EVALUATION OF SELECTED CELLULOSIC ENERGY CROPS FOR THE SOUTHEASTERN UNITED STATES

by

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ABSTRACT

Encouraging progress towards commercial production of cellulosic biofuels has recently raised the importance of identifying economically feasible and environmentally sustainable cellulosic biomass supply chains. In this regard, dedicated cellulosic energy crops are superior to agricultural residues due to their higher yield which results in less area needed to produce a given quantity of biomass and, therefore, lower transportation costs. A substantial amount of research has been conducted on perennial cellulosic energy crops such as switchgrass (*Panicum virgatum* L.), giant reed (*Arundo donax* L.) and mimosa (*Albizia julibrissin* Durazz.), but relatively little attention has been paid to annuals that could be rotated with existing row crops without competing with them for land. Moreover, little or no information is available on long-term (>10 years) yields and soil impacts of energy crops and the yield responses to critical economic factors. Therefore, the overall goal of research reported in this dissertation was to evaluate yield and soil impacts of selected potential energy crops for the southeastern United States.

The first-two experiments of the project evaluated three common winter annuals (black oat (*Avena strigosa* Schreb.), rye (*Secale cereale* L. subsp. *cereale*) and annual ryegrass (*Lolium multiflorum* Lam.)) and three summer annuals (forage sorghum (*Sorghum bicolor* spp.), pearl millet (*Pennisetum americanum* (L.) R. Br.) and sorghum-sudangrass (*Sorghum bicolor* (L.) Moench *nothosubsp. drummondii* (Steud.) de Wet ex Davidse)) in a range of crop rotation systems. Compared to black oat and ryegrass, rye was the most suitable winter crop for biomass production in rotation with cotton

(*Gossypium hirsutum* L.), peanuts (*Arachis hypogaea* L.) and soybeans (*Glycine max* (L.) Merr.). For the three winter annuals in rotation with the three summer crops for year-round biomass production, with either conventional-till or no-till management, double-cropping systems that included pearl millet or forage sorghum under no-till management were superior to other cropping systems under either tillage treatment in the first year. However, within each tillage treatment, double-cropping systems that included forage sorghum or sorghum-sudangrass were superior to other cropping systems in the second and third years.

The other five experiments in the project evaluated giant reed, mimosa and switchgrass for biomass production. Giant reed and mimosa provided much higher biomass yield than switchgrass in long-term experiments, even though they received no fertilization, while switchgrass received a medium amount of N fertilizer annually. In contrast to traditional summer row crops such as corn, cotton and soybeans, rainfall did not have large effects on biomass yields of these three perennials, and neither did age of stand. Biomass yield of switchgrass increased at a declining rate as N levels increased, but subsoiling did not improve yield and interseeding crimson clover actually decreased yield. Biomass yield of giant reed was not improved by application of broiler litter. While there was no difference in biomass yield between annual and biennial harvests in winter, biennial harvesting will likely result in lower cost Mg^{-1}. Biomass production of giant reed was reached a maximum in mid-September to mid-November. Long-term biomass production of giant reed and switchgrass tended to decrease topsoil pH and extractable Mg and Ca contents compared to an adjacent area under bahiagrass (*Paspalum notatum* Flüggé), and giant reed seemed to increase extractable P and K.

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CHAPTER 1 EVALUATION OF WINTER ANNUALS FOR BIOMASS PRODUCTION IN ROTATION WITH TRADITIONAL SUMMER ROW CROPS

ABSTRACT

Encouraging progress in commercial production of cellulosic biofuels, together with a need to avoid disruption of current food, feed and fiber supplies, could rapidly lead to a shortage of land to produce biomass. However, millions of acres used for production of traditional summer row crops in the Southeast are idle during the winter, and could be used to produce biomass from winter annuals. This 3-yr small plot study evaluated three winter annuals (black oat (*Avena strigosa* Schreb.), rye (*Secale cereale* L. subsp. *cereale*) and annual ryegrass (*Lolium multiflorum* Lam.)) for biomass production, in rotation with three summer row crops (cotton (*Gossypium hirsutum* L.), peanuts (*Arachis hypogaea* L.) and soybeans (*Glycine max* (L.) Merr.)) that are widely grown in the Southeast. All plots were disked and fertilized during the summer, according to standard recommendations by the Alabama Cooperative Extension Service. Rye provided higher ($P<0.10$) biomass yield over the three years (9.0, 5.9 and 4.6 Mg/ha in 2007-08, 2008-09 and 2009-10 winter seasons, respectively) than black oat and ryegrass. The variation in biomass yields over time was related to low temperature and solar radiation. Yields of the three summer crops were higher following rye, relative to yields following black oat and ryegrass in 2008 and 2010. In 2009, this trend was not observed, possibly because of the very high rainfall during the summer growing season. It is concluded that, compared to black oat and ryegrass, rye was the most suitable winter crop for biomass production in rotation with the three summer crops evaluated in this study.

Keywords: winter annuals; cellulosic biomass production; crop rotation; summer row crops; cellulosic energy crops

1.1 INTRODUCTION

First generation bioenergy feedstocks include food crops such as sugarcane, corn and soybeans, which are high in sugar, starch and/or oil content, and can be converted into liquid biofuels using existing technology. Two well-known processes in commercial production of first-generation biofuels are sugarcane-to-ethanol in Brazil and corn-to-ethanol in the US. Unlike first-generation bioenergy feedstocks, next-generation bioenergy feedstocks, (i.e., ligno-cellulosic biomass) are derived from non-food sources, including wood, tall grasses, and forestry and crop residues, which are harvested for their cellulosic biomass and can only be converted into liquid biofuels by more complex conversion technologies that are still under development. Advances in recent years have indicated that numerous technologies which can use a variety of cellulosic biomass feedstocks to produce various liquid biofuels, including cellulosic ethanol, green gasoline, diesel and jet fuel, are currently under development (Kunkes et al., 2008; Regalbuto, 2009). Commercial production of cellulosic drop-in replacement biofuels at a cost that is competitive with fossil fuels could occur within the next five years (Solecki et al., 2012), thus increasing the need to develop economically viable and environmentally sustainable cellulosic biomass supply chains.

The Energy Independence and Security Act of 2007 (EISA) mandated that 16 billion gallons of biofuel be produced from cellulosic biomass and used in the US by 2022. At a conversion ratio of 90 gallons per dry ton of cellulosic biomass, this means that 180 million dry tons of cellulosic material will have to be available annually by 2022 (USDA, 2009). Together with a need to avoid disruption of current food, feed and fiber supplies, this could rapidly lead to a shortage of land to produce cellulosic biomass. Meeting the ambitious targets that have been set by EISA is a major challenge. Some have suggested establishing low-input prairie on degraded agricultural lands for cellulosic biomass production (Tilman et al., 2006), but others argue that this approach is inadequate to meet target production (Russelle et al., 2007). With this background of considerable controversy, it is evident that a wide variety of approaches is needed to meet the cellulosic biofuel goals of EISA, and also minimize any negative impacts on existing commodities.

One possible approach may be to include cellulosic biomass production in existing summer row crop systems that are currently fallow in winter: millions of acres are currently used for production of traditional summer row crops in the Southeast, but are idle during the winter and could be used to produce biomass from winter annuals. Winter crops in a double cropping system are commonly planted as unharvested cover crops to improve soil and water conditions for subsequent summer crops. The benefits of planting winter cover crops include preventing soil erosion and enhancing soil organic matter (SOM) , thus improving soil quality and productivity (Calonego and Rosolem, 2010). For example, over-seeding rye into standing corn increased corn yield (Schroder et al., 1996; Kuo et al., 2000; Coelho et al., 2005). Cereal rye, annual ryegrass and oats are common winter cover crop species, and are well adapted to cool conditions that prevail in the fall-winter-spring season in the southeastern U.S. However, little is known about using winter annuals for biomass production in rotation with traditional summer row crops. Therefore, the objective of this study was to evaluate three common winter annuals (black oat, rye and ryegrass) for biomass production, in rotation with three summer row crops (cotton, peanuts and soybean) that are widely grown in the Southeast.

1.2 MATERIALS AND METHODS

1.2.1 Treatments and experimental design

This experiment was initiated in the winter of 2007 and conducted for 3 years at the E.V. Smith Research Center, Plant Breeding Unit of the Alabama Agricultural Experiment Station near Tallassee, Alabama on a Wickham sandy loam (fine-loam, mixed, semiactive, thermic Typic Hapludult). The field had been planted with white lupin (*Lupinus albus* L.) in the previous season. The experiment was laid out as a two-factor factorial randomized complete block (RCB) design with four replicates. Nine different double cropping systems evaluated in this study included all combinations of three winter annuals and three summer crops: specifically rye, black oat or ryegrass in winter, followed by cotton, peanuts or soybeans in summer. Plot size was 3.6× 9.0m.

1.2.2 Crop rotation

Tillage operations, fertilizer application and planting were conducted within one day in early November for all winter seasons. Plots were disked to a depth of 10-15 cm and chisel plowed to a depth of 15 cm, followed by leveling, then fertilization with ammonium nitrate at a rate of 112 kg N ha^{-1}. After applying fertilizer, black oat, rye and annual ryegrass were seeded using a grain drill set at a row spacing of 17.8 cm.

For the summer season, tillage operations and planting were also conducted within one day in mid-May for all three summer crops. After removing biomass of winter annuals, plots were disked, chisel plowed and leveled as described above for winter season crops, then planted with cotton, peanuts and soybean using a planter set at a row spacing of 91.4 cm. Given that peanuts and soybean are legumes, N fertilizer was only applied to cotton plots in the form of ammonium nitrate at a rate of 67 kg N ha^{-1}. In addition, P and K were applied based on soil test results.

All plots were cultivated, and herbicide and pesticide treatments were applied when necessary over the three years. Glyphosate (Roundup) herbicide was applied to all plots 12 days before planting summer row crops, aldicarb (Temik) pesticide was applied to cotton and peanut plots and pentachloronitrobenzene (Terraclor) fungicide was applied to all plots at planting. To control leaf spot and white mold diseases, chlorothalonil (Echo/ Equus) fungicides were applied to peanuts six times at two week intervals starting about 35 to 45 days after planting in each summer season.

1.2.3 Data collection

At the end of each growing season, the center six rows of each winter annual plot were cut to a 5-cm stubble height with a sickle bar mower. Fresh biomass weight of harvested material from each plot was measured using a hanging scale in the field. Biomass subsamples taken from each plot were dried at 60°C for 72 h for dry matter determination. At maturity, cotton defoliants including S,S,S-Tributyl phosphorotrithioate (Def-6), ethephon (BollBuster) and Thidiazuron (Takedown) were used for the removal of leaves from cotton plants. Seed cotton was then picked in the central two rows of each cotton plot, using a John Deere 9920 (John Deere, Dumas, Arkansas) two row spindle cotton picker. Cotton lint yield was estimated by assuming a 39% ginning efficiency. Peanuts and soybeans were harvested from the central two rows of each plot with a peanut combine and soybean plot combine, respectively. Grain moisture was measured at harvest using a moisture meter and reported grain yields were adjusted accordingly. After harvesting border rows, cotton, peanut and soybean plots were mowed and prepared for planting winter annuals.

1.2.4 Data analysis

Statistical analysis of yield data from both summer and winter seasons were conducted using SAS v9.2 PROC GLIMMIX. Block was considered a random factor, whereas year, summer and winter crop factors and their interactions were tested as fixed effects. The critical *P*-value of 0.10 was used as cutoff for testing these fixed effects, and determination of differences in least-squares means was based on adjusted *P*-value obtained by using the option ADJUST=SIMULATE in the LSMEANS statement.

Biomass yield data from the 2008-09 and 2009-10 winter seasons were first analyzed to determine the yield performance of the three winter annuals as affected by the different summer row crops. Since there was no difference in biomass yields of the three winter annuals under different summer row crop systems in the 2008 and 2009 winter seasons, all winter biomass yield data were pooled to determine the yield of the three winter annuals over the three years. For each summer crop species, yield data from the three years were also pooled for analysis.

1.3 RESULTS AND DISCUSSIONS

1.3.1 Weather conditions

Daily temperature and monthly precipitation patterns are presented in Figure 1-1 and Table 1-1, respectively. Rainfall was close to long term averages in the 2007, 2008 and 2010 growing seasons, but very high in 2009. The summer (May to October) and winter (November to April) growing season rainfall for 2009 was 941 and 814 mm, respectively, which is 324 and 48 mm higher than the average rainfall received during the past 10 years. The cumulative chill hours (temperatures below 7.2 °C) in the winter season of 2009 was higher than that in winter seasons of 2007 and 2008 (1211, 1171 and 1576 hours in 2007-08, 2008-09 and 2009-10 winter seasons, respectively) (Figure 1-2) probably because of lower cumulative solar radiation (Figure 1-3). However, monthly minimum temperatures were very similar in winter seasons of 2007 and 2009 (Figure 1-4).

1.3.2 Winter biomass yield

Biomass yield of winter annuals was not affected by summer row crops, but was higher for rye than for annual ryegrass and black oat for which yield did not differ (Figure 1-5). A year × crop species interaction was observed, with yield of rye decreasing relatively less with lower temperatures and less sunlight than that of black oat and annual ryegrass (Figures 1-2, 1-3, 1-4 and 1-6). In particular, biomass yields for rye, black oat and ryegrass in the 2009-10 winter season decreased by 16.9%, 68.1% and 67.9%, respectively, when compared to yields in the 2008-09 season (Figure 1-6). This suggests that rye is more cold tolerant than the other two winter annuals, which is consistent with the observations of others (Stichler, 1997; Lemus, 2008).

