</td>
<td>2.165</td>
<td>0.635</td>
<td>16</td>
<td>0.05*</td>
</tr>
<tr>
<td>Cottonwood</td>
<td>1</td>
<td>Willow</td>
<td>2</td>
<td>4.045</td>
<td>1.143</td>
<td>3.14</td>
<td>0.53</td>
</tr>
<tr>
<td>Cottonwood</td>
<td>1</td>
<td>Cottonwood</td>
<td>3</td>
<td>2.396</td>
<td>0.635</td>
<td>16</td>
<td>0.02*</td>
</tr>
<tr>
<td>Cottonwood</td>
<td>1</td>
<td>Willow</td>
<td>3</td>
<td>4.428</td>
<td>1.143</td>
<td>3.14</td>
<td>0.42</td>
</tr>
<tr>
<td>Willow</td>
<td>1</td>
<td>Cottonwood</td>
<td>2</td>
<td>-2.310</td>
<td>1.143</td>
<td>3.14</td>
<td>1.00</td>
</tr>
<tr>
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The interaction plot (Figure 3.6) suggests interaction between species and harvest frequencies represented by non-parallel lines. It shows that the biomass production of eastern cottonwood is higher for harvest frequency 1, however black willow yielded highest biomass for harvest frequency 2 (two times harvest through year 6). Similarly, eastern cotton had higher biomass production compared to black willow in all harvest frequency levels.
The pairwise comparison (Table 3.4) showed that there were significant differences between eastern cottonwood with different spacing ($p = 0.03$), eastern cottonwood and black willow with same spacing ($p = 0.005$), and eastern cottonwood and black willow with different spacing ($p = 0.004$). Eastern cottonwood with spacing 3.7 x 3.7 m produced 21.60 Mg/ha less biomass than with spacing 2.7 x 1.8 m. Black willow with spacing 3.7 x 3.7 m also produced lower biomass by 33.73 Mg/ha than eastern cottonwood with 2.7 x 1.8 m. Similarly, eastern
cottonwood with spacing 2.7 x 1.8 m yielded higher biomass by 31.75 Mg/ha than black willow

<table>
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Table 3.4 Pairwise comparison between species and harvest frequency for spacing 2.7 x 1.8 m and 3.7 x 3.7 m

The non-parallel plots represented the interaction between species, spacing and biomass (Figure 3.7). When the spacing was 3.7 x 3.7 m, both species had lower biomass production, however the biomass production increased when the spacing narrowed to 2.7 x 1.8 m.
Figure 3.7  Interaction plot between species, spacing and biomass for spacing 2.7 x 1.8 m and 3.7 x 3.7 m
CONCLUSIONS

The increasing global population and bioenergy demand has attracted people’s attention towards SRWC. In U.S., willow and poplars has been extensively planted for the production of bioenergy and biofuels (Volk et al. 2011). However, the sustainable production and supply to meet the increasing energy demand seems only possible with the yield improvement of these plants. Research have shown that the biomass production of SRWC is dependent on various factor such as soil, climate, genotype, fertilization, spacing and rotation length (Stolarski et al. 2015). Among these factors, this study focused on the effects of planting spacing and harvest frequency in the biomass yield of black willow and eastern cottonwood.

Eastern cottonwood had higher biomass yield in all the spacing and harvest frequency levels and yielded about 3.8 times more biomass than black willow. This indicated that the plantation of eastern cottonwood would be more beneficial than black willow in terms of biomass and bioenergy production. However, the higher biomass production of eastern cottonwood can also be attributed to the cuttings used for plantation as they were obtained from a nursery contrary to the pond willow used in this study. In addition, black willow also experienced higher die back which was partially the result from deer browsing as black willow are preferred species by deer for grazing. Eastern cottonwood was more productive in narrower spacing with single harvest in 6 years rotation however, for black willow biennial and triennial harvest yielded higher biomass. Spacing wider than 2.1 x 0.8 m yielded lower biomass for both the species.

In conclusion, eastern cottonwood performed better in narrower spacing while black willow yielded higher biomass in slightly wider spacing. Eastern cottonwood planted at spacing 0.9 x 0.9 m and harvested once at year six resulted in maximum biomass production. Black
willow planted at spacing 2.1 x 0.8 m and harvested every 3 years resulted in maximum biomass at age six. For the narrower spacing, the harvest frequency also significantly affected the biomass production for both species.

The findings from this study might be useful to landowners and government agencies in the future plantation works as they provide the spacing and harvest frequency combinations in which these species had better biomass production. This result would be used to enhance the biomass yield of bioenergy crops such as black willow and eastern cottonwood and obtain sustainable bioenergy production.
LITERATURES CITED


CHAPTER IV
SUMMARY

The overall aim of this thesis was to evaluate the biomass production of black willow and eastern cottonwood in the Lower Mississippi Alluvial Valley. Specific objectives were to develop an allometric equation to estimate above ground biomass of black willow and eastern cottonwood and to determine the effects of harvest frequency and planting spacing in the biomass production potential of black willow and eastern cottonwood.

Eight different linear and log transformed models were tested using dbh, height and their combinations as the predictor variables of biomass. The data was collected destructively from the sample trees to fit the model. Bias, bias%, RMSE, and RMSE% were evaluated among the models to determine the best fitting model. Furthermore, cross validation of the model was done to evaluate the accuracy in the prediction of the models. Model M5 (D2H as predictor) was the best fitting model for both species with lower bias and RMSE values. Similarly, when comparing training and testing dataset, this model generated satisfactory results with very low increase in bias and RMSE. Similarly, log transformed model S2 (HD, stand age, and TPH as predictors) proved to be the best fitting model for area level estimation based on higher R², lower SE and homogeneous distribution of residuals.

The biomass production response of black willow and eastern cottonwood to different spacing and harvest frequency were estimated using mixed effects models. The harvest frequency was statistically significant for the eastern cottonwood but not for black willow for
spacing 0.9 x 0.9 m and 2.1 x 0.8 m. However, species by harvest frequency, and spacing by harvest frequency interactions were not significant for both species. Average biomass production per ha of eastern cottonwood were higher in all treatment combinations than black willow.

To conclude the study, eastern cottonwood, and black willow both have higher biomass production potential and can be a sustainable solution to solve the increasing wood energy demands. However, the choice of species should depend on the objective of plantation, availability of capitals and landowners intention because eastern cottonwood had higher yield but also required high input (insecticide, and herbicide) whereas, biomass production of black willow were lower and also required comparatively lower input (herbicide only) than eastern cottonwood.

The results of this study also provided a better insight to enhance the biomass production of two energy crops; eastern cottonwood and black willow and estimate their biomass through non-destructive sampling. This study showed the response of these species to different spacing and harvest frequencies levels and gave the treatment combination which yielded the maximum biomass in both species. These results could be used to have higher yield and sustainable production of biomass/bioenergy fulfilling the present and future energy demands.