1.3.3 Summer row crop yield

A winter crop × year interaction was observed for summer row crop yields. All three summer crop yields were highest after rye, followed by yields after black oat and ryegrass in 2008 and 2010 (Table 1-2). Based on studies by Barnes and Putnam (1986), Bauer and Reeves (1999), and Price et al., (2008), this result could be due to differences among these winter crops in allelopathic effects. In 2009, differences in yield of summer crops following the three winter crops were not observed, possibly because of the very high rainfall during the summer growing season which could have reduced allelopathy, as observed by Eerens et al. (1998).

1.4 CONCLUSION

Due to rye providing the highest biomass yield and having the lowest negative impact on summer row crop yield, rye appears to be better for winter biomass production than black oat and annual ryegrass when grown in rotation with cotton, peanuts or soybeans in the southeastern US.

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Table 1-1 Monthly and growing season precipitation 2007-2010.

Year	Precipitation (mm)													
	Month												Winter growing season	Summer growing season
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.		
2007											55	94	540	
2008	111	102	77	101	64	50	126	252	19	83	93	82	685	594
2009	52	105	244	109	262	100	75	192	148	164	154	276	814	941
2010	152	76	124	32	176	56	128	122	46	31				560
Average (1997-2006)	107	127	181	129	92	141	118	97	104	65	123	104	766	617

Table 1-2 Yields of summer row crops in 2008-2010.

Year	Winter crop	Yield of summer row crop (kg ha^{-1})		
		Cotton lint	Peanut grain	Soybean grain
2008	Ryegrass	893±79^{a}	3746±222^{b}	2080±153^{c}
	Black oat	951±79^{a}	3864±222^{b}	2757±210^{b}
	Rye	1001±144^{a}	4905±222^{a}	3244±66^{a}
2009	Ryegrass	57±25^{a}	2300±49^{a}	1654±295^{a}
	Black oat	68±25^{a}	1894±222^{b}	1816±210^{a}
	Rye	60±25^{a}	2582±427^{a}	1051±210^{b}
2010	Ryegrass	286±25^{b}	214±49^{b}	1221±210^{b}
	Black oat	360±79^{ab}	221±49^{b}	1675±210^{ab}
	Rye	534±79^{a}	343±49^{a}	1960±295^{a}

Means within each column and in the same year with different superscripts differ (P<0.10).

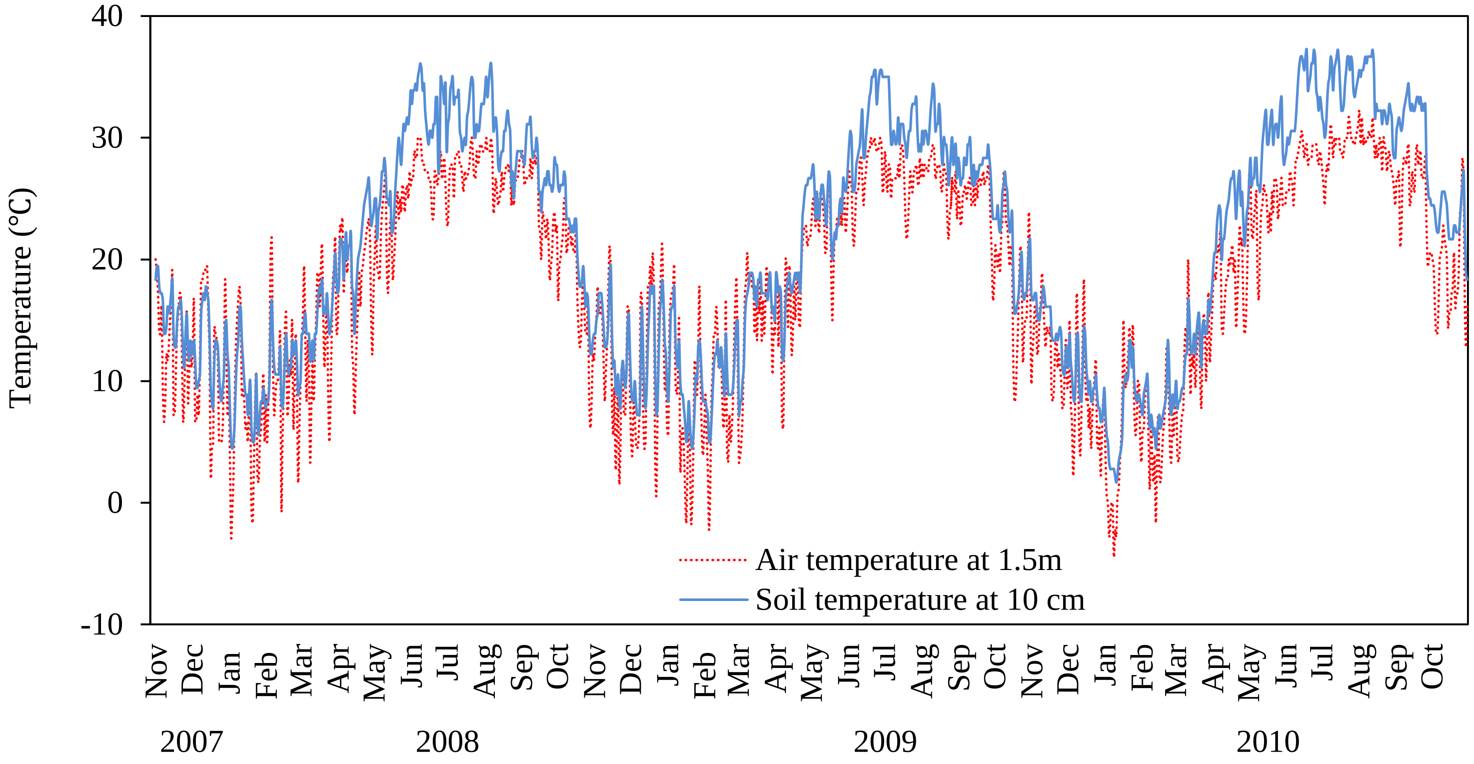

Figure 1-1 Average daily air and soil temperatures from November 2007 to October 2010.

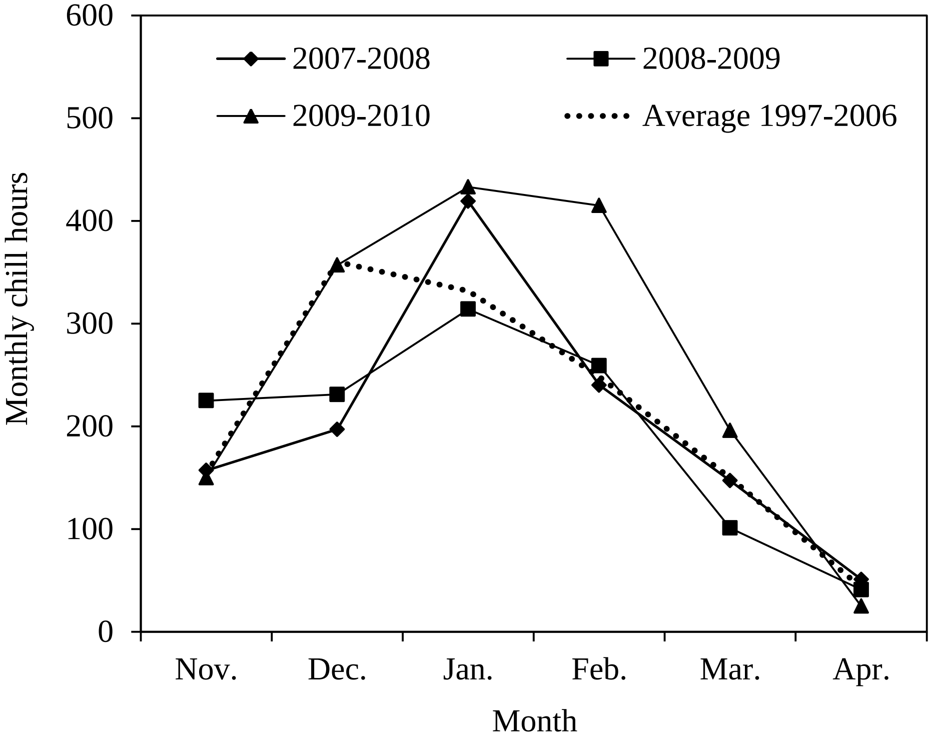

Figure 1-2 Monthly chill hours in winter seasons between 2007 and 2010.

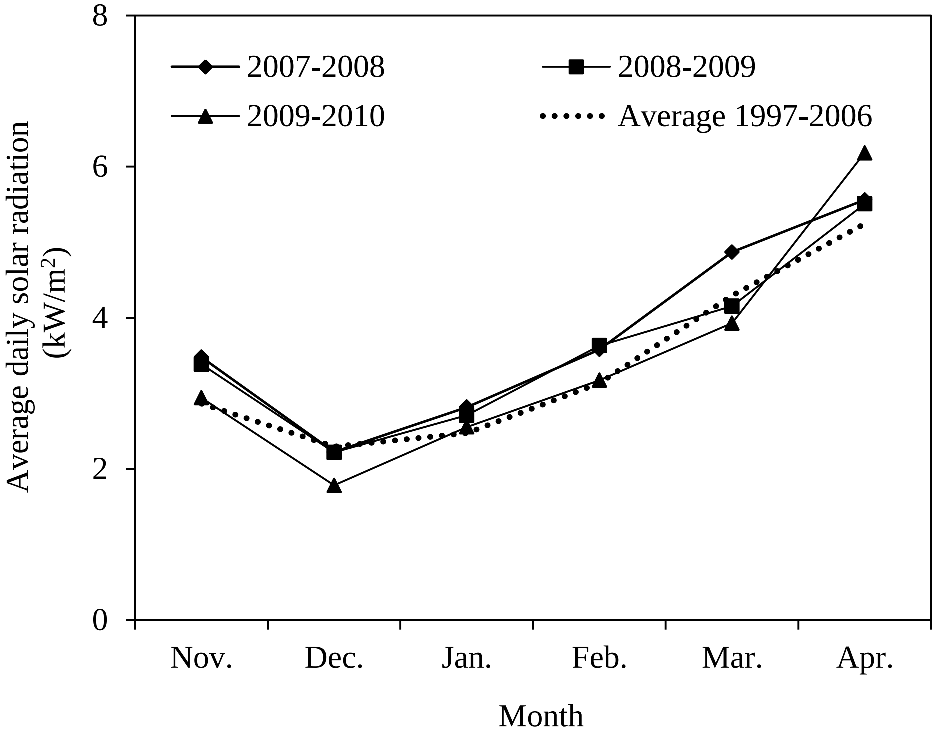

Figure 1-3 Average daily solar radiation in each month of winter seasons between 2007 and 2010.

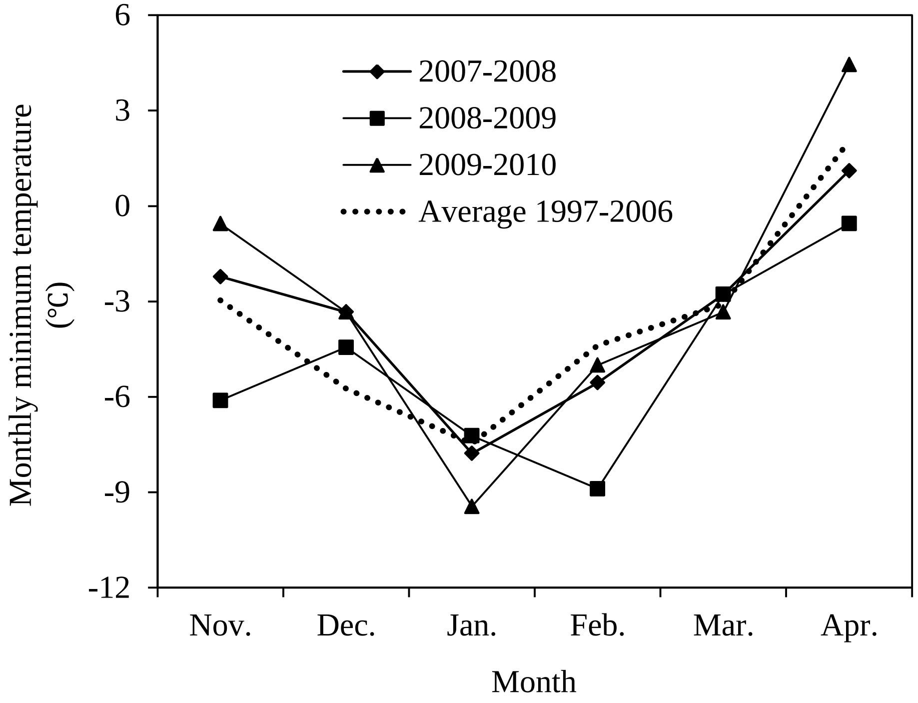

Figure 1-4 Monthly minimum air temperature in winter seasons between 2007 and 2010.

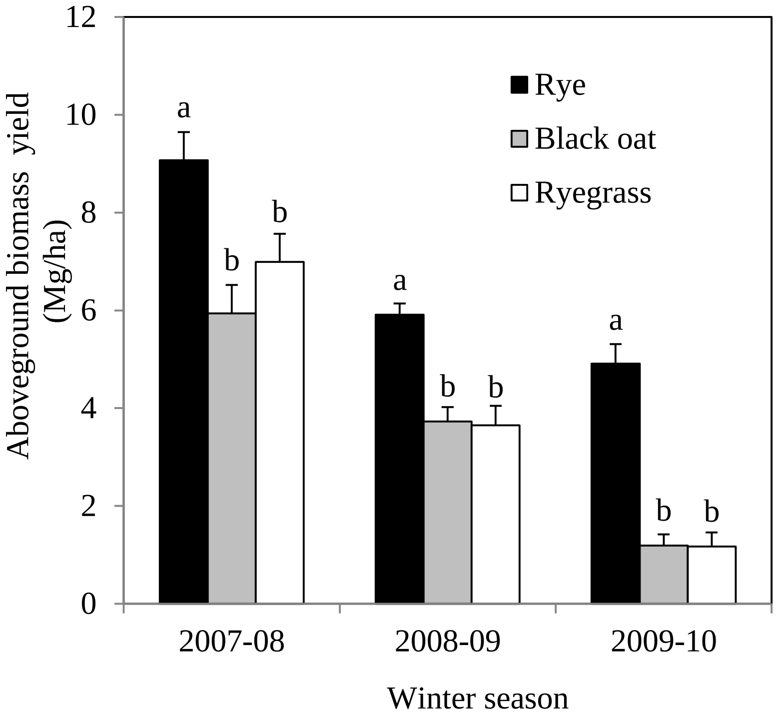

Figure 1-5 Biomass yields of the three winter annuals within each winter growing season. Means within each year with different letters differ (*P*<0.10).

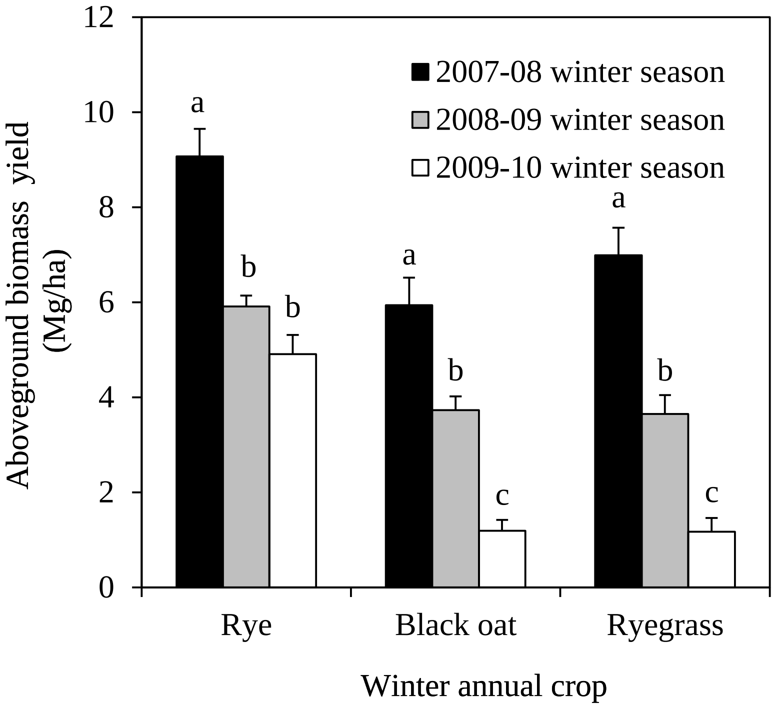

Figure 1-6 Biomass yields of each winter annual crop across the three winter growing seasons.

Means within each winter annual crop with different letters differ (*P*<0.10).

CHAPTER 2 EVALUATION OF WINTER ANNUALS IN ROTATION WITH TRADITIONAL SUMMER FORAGE CROPS FOR YEAR-ROUND BIOMASS PRODUCTION IN ALABAMA

ABSTRACT

Compared to annuals, dedicated perennial energy crops are currently receiving more attention for cellulosic biomass production, partly because they avoid annual seed and planting costs, and appear to be affected less by low rainfall. However, perennial crops are often difficult to establish and slow to reach maximum yield, and are typically warm-season species which grow rapidly for only a few months in the year. Warm-season and/or cool-season annuals could alleviate these limitations. Therefore, the objective of this 3-yr small plot study was to evaluate three common winter annuals (black oat (*Avena strigosa* Schreb.), rye (*Secale cereale* L. subsp. *cereale*) and annual ryegrass (*Lolium multiflorum* Lam.)) in rotation with three summer forage crops (forage sorghum (*Sorghum bicolor* spp.), pearl millet (*Pennisetum americanum* (L.) R. Br.) and sorghum-sudangrass (*Sorghum bicolor* (L.) Moench *nothosubsp. drummondii* (Steud.) de Wet ex Davidse)) for year-round biomass production under conventional-till and no-till management in central Alabama.

Biomass yield of all winter annuals was higher under conventional tillage than under no-till management, and ryegrass provided higher biomass yield than black oat and rye. Similarly, compared to no-till treatment, conventional tillage produced much higher biomass yield for all three summer crops in the third summer season, although conventional tillage did not result in greater production versus no-till for biomass production of the three summer forage crops in the first two summer seasons. Yield differences among summer crops as affected by different winter crops were relatively low under both tillage treatments except for sorghum-sudangrass under no-till, in which case yield was higher following rye than after black oat and ryegrass. Except for the second year of the study when biomass yields of sorghum-sudangrass and pearl millet did not differ, forage sorghum and sorghum-sudangrass provided higher biomass yield than pearl millet under both tillage treatments. For total annual biomass production, double-cropping systems with forage sorghum or sorghum-sudangrass under conventional tillage generally provided higher biomass yield than other double-cropping systems under both tillage treatments, although a yield advantage for double-cropping systems with pearl millet or forage sorghum was observed under no-till management in the first year.

It is concluded that forage sorghum and sorghum-sudangrass under conventional tillage would be suitable for biomass production in a long term system.

Keywords: cellulosic biomass production; crop rotation; winter annuals; summer forage crops

2.1 INTRODUCTION

Unlike first-generation bioenergy feedstocks, next-generation bioenergy feedstocks, (i.e., ligno-cellulosic biomass) are derived from non-food sources, including wood, tall grasses, and forestry and crop residues, which are harvested for their cellulosic biomass and can only be converted into liquid biofuels by complex conversion technologies (Worldwatch Institute, 2007). Advances in recent years have indicated that numerous technologies which can use a wide range of cellulosic biomass feedstocks to produce various liquid biofuels, including cellulosic ethanol, green gasoline, diesel and jet fuel are currently under development (Kunkes et al., 2008; Regalbuto, 2009.). Commercial production of cellulosic drop-in replacement biofuels at a cost that is competitive with fossil fuels could occur within the next five years (Solecki et al., 2012). This progress towards development of commercially viable conversion technologies, together with the Energy Independence and Security Act of 2007 (EISA), which mandated that 16 billion gallons of biofuel be produced from cellulosic biomass and used in the US by 2022, increases the need to develop economically viable and ecologically sustainable cellulosic biomass supply systems.

Compared to annuals, dedicated perennial energy crops are currently receiving more attention for cellulosic biomass production, partly because they avoid annual seed and planting costs, and appear to be affected less by low rainfall. However, perennial crops are often difficult to establish and slow to reach maximum yield, and are typically warm-season species which grow rapidly for only a few months in the year. For example, to mitigate slow establishment and the related economic loss, a given area of land could be planted to annual biomass crops and replaced with a perennial by planting the perennial on just part of the area each year over a period of several years. In addition, under certain circumstances winter and summer annual biomass rotations may provide higher and more profitable yields than some perennials. Forage sorghum, sorghum-sudangrass and pearl millet are forage crops that are commonly grown in the Southeast.

In addition, winter annuals such as cereal rye, annual ryegrass and oats are commonly planted in the region as unharvested or grazed cover crops to improve soil and water conditions for subsequent summer crops. Benefits of planting winter cover crops include preventing soil erosion and enhancing soil organic matter (SOM) thereby improving soil quality and productivity (Calonego and Rosolem, 2010). For example, studies showed that over-seeding rye into standing corn increased corn yield (Schroder et al., 1996; Kuo et al., 2000; Coelho et al., 2005). However, little is known about use of winter annuals in rotation with summer forage crops under conventional tillage or no-till management for year-round biomass production. Therefore, the objective of this study was to evaluate three common winter annuals (black oat, rye and ryegrass) in rotation with three summer forage crops (forage sorghum, sorghum-sudangrass and pearl millet) for year-round biomass feedstocks production under conventional tillage or no-till management in central Alabama.

2.2 MATERIALS AND METHODS

2.2.1 Treatments and experimental design

This experiment was initiated in the winter of 2007 and conducted for 3 years at the E.V. Smith Research Center, Plant Breeding Unit of the Alabama Agricultural Experiment Station near Tallassee, Alabama on a Wickham soil (fine-loam, mixed, thermic Typic Hapludult). The field had been planted with wheat using conventional tillage in the 2006-07 winter season, and fallowed in the summer of 2007. The experiment was laid out in a split-plot design with four replications. Conventional tillage and no-till management were assigned to whole plots, and cropping systems were assigned to sub-plots. The nine cropping systems that were evaluated included all combinations of rye, black oat or ryegrass in winter, followed by forage sorghum, sorghum-sudangrass or pearl millet in summer. Size of sub-plots was 3.6 × 9.0m.

2.2.2 Crop rotation

Tillage operations, fertilizer application and planting were conducted within one day for all winter and summer seasons. Whole plots for conventional tillage treatment were disked to a depth of 10-15 cm, and chisel plowed to a depth of 15 cm. Seeds of winter and summer annuals were drilled to designated plots using a planter set at a row spacing of 17.8 cm. Four days after planting winter annuals, all plots were fertilized with 112 kg N ha^{-1}, 45 kg P ha^{-1} and 45 kg K ha^{-1} in all three winter seasons. For summer seasons, all plots were fertilized with 112 kg N ha^{-1}. Table 2-1 provides more details on cultivars, seeding rate, and planting and harvesting times.

All plots were cultivated when necessary over the three years and glyphosate (Roundup) herbicide was applied to all plots 12 days before planting summer forage crops.

2.2.3 Data collection

At the end of each growing season, the central six rows of each winter and summer crop plot were cut to a 5-cm stubble height with a sickle bar mower. Fresh biomass weight of the harvested area in each plot was measured using a hanging scale in the field. Biomass subsamples taken from each plot were dried at 60°C for 72 h for dry matter determination. After sampling central rows, border rows were cut off and removed from the plots.

2.2.4 Data analysis

Statistical analysis of biomass yield data from both summer and winter seasons was conducted using SAS v9.2 PROC GLIMMIX. Block was considered as a random factor, whereas tillage, year, and summer and winter crops and their interaction terms were tested as fixed effects. The critical *P*-value of 0.10 was used as cutoff for testing these fixed effects, and determination of differences in least-squares means was based on adjusted *P*-value obtained by using the option ADJUST=SIMULATE in the LSMEANS statement.

2.3 RESULTS AND DISCUSSIONS

2.3.1 Weather conditions

Rainfall was close to long-term averages in the 2007, 2008 and 2010 growing seasons, but very high in 2009 (Table 2-2). The summer (May to October) and winter (November to April) growing season rainfall of 2009 were 941 and 814 mm, which are 324 and 48 mm higher than the average of past 10 years, respectively. The accumulative chill hours (temperatures below 7.2℃) in winter season of 2009 were higher than in winter seasons of 2007 and 2008 (1211, 1171 and 1576 hours in 2007-08, 2008-09 and 2009-10 winter seasons, respectively) (Figure 2-1) probably because the accumulative solar radiation in this winter season was also lower (Figure 2-2). However, monthly minimum temperatures were very similar in winter seasons of 2007 and 2009 (Figure 2-3).

2.3.2 Winter biomass yield

Analysis of data from the second and third years of the study indicated that summer crops did not affect biomass yields of winter crops. Therefore, biomass yield data from all three years were pooled for further analysis, and this revealed a three-way interaction between year, tillage method and winter crop (Figures 2-4, 2-5 and 2-6) (P<0.01). When compared to no-till management, under conventional tillage yield was higher for black oat in the first and second years of the study compared to the third year, and for ryegrass it was higher in the second and third years compared to the first year (Figure 2-4). Within each tillage treatment, yield difference among the three winter annuals was relatively small in both the 2007-08 and 2008-09 winter seasons, but ryegrass provided higher biomass yield than black oat and rye under conventional tillage and higher yield than rye under no-till management in the 2009-10 winter season (Figure 2-5). In addition, within each tillage treatment yields for all three winter annuals were high in the 2007-08 and 2008-09 winter seasons, but decreased substantially in the 2009-10 winter season (Figure 2-6). This variation in biomass yield over time corresponded with the variation in average daily solar radiation, and cumulative chill hours (Figures 2-1, 2-2 and 2-3), and was lowest for ryegrass, followed by black oat and rye. This result is not consistent with that from another study conducted at the same location over the same period which may be due to differences between the sites of the two experiments. In particular, the site of this experiment was subject to periodic waterlogging whereas the other site was not, and it is possible that there is a difference in tolerance to waterlogging among the winter crops that were included in both studies.

2.3.3 Summer biomass yield

Analysis of biomass yield from summer crops indicated a year × tillage × summer crop interaction, and a tillage × winter crop × summer crop interaction ($P<0.01$).

2.3.3.1 Interaction of year, tillage and summer crop

Yield variation over time for the three summer forage crops by tillage treatment was complicated (Figure 2-7). Under both tillage treatments, sorghum-sudangrass achieved significantly higher biomass yield in the 2010 summer season than in the 2008 and 2009 summer seasons, while biomass yield for pearl millet was higher in the 2008 summer season than in the 2009 and 2010 summer seasons. For forage sorghum, biomass yield variation over time was totally different under the two tillage treatments: yield increased over time under conventional tillage, but decreased over time under no-till management. In general, biomass yield for the three summer forage crops under conventional tillage tended to increase over time, while yield for pearl millet and forage sorghum under no-till tended to decrease over time.

Effect of tillage on biomass yield for the three summer forage crops was very consistent within each summer season (Figure 2-8). In the first season, all three summer crops except for sorghum-sudangrass provided significantly higher biomass yield under no-till management than under conventional tillage. The yield differences observed in the first season under no-till management were not observed in the second summer season:

yield difference between the two tillage treatments for the three summer forage crops was small. Conversely, conventional tillage enhanced biomass yield for all three summer crops in the third summer season when compared to no-till. This may be due to soil compaction increasing with time and limiting growth under no-till management. Forage sorghum and sorghum-sudangrass provided higher biomass yield than pearl millet under all tillage systems within each year except in the 2008 summer season under no-till management ($P<0.05$) (Figure 2-9).

2.3.3.2 Interaction of tillage, winter crop and summer crop

Average biomass yield of pearl millet after all winter crops under both tillage treatments was lower than that of forage sorghum and sorghum-sudangrass, and forage sorghum provided similar biomass yields to those of sorghum-sudangrass under all combinations of winter crop and tillage method, except that after rye under no-till management sorghum-sudangrass produced higher biomass yield than forage sorghum (Figure 2-10).

Average biomass yield for all three summer crops over the three summer seasons after the three winter annuals under both tillage treatments was not different except for sorghum-sudangrass under no-till treatment providing higher yields after rye than after black oat and ryegrass (Figure 2-11). This is possibly because ryegrass and black oat have greater allelopathic effects on sorghum-sudangrass under no-till treatment than that of rye, while conventional tillage dilutes such an effect. This suggestion is based on the fact that allelopathic effects of rye, ryegrass and black oat have been recorded on a number of plant species such as white clover, corn and cotton (Barnes and Putnam, 1986; Bauer and Reeves, 1999; Price et al., 2008).

Average biomass yield for forage sorghum and sorghum-sudangrass after all winter crops except for sorghum-sudangrass after rye was higher under conventional tillage than under no-till, while higher yield for pearl millet after all winter annuals was observed under no-till management, but not under conventional tillage (Figure 2-12).

Notwithstanding the year × tillage × summer crop interaction and the tillage × winter crop × summer crop interaction, conventional tillage generally provided higher summer biomass yield than no-till management, and forage sorghum and sorghum-sudangrass provided higher yields than pearl millet.

2.3.4 Total annual biomass yield of winter and summer seasons

Because summer biomass production produced 63.0 to 90.4% of total annual biomass yield, it follows that summer production had a greater effect on total yield than winter production. Analysis of total annual biomass yield data revealed a year × tillage method × cropping system interaction; yield differences among the nine double-cropping systems (black oat+pearl millet (BOPM), black oat+forage sorghum (BOS), black oat+sorghum-sudangrass (BOSS), rye+pearl millet (RPM), rye+forage sorghum (RS), rye+sorghum-sudangrass (RSS), ryegrass+pearl millet (RGPM), ryegrass+forage sorghum (RGS), ryegrass+sorghum-sudangrass (RGSS)) was not consistent over the three years and across tillage methods (Figure 2-13). Under conventional tillage, annual total biomass yield among the nine double-cropping systems was similar in 2008, while in 2009 and 2010 systems containing forage sorghum or sorghum-sudangrass provided higher yields than systems which included pearl millet. Under no-till management, biomass yield for double-cropping systems containing pearl millet or forage sorghum was higher than that for cropping systems containing sorghum-sudangrass in 2008, with the exception of sorghum-sudangrass after rye. The yield trend among the nine double-cropping systems was consistent in 2009 and 2010 under both tillage treatments: systems containing forage sorghum and sorghum-sudangrass produced higher biomass yield than systems that included pearl millet in 2009 and 2010.

Annual total biomass yield variation over time for the nine double-cropping systems was inconsistent under different tillage management (Figure 2-14). Under conventional tillage, biomass yield for double-cropping systems containing forage sorghum or sorghum-sudangrass increased over time, while yield for cropping systems containing pearl millet decreased over time. However, except for sorghum-sudangrass after rye under no-till treatment, biomass yield for all double-cropping systems decreased over time. Effect of tillage on total annual biomass yield for the nine double-cropping systems varied by year (Figure 2-15). In 2008, conventional tillage resulted in lower total biomass yield for all nine double-cropping systems, except for those involving sorghum-sudangrass, while yield from the two tillage methods was similar for all cropping systems in 2009. Conversely, except for systems containing rye in 2010, conventional tillage enhanced total annual biomass yield for all double-cropping systems compared to no-till management.

In this study, highest summer yield and total annual biomass yield were 35.1 Mg ha^{-1} for sorghum-sudangrass and 41.9 Mg ha^{-1} for ryegrass+sorghum-sudangrass systems under conventional-till in 2010, respectively, which are approximately twice that of Alamo switchgrass with fertilization at 112 kg N ha^{-1} in same year and location.

2.4 CONCLUSIONS

Even though data analysis in this study revealed several complex interactions, results still allow some useful general conclusions to be drawn:

- summer crop and system yields were higher than those recorded for switchgrass at the same location
- compared to production of summer crops in the rotation, winter crop yield was relatively low, suggesting that economic analysis should be conducted to determine if this phase of the system is economically viable;
- conventional tillage generally provided higher biomass yields than no-till management, but again, economic analysis is needed to determine if the higher cost associated with conventional tillage would be offset by the higher yields;
- systems that included forage sorghum or sorghum-sudangrass generally provided the highest yields, but sorghum-sudangrass would likely be easier to dry, so would be recommended if a dry feedstock is needed; and
- additional research should include economic analysis and summer crops grown alone as well as in rotation with winter crops.

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Table 2-1 Cultivars, seeding rates, and planting dates and harvest dates of winter annuals and summer crops.

Season	Year	Crop	Variety	Seeding rate	Planting date	Harvest date
Fall/spring	2007/2008	Black oat	Soil Saver	78 kg ha^{-1}	November 14, 2007	April 29, 2008
		Rye	Winter Grazer	100 kg ha^{-1}	November 14, 2007	April 29, 2008
		Ryegrass	Marshall	11 kg ha^{-1}	November 14, 2007	April 29, 2008
Summer	2008	Forage sorghum	Evergreen BMR	17 kg ha^{-1}	June 9, 2008	October 1, 2008
		Pearl millet	Pearlex II	17 kg ha^{-1}	June 9, 2008	October 1, 2008
		Sorghum-sudangrass	Sugar Grazer 2	17 kg ha^{-1}	June 9, 2008	October 1, 2008
Fall/spring	2008/2009	Black oat	Soil Saver	100 kg ha^{-1}	November 12, 2008	May 6, 2009
		Rye	Elbon	100 kg ha^{-1}	November 12, 2008	May 6, 2009
		Ryegrass	Marshall	11 kg ha^{-1}	November 12, 2008	May 6, 2009
Summer	2009	Forage sorghum	Evergreen BMR	17 kg ha^{-1}	June 19, 2009	October 2, 2009
		Pearl millet	Pearlex II	17 kg ha^{-1}	June 19, 2009	October 2, 2009
		Sorghum-sudangrass	Sugar Grazer 2	17 kg ha^{-1}	June 19, 2009	October 2, 2009
Fall/spring	2009/2010	Black oat	Soil Saver	100 kg ha^{-1}	November 9, 2009	May 6, 2010
		Rye	Elbon	100 kg ha^{-1}	November 9, 2009	May 6, 2010
		Ryegrass	Marshall	11 kg ha^{-1}	November 9, 2009	May 6, 2010
Summer	2010	Forage sorghum	Evergreen BMR	28 kg ha^{-1}	June 10, 2010	October 6, 2010
		Pearl millet	Pearlex II	17 kg ha^{-1}	June 10, 2010	October 6, 2010
		Sorghum-sudangrass	Sugar Grazer 2	28 kg ha^{-1}	June 10, 2010	October 6, 2010

Table 2-2 Monthly and growing seasonal precipitation between 2007 and 2010.

Year	Precipitation (mm)													
	Month												Winter growing season	Summer growing season
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.		
2007											55	94	540	
2008	111	102	77	101	64	50	126	252	19	83	93	82	685	594
2009	52	105	244	109	262	100	75	192	148	164	154	276	814	941
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Average (1997-2006)	107	127	181	129	92	141	118	97	104	65	123	104	766	617

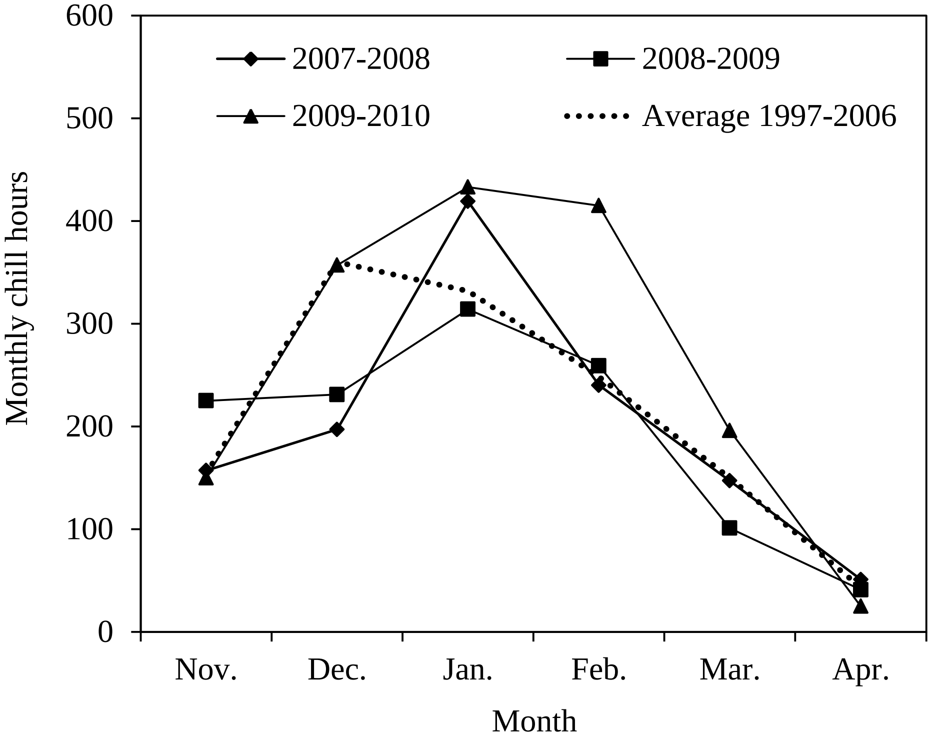

Figure 2-1 Monthly chill hours in winter seasons between 2007 and 2010.

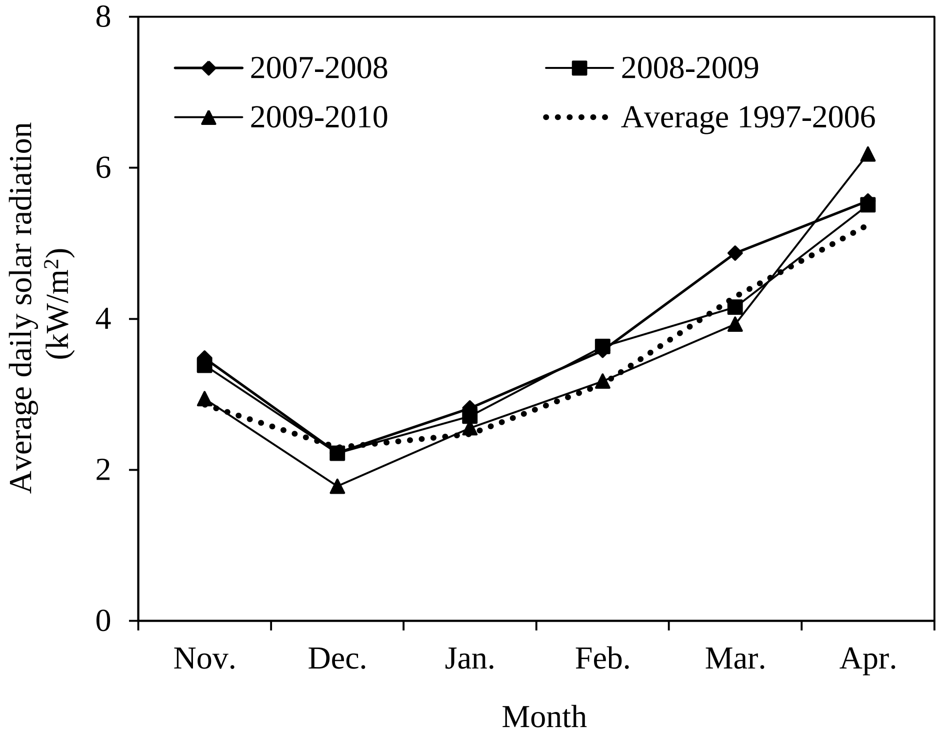

Figure 2-2 Average daily solar radiation in each month of the winter seasons between 2007 and 2010.

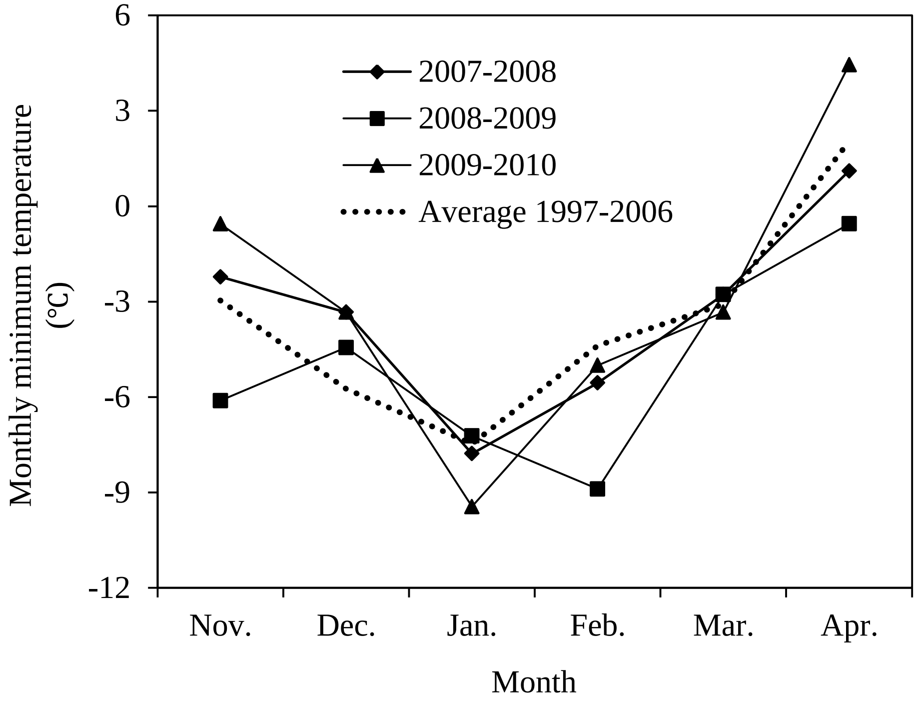

Figure 2-3 Monthly minimum air temperature in winter seasons between 2007 and 2010.

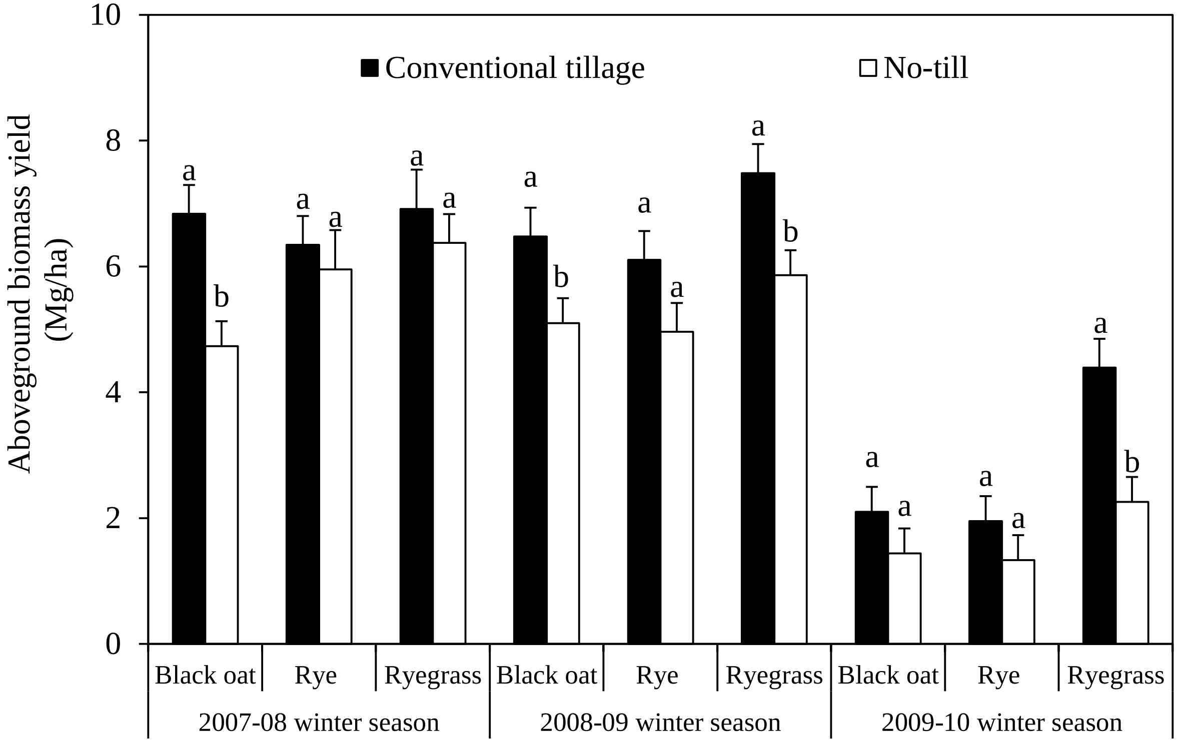

Figure 2-4 Biomass yield for conventional tillage and no-till management for black oat, rye and ryegrass across winter seasons. Means within each winter crop and winter season with different letters differ (P<0.05).

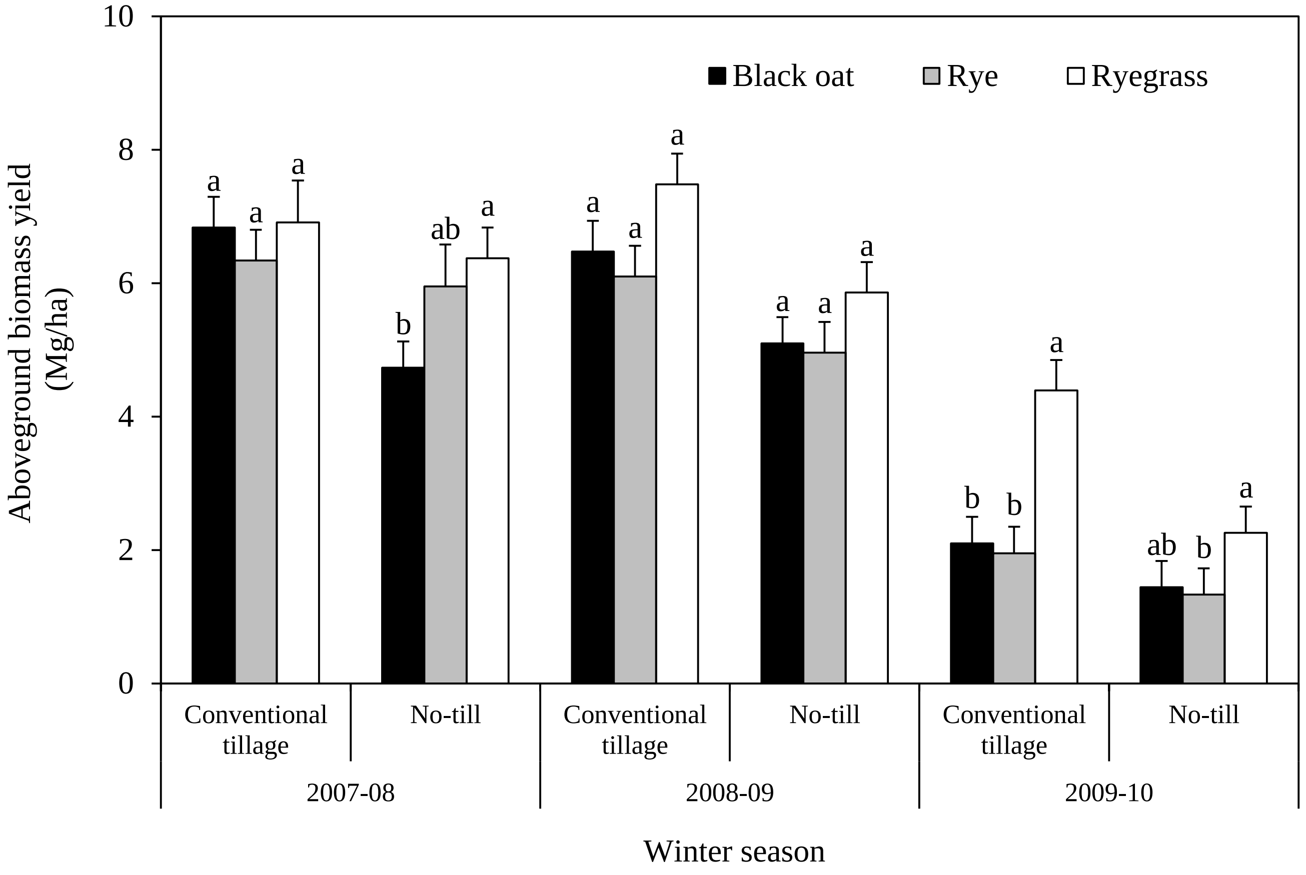

Figure 2-5 Biomass yield for black oat, rye and ryegrass across winter seasons and tillage method.

Means within each tillage treatment and winter season with different letters differ (*P*<0.05)

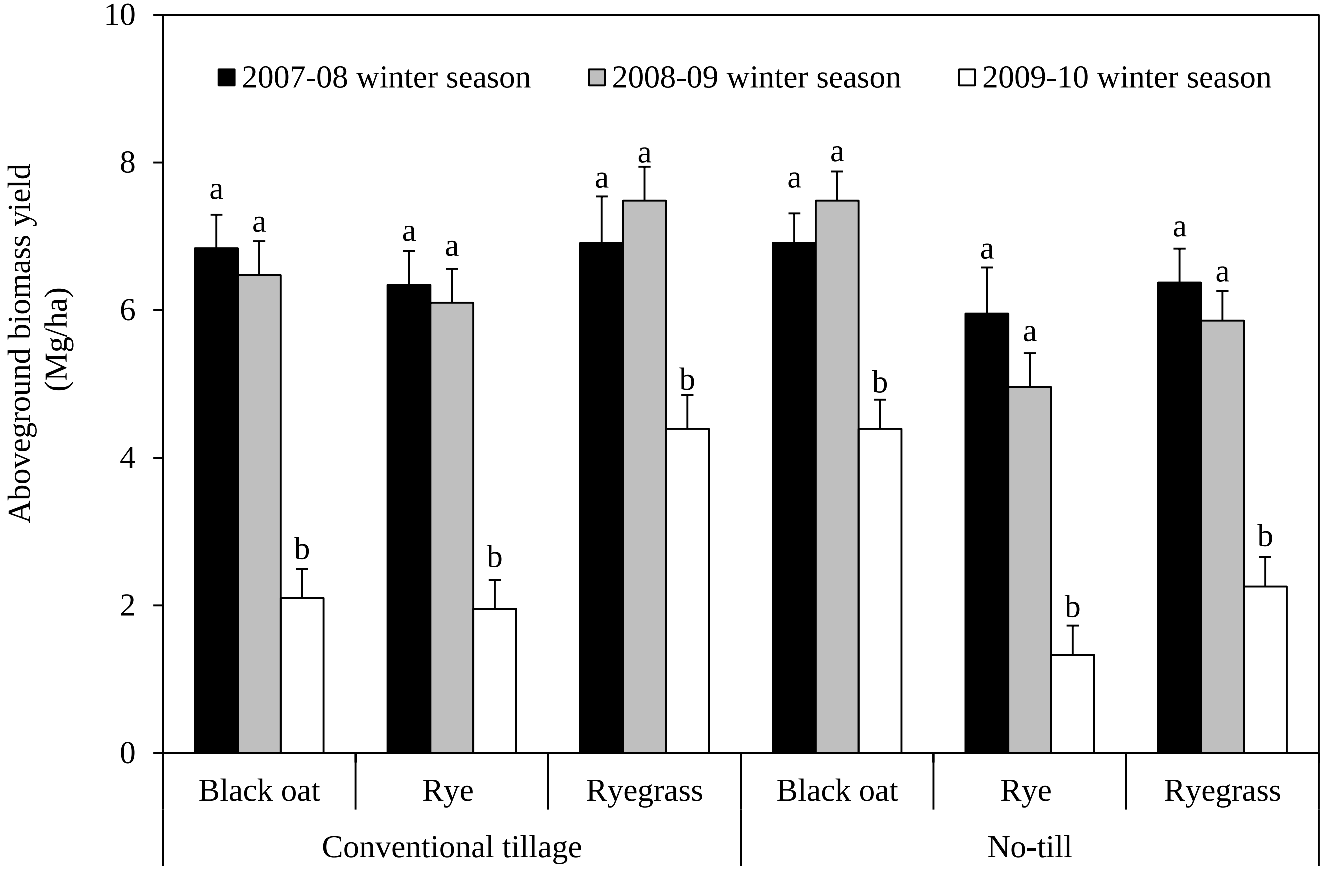

Figure 2-6 Biomass yield for black oat, rye and ryegrass over time and across tillage method.

Means within each winter crop and tillage treatment with different letters differ (*P*<0.05).

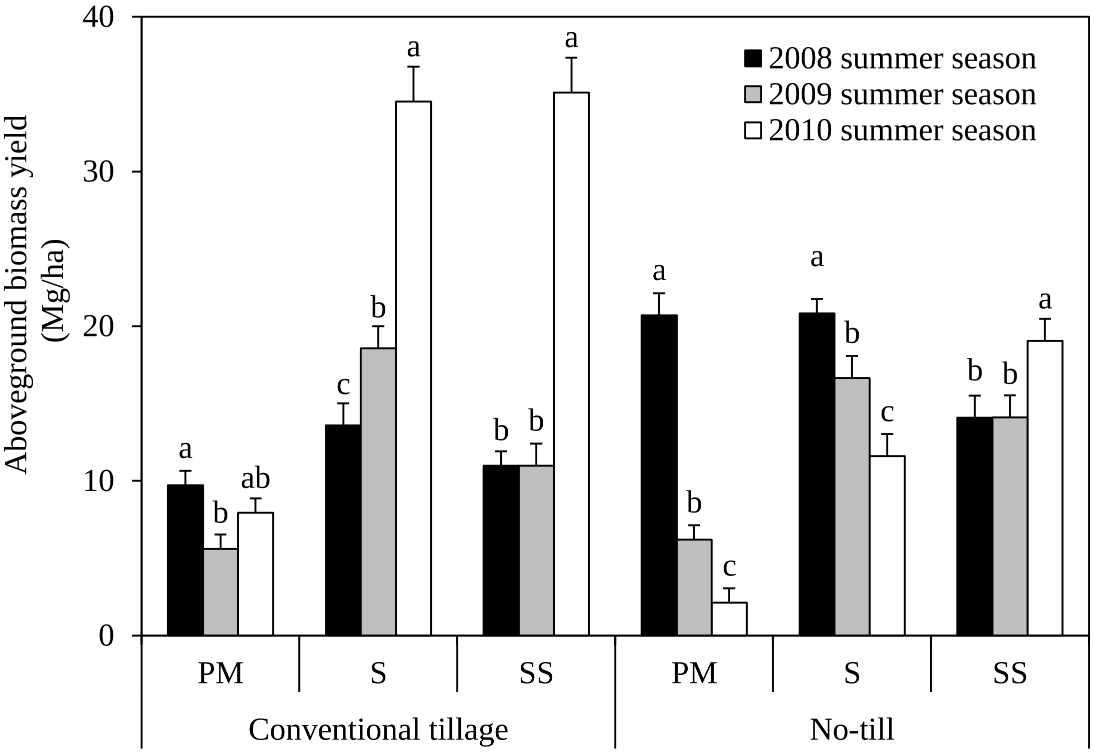

Figure 2-7 Biomass yield for pearl millet, forage sorghum and sorghum-sudangrass over time and across tillage method.

Means within each summer forage crop and tillage treatment with different letters differ (*P*<0.05)

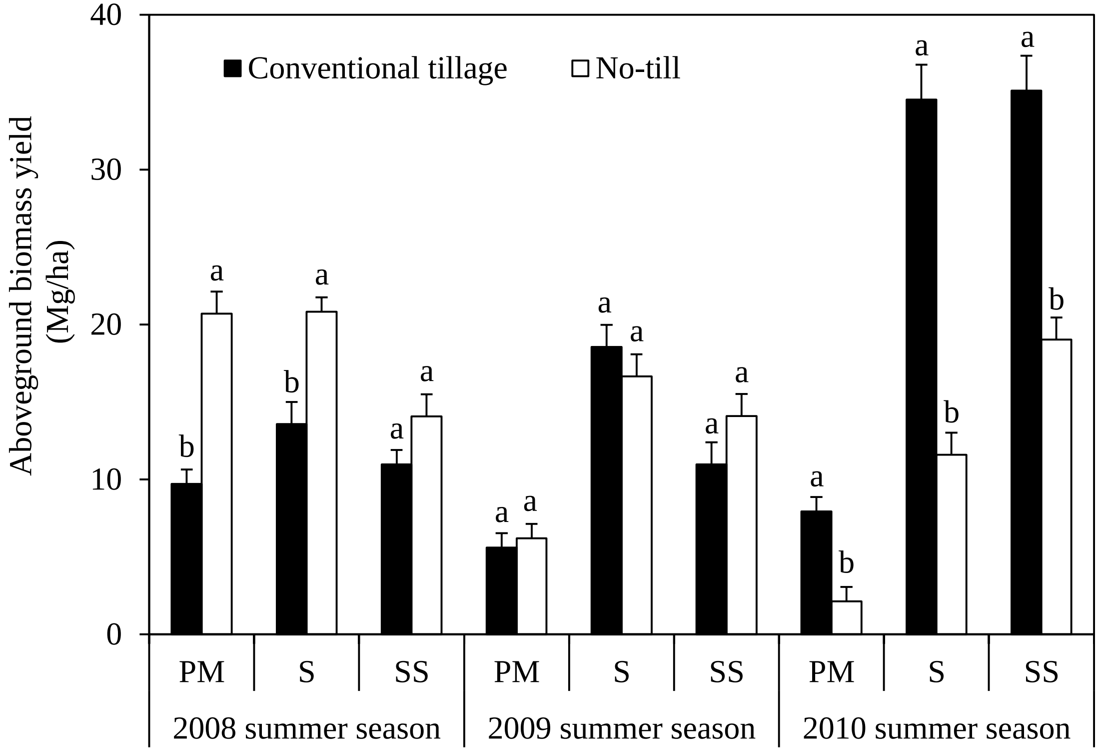

Figure 2-8 Effect of tillage method on biomass yields of pearl millet (PM), forage sorghum (S) and sorghum-sudangrass (SS) over time.

Means within each summer forage crop and year with different letters differ (*P*<0.05)

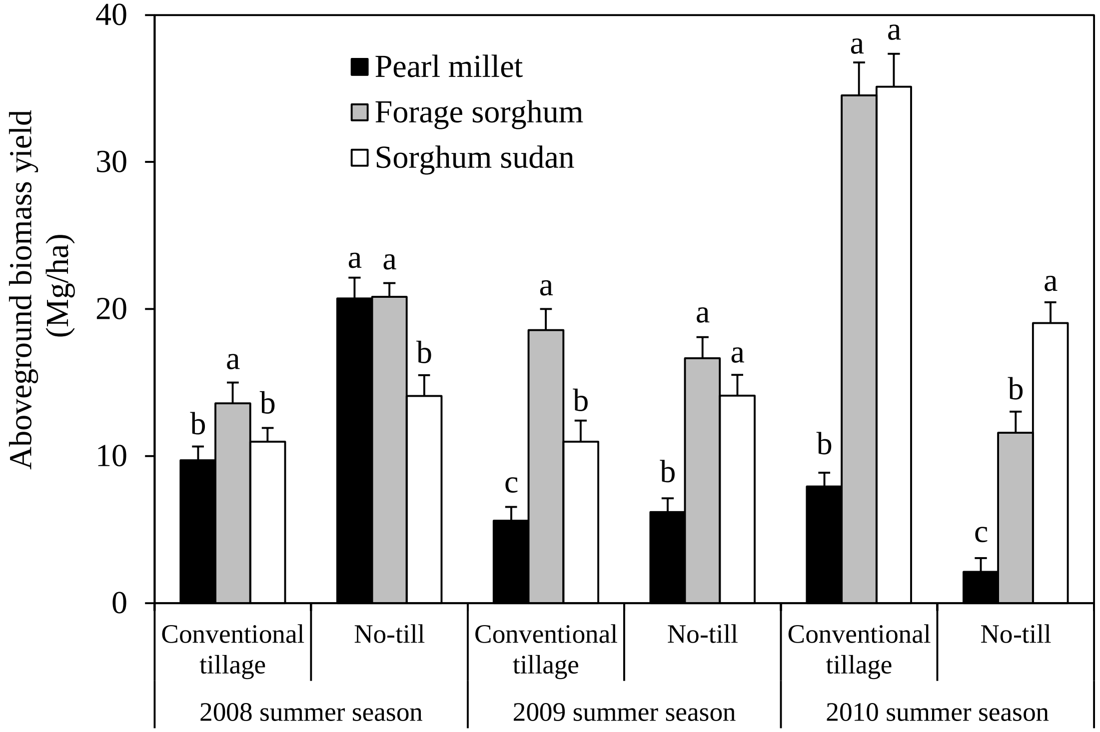

Figure 2-9 Biomass yield of pearl millet, forage sorghum and sorghum-sudangrass as influenced by year and tillage method.

Means within each tillage treatment and year with different letters differ (P<0.05).

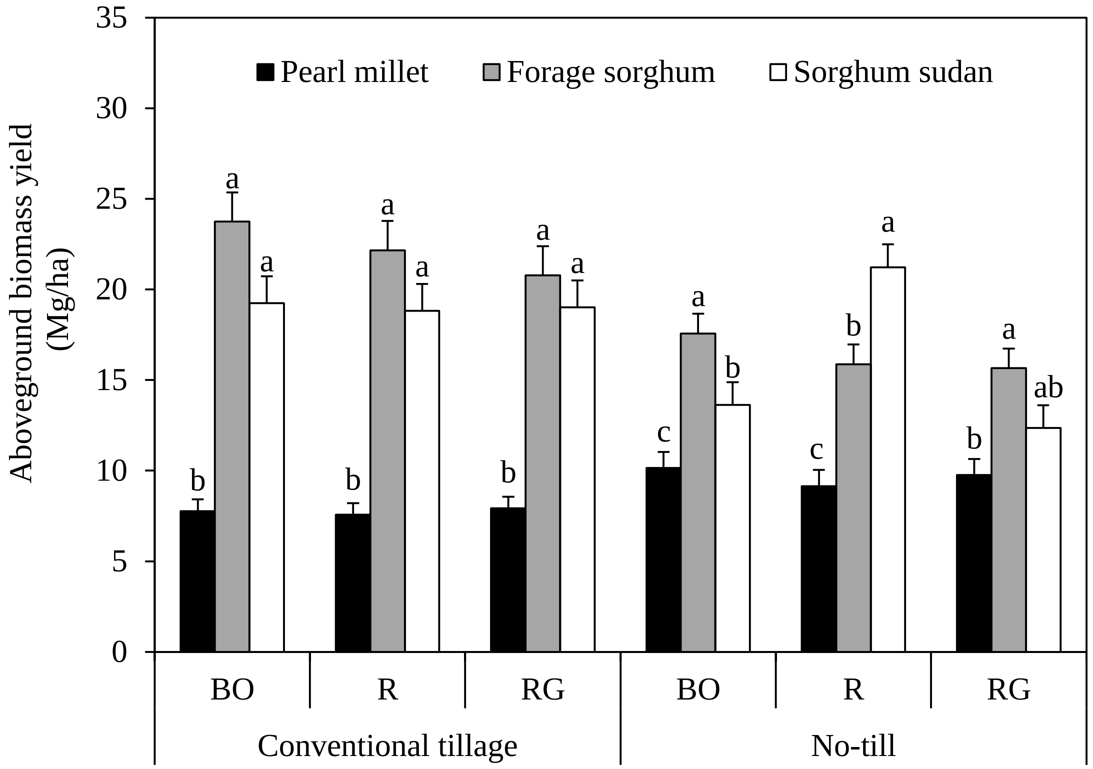

Figure 2-10 Biomass yield of pearl millet, forage sorghum and sorghum-sudangrass as influenced by tillage method and winter crops (black oat (BO), rye (R), and ryegrass (RG)).

Means within each winter crop and tillage treatment with different letters differ (*P*<0.05).

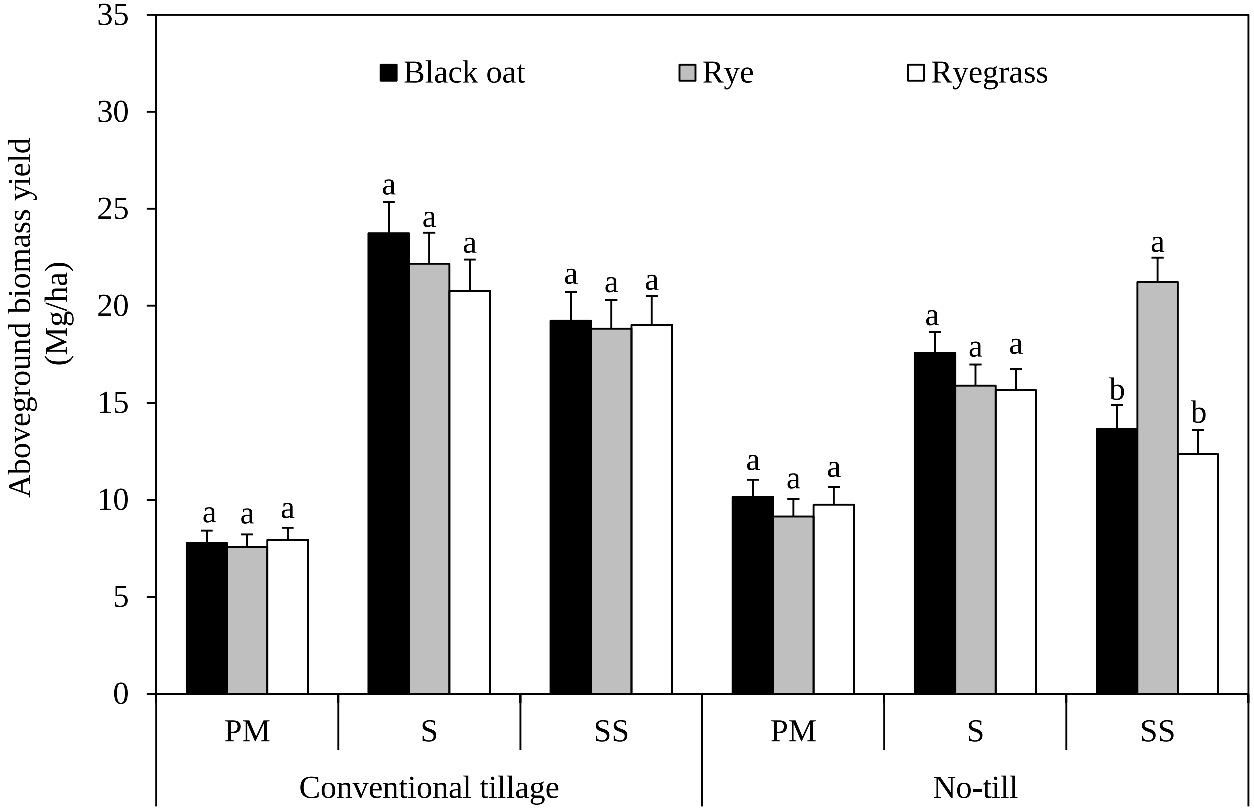

Figure 2-11 Effect of winter crop on biomass yield for pearl millet (PM), forage sorghum (S) and sorghum-sudangrass (SS) under different tillage methods.

Means within each summer crop and tillage method with different letters differ (*P*<0.0001).

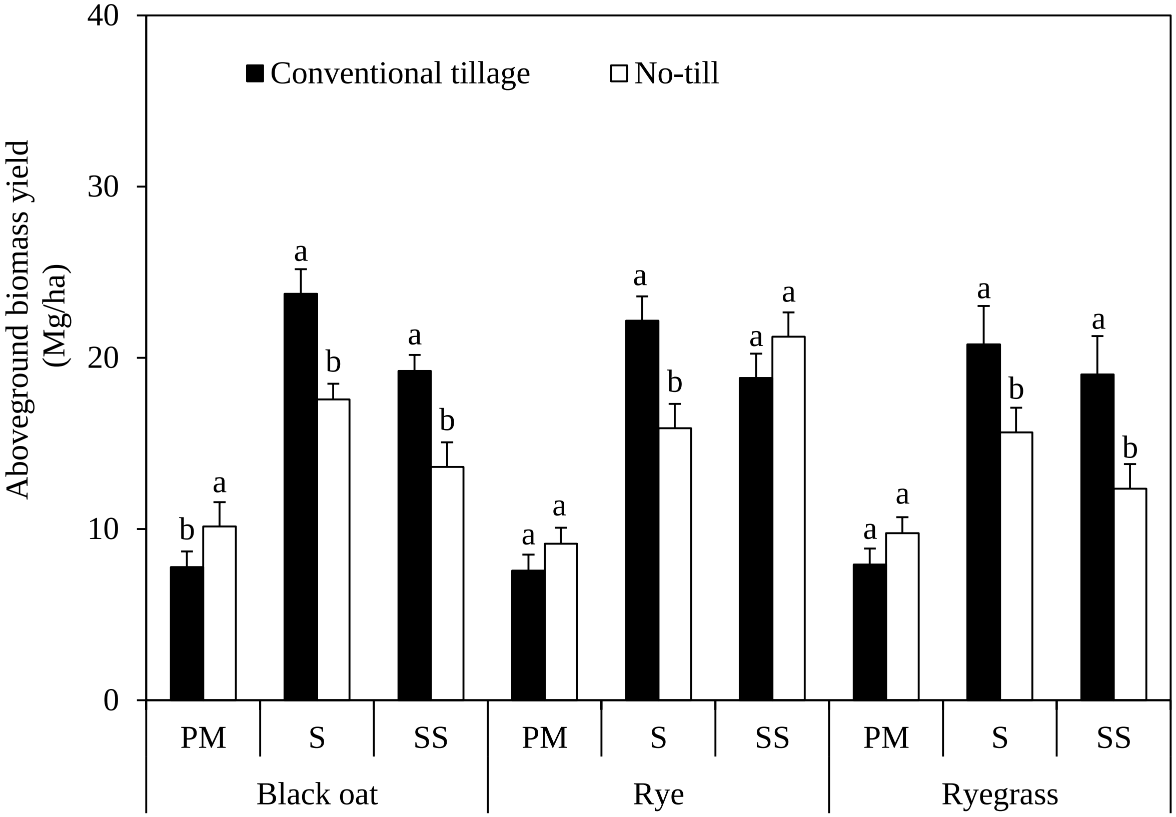

Figure 2-12 Effect of tillage method and winter crop on biomass yields of pearl millet (PM), forage sorghum (S) and sorghum-sudangrass (SS).

Means within each summer crop and winter crop with different letters differ (*P*<0.05).

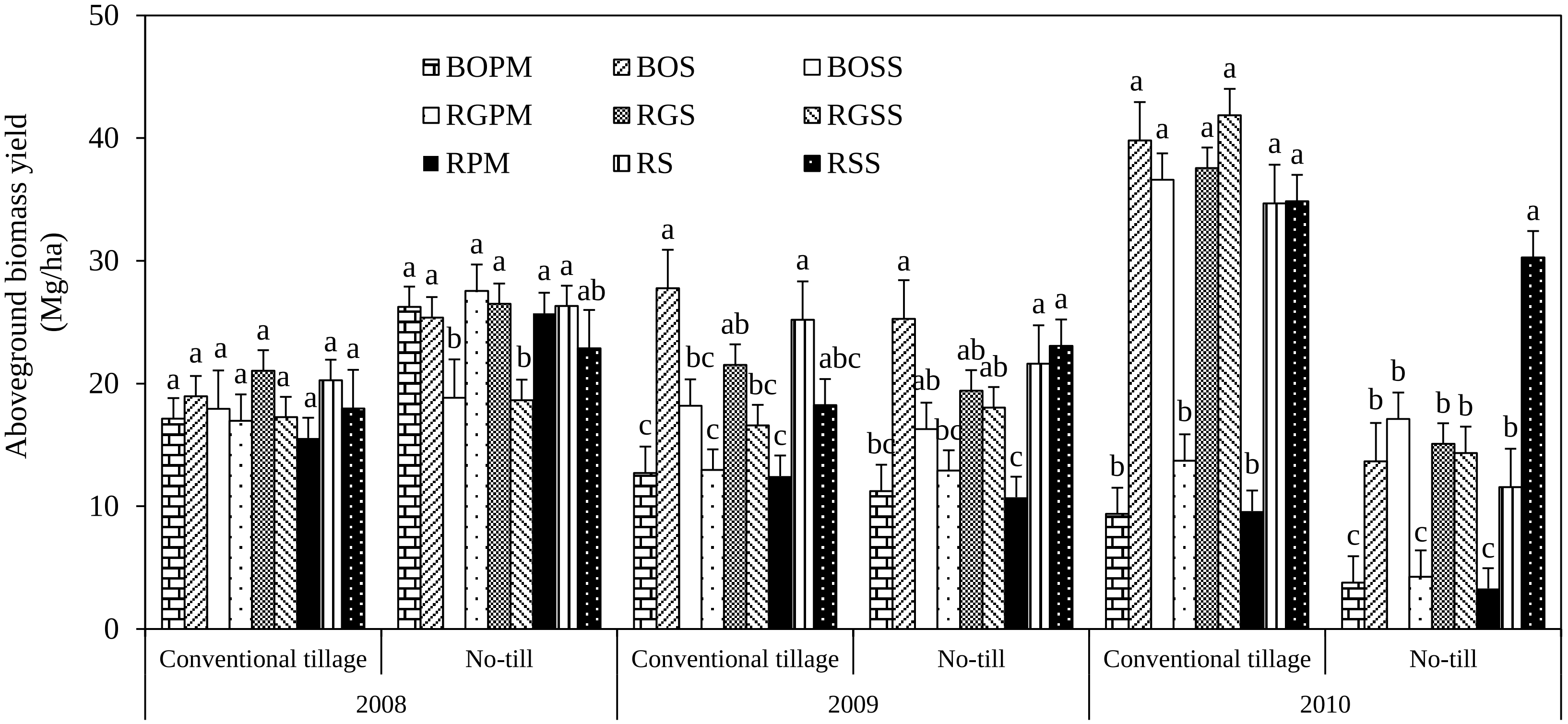

Figure 2-13 Total annual biomass yield among different double-cropping systems (black oat+pearl millet (BOPM), black oat+forage sorghum (BOS), black oat+sorghum-sudangrass (BOSS), rye+pearl millet (RPM), rye+forage sorghum (RS), rye+sorghum-sudangrass (RSS), ryegrass+pearl millet (RGPM), ryegrass+forage sorghum (RGS), ryegrass+sorghum-sudangrass (RGSS)) across years.

Means within each tillage treatment and year with different letters differ (*P*<0.05).

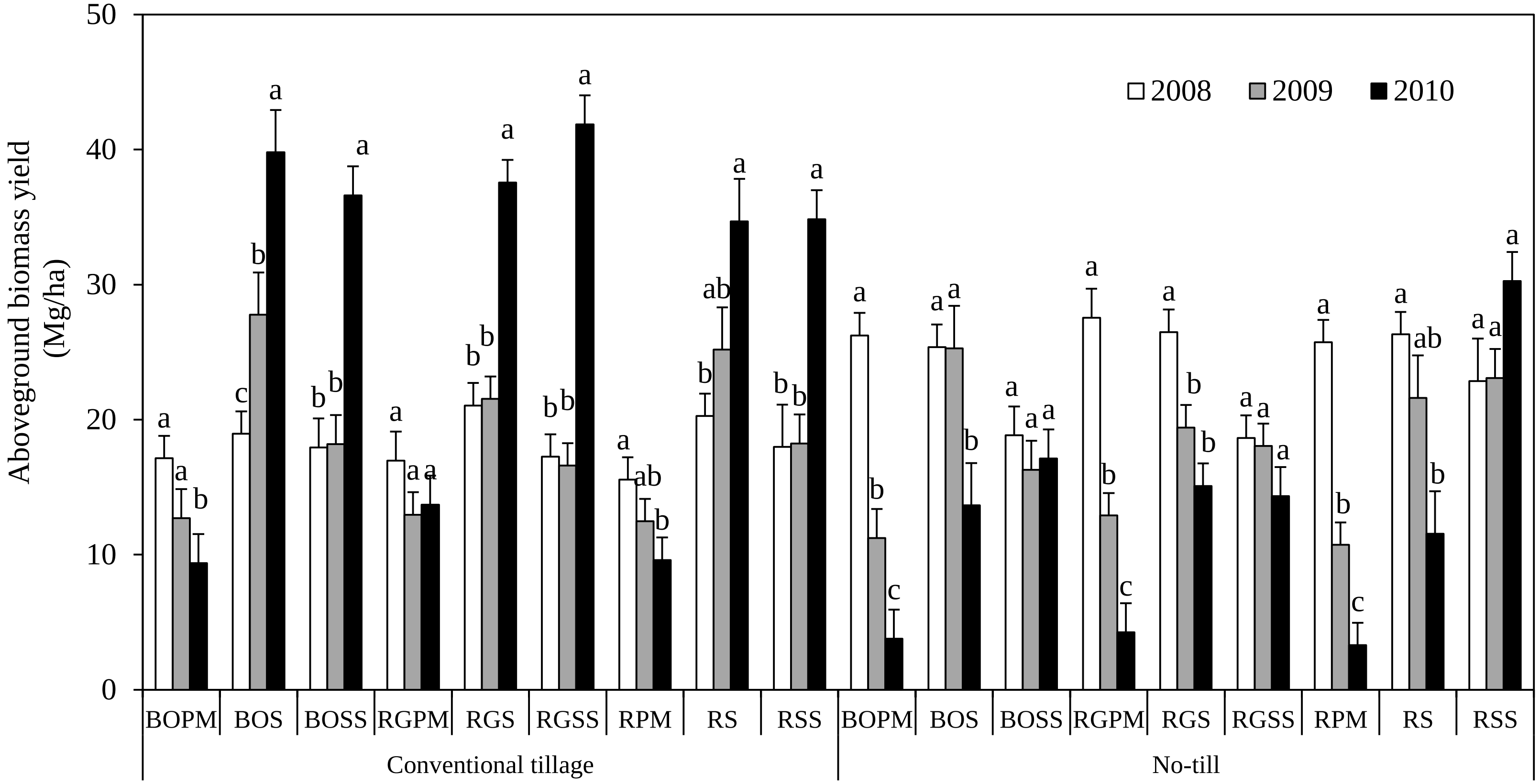

Figure 2-14 Total annual biomass yield for the nine double-cropping systems (black oat+pearl millet (BOPM), black oat+forage sorghum (BOS), black oat+sorghum-sudangrass (BOSS), rye+pearl millet (RPM), rye+forage sorghum (RS), rye+sorghum-sudangrass (RSS), ryegrass+pearl millet (RGPM), ryegrass+forage sorghum (RGS), ryegrass+sorghum-sudangrass (RGSS)) over time and across tillage methods.

Means within each double-cropping system and tillage treatment with different letters differ (*P*<0.05).

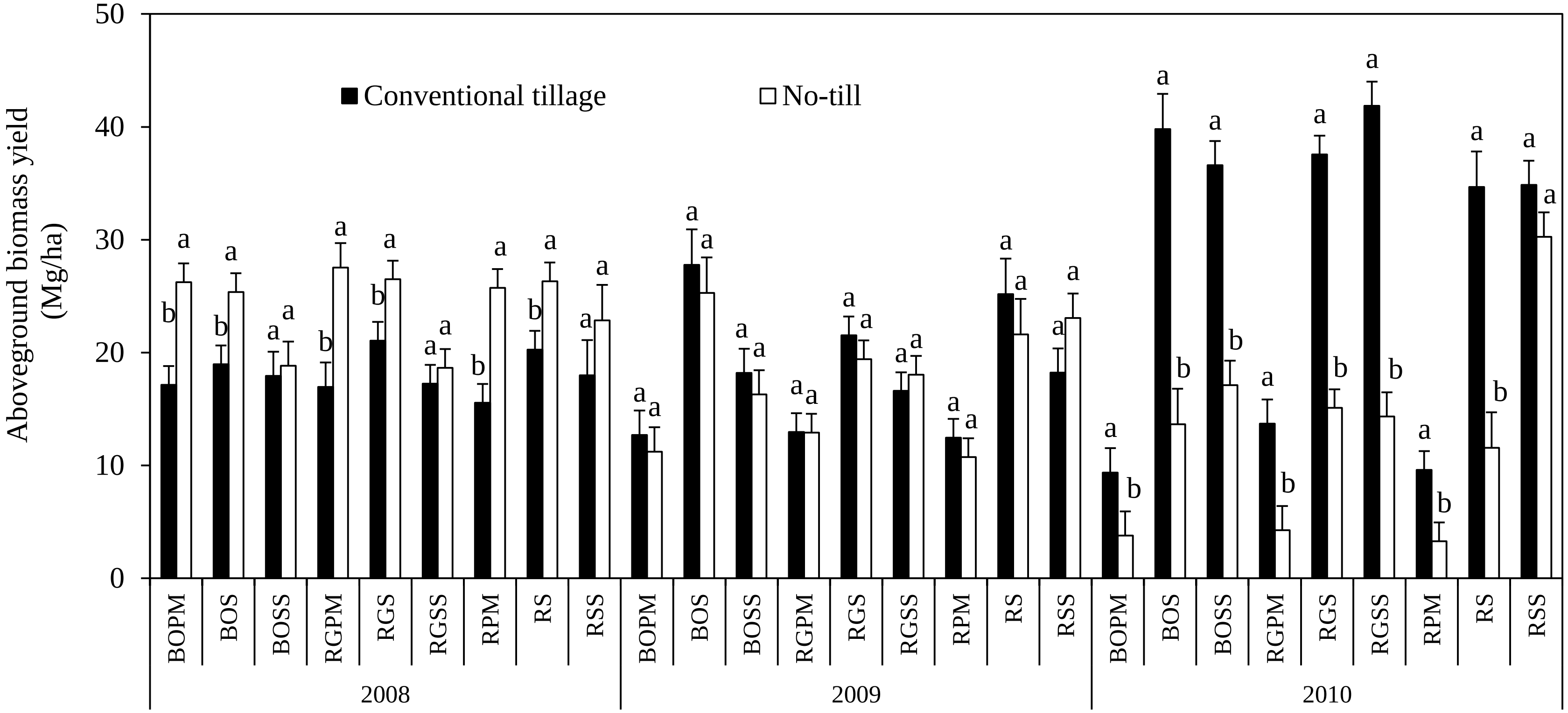

Figure 2-15 Total annual biomass yield for the nine double-cropping systems (black oat+pearl millet (BOPM), black oat+forage sorghum (BOS), black oat+sorghum-sudangrass (BOSS), rye+pearl millet (RPM), rye+forage sorghum (RS), rye+sorghum-sudangrass (RSS), ryegrass+pearl millet (RGPM), ryegrass+forage sorghum (RGS), ryegrass+sorghum-sudangrass (RGSS)) across years and tillage methods.

Means within each cropping system and year with different letters differ (*P*<0.05).

CHAPTER 3 LONG-TERM YIELDS AND SOIL IMPACTS OF GIANT REED, SWITCHGRASS AND MIMOSA GROWN FOR BIOMASS PRODUCTION IN ALABAMA

ABSTRACT

Encouraging progress towards commercialization of technologies that can convert cellulosic biomass into various liquid biofuels is increasing the need to develop economically viable and environmentally sustainable biomass supply chains. Giant reed (*Arundo donax* L.) and switchgrass (*Panicum virgatum* L.) have been extensively evaluated for biomass production in southern Europe and the US, respectively, both with very favorable results. Mimosa (*Albizia julibrissin* Durazz.) is a perennial, woody cellulosic energy crop that also has high yield potential. However, no long-term (> 10 years) data are available on stand longevity, yield response to critical factors such as rainfall, and soil impacts of these three energy crops. Therefore, the aim of this research was to determine long-term biomass yields and soil impacts of giant reed, mimosa and switchgrass as influenced by age of stand and rainfall in Alabama. Average annual dry biomass yields for mimosa, giant reed, and switchgrass were 40.09, 35.46 and 23.49 Mg ha^{-1}, respectively. In contrast to traditional summer row crops such as corn, cotton and soybeans, rainfall had relatively minor effects on biomass yields of these three perennial energy crops, and effects of stand age were also relatively small. Compared to adjacent bahiagrass (*Paspalum notatum* Flüggé), soil pH and soil Mg and Ca contents appeared to be lower after long term production of giant reed and switchgrass, but soil P and K contents were higher in giant reed plots.

Keywords: perennial cellulosic energy crops; giant reed; mimosa; switchgrass; cellulosic biomass production; long-term yield; soil impact

3.1 INTRODUCTION

Unlike first-generation feedstocks, next-generation feedstocks, i.e., ligno-cellulosic biomass, are derived from non-food sources, including wood, tall grasses, and forestry and crop residues. Compared to starch and sugar feedstocks, these materials can only be converted into liquid biofuels by more complex, advanced conversion technologies (Worldwatch Institute, 2007). Several technologies that are currently under development can use a wide range of cellulosic biomass feedstocks to produce various liquid biofuels, including cellulosic ethanol, green gasoline, diesel, and jet fuel (Kunkes et al., 2008; Regalbuto, 2009.). Commercial production of cellulosic drop-in replacement biofuels at a cost that is competitive with fossil fuels could occur within the next five years (Solecki et al., 2012). This progress, together with the demand to meet the ambitious national goal mandated by the Energy Independence and Security Act of 2007 of producing 16 billion gallons of biofuels from cellulosic biomass by 2022, emphasizes the need to develop economically viable and environmentally sustainable biomass supply systems.

Dedicated perennial cellulosic energy crops have received considerable research attention because of their high productivity and relatively low feedstock costs when compared to agricultural residues. Giant reed (*Arundo donax* L.), mimosa (*Albizia julibrissin* Durazz.) and switchgrass (*Panicum virgatum* L.) have shown substantial potential as dedicated cellulosic energy crops in the southeastern US. Switchgrass, a native perennial grass, has been extensively evaluated since the 1980's (Sanderson et al., 1996; McLaughlin and Walsh, 1998; Bransby et al., 1999; McLaughlin and Kszos, 2005). It is widely adapted to different climates and soil conditions because of its high levels of drought, cold and heat tolerance. After establishment, switchgrass can survive for a long time without the need for replanting. Among the cultivars that are commercially available, 'Alamo' was identified as the best in terms of yield potential in Texas and Alabama (Ocumpaugh et al. 2003; Crider, 2009). The typical yield of 'Alamo' switchgrass ranges from 16 to 35 Mg ha^{-1} y^{-1} (Huang, 2010).

Giant Reed is a perennial rhizomatous grass that is native to East Asia (Polunin and Huxley, 1987), occurring in both grasslands and wetlands, and it grows widely in the Mediterranean region. Unlike switchgrass, giant reed is sterile, so it must be propagated vegetatively from stem cuttings or rhizome pieces, or by micro-propagation. Giant reed has been extensively evaluated since the 1980's as a dedicated cellulosic energy crop for bioenergy production in southern Europe

(Vecchiet et al., 1996; Merlo et al., 1998; Hidalgo and Fernandez, 2001; Lewandowski et al., 2003). Biomass yields are typically 20-40 Mg ha^{-1} $year^{-1}$ without any fertilization after establishment (Angelini et al., 2005; Cosentino et al., 2005; Angelini et al., 2009). Mimosa was introduced to the US in 1745 and is grown primarily for use as an ornamental shade tree because it produces clusters of pink flowers in early summer. Like switchgrass, mimosa can be established from seed by using conventional seed drills and this greatly reduces the cost of establishment compared to crops that need to be planted with vegetative material. Unlike giant reed and switchgrass, mimosa is a legume species, which means that less nutrient inputs are necessary to support growth. In the late 1990s, Bransby et al. (2000) started to evaluate mimosa as a dedicated energy crop for cellulosic biomass production and reported a biomass yield of 37.3 Mg ha^{-1} yr^{-1} in Alabama.

Long-term biomass yield, stand longevity, and yield response to rainfall, and impacts on soil are important factors that influence the economic viability and environmental sustainability of cellulosic energy crops. However, no information is available on these factors as they relate to giant reed, mimosa and switchgrass. Therefore, this study aimed to provide long-term yield data for giant reed, mimosa and Alamo switchgrass grown in central Alabama, to evaluate soil impacts of the three dedicated energy crops after long-term biomass production, and to determine their yield responses to stand age and rainfall.

3.2 MATERIALS AND METHODS

3.2.1 Treatments and experimental design

Separate small plot experiments were conducted at the E.V. Smith Research Center, Plant Breeding Unit (PBU) and Field Crop Unit (FCU) of the Alabama Agricultural Experiment Station in central Alabama. Soils at PBU and FCU were a Wickham sandy loam (fine-loam, mixed, semiactive, thermic Typic Hapludult) and a Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudult), respectively. The sites were fallowed prior to planting giant reed, mimosa and switchgrass. Each experiment contained four replicate plots which were disked and leveled before establishment.

In the spring of 1988, Alamo switchgrass seed was drilled into prepared plots at the PBU with rows 20 cm apart at a seeding rate of 11.3 kg ha^{-1}. Plots were 1.5 m wide and 6.0 m long, and received 84 kg N ha^{-1} annually, split into two equal applications in March and again after the first harvest.

In the spring of 1989, mimosa seedlings were planted into prepared plots at the FCU at a density of 22,536 trees ha^{-1}, with 91 cm between rows. Plots were 3.6 m wide and 6.0 m long, and received no fertilizer.

In the spring of 1999, stem segments of giant reed that were approximately 1 m long were obtained from southern California and hand-placed end-to-end in four furrows 75 cm apart, and covered with 5-7.5 cm of soil in each prepared plot at the PBU. Plots were 3 m wide and 9 m long. They were fertilized with ammonium nitrate at a rate of 112 kg N ha^{-1} in May 2000, but received no fertilizer in subsequent years.

3.2.2 Data collection

After establishment, biomass from giant reed and mimosa were harvested in late October each year, and switchgrass was harvested in early August and again in late October. In each plot, giant reed plants in a 1-m^2 area and switchgrass plants in the middle two rows of each plot were cut to a 5-cm above ground level. Mimosa plants were cut to a 20 cm above ground level from the two center rows of each plot. All harvested plant material was weighed immediately to determine fresh weight in the field by using a hanging scale. Subsamples taken from each plot were dried at 60°C for 72 h for dry matter determination. Yield data for mimosa and giant reed were not recorded in 2004 and 2008, respectively. In early August of 2009, 2010 and 2011, fiberglass mesh sheets 0.58-m wide and 6.0-m long were placed between the central two rows of each mimosa plot to measure leaf residues that sloughed as the summer progressed (Plate 3-1). This material was dried at 60°C for 72 h for determination of dry matter, and its N content was measured by using a CNS Analyzer (LECO CNS-2000 Macro Analyzer; LECO Corp., St. Joseph, Michigan). In late fall 2012, one topsoil (0-20 cm) sample was taken from each switchgrass, giant reed and mimosa plot, and from adjacent areas colonized naturally with bahiagrass (*Paspalum notatum* Flüggé) that had been maintained by mowing periodically without removal of mowed material, and that had not been fertilized. These samples were used to determine soil pH, and soil extractable phosphorus (P), potassium (K), magnesium (Mg) and calcium (Ca) contents.

3.2.3 Data analysis

For each species, biomass yield was analyzed by means of analysis of variance using SAS v9.2 PROC MIXED procedure, assuming year as a fixed effect. Regression analyses of biomass yield against age and rainfall were performed for giant reed, mimosa and switchgrass by using the SAS PROC REG procedure, and also for yield of corn, cotton and soybeans obtained from variety trials (Glass et al., 2000-2011) with rainfall (March to September), to facilitate observational comparisons of crop responses to these variables. Since each perennial cellulosic energy crop was grown in a separate experiment, statistical comparisons across species were not valid. However, because these experiments were conducted for very long periods at the same time and location, and under the same weather conditions and similar soil conditions, observational differences (as opposed to statistical differences) are considered valuable, especially if they were large and consistent over time.

3.3 RESULTS AND DISCUSSIONS

3.3.1 Weather conditions

Growing season (March to October) rainfall was close to the long term average (824 mm) in all years from 1989 to 2011, except for very high rainfall in 1989, 2003 and 2009 and very low rainfall in 2000 and 2007 (Figure 3-1). Mean minimum air temperature in winter was -8.8 ℃ and mean maximum air temperature in summer was 37.5 ℃. Air temperature over 40 ℃ was recorded in the summer of

2000 and 2007, and a minimum air temperature of -12 ℃ was recorded in the winter of 2002.

3.3.2 Biomass yield

By fall of 2011 switchgrass, giant reed and mimosa plots had been harvested annually for 23, 13 and 22 years after establishment, respectively, and there was no visual evidence of stand deterioration in plots of all three species. Biomass yield for each of the three perennial energy crops varied over time ($P<0.05$). During the experimental years, highest yields for switchgrass, giant reed and mimosa were 34.6, 43.6 and 59.5 Mg ha^{-1}, respectively (Figure 3-2). Overall, mimosa provided the highest biomass yield, followed by giant reed and switchgrass, even though mimosa and giant reed received no maintenance fertilizer. Average annual dry biomass yields for mimosa from the eighth year to 2011, giant reed and switchgrass from the third year to 2011were 40.09, 35.46, and 23.49 Mg ha^{-1}, respectively. The remarkably high yields recorded for mimosa and giant reed suggest that both of these crops are able to fix N, even though giant reed is not a legume. In this case, endophytic bacteria and beneficial bacteria in the rhizosphere could be involved because several bacteria strains with strong N-fixing and/or P-solubilizing abilities have recently been isolated from giant reed in Alabama (Xu, 2011).

Biomass yield of giant reed increased slightly with age of stand, but yields of mimosa and switchgrass were not affected by stand age (Figure 3-3). This suggests that under the management regimes implemented in this study, stands of giant reed, switchgrass and mimosa can be expected to be productive for at least 13, 23 and 22 years after establishment, respectively, before needing to be re-established. Biomass production of the three perennial cellulosic energy crops was not affected by rainfall (Figure 3-4). Recognizing that rainfall in 2000 and 2007 was among the lowest on record (Figure 3-1), these results indicate that all three perennial crops evaluated in this study are extremely resistant to drought, thus minimizing weather-related losses. In contrast, yield of traditional row crops such as corn, cotton and soybeans was strongly influenced by growing season rainfall (Figures 3-5 and 3-6), indicating that production of all of these annual crops is subject to high weather-related risk. A probable reason for the high resistance of the perennial crops to drought is existence of a large, deep and permanent root system, whereas the extent of the root system of annual crops is relatively limited, especially in the first half of the growing season. For example, at the same location as this study Ma (1999) discovered that mature switchgrass roots extended to a depth of over 3 m in the soil.

3.3.3 Soil impacts

Soil pH and nutrients from giant reed, switchgrass and mimosa plots appeared to be different when compared to adjacent bahiagrass. Soil obtained from giant reed, mimosa and switchgrass plots had lower Mg and Ca than that obtained from bahiagrass (Table 3-1). In particular, topsoil extractable Mg for giant reed, switchgrass and mimosa was 21, 49 and 320 kg ha^{-1} lower than that for bahiagrass, respectively, and soil extractable Ca was 353, 339 and 631 kg ha^{-1} lower. Soil pH for switchgrass and giant reed was 0.3 and 1.5 units lower than that for bahiagrass, respectively, which is consistent with the level of soil extractable Ca. However, this trend was not evident for mimosa. Soil extractable P and K for switchgrass plots was 74 and 157 Mg ha^{-1} lower, respectively, than that for bahiagrass, and for mimosa the values were 15 and 71 Mg ha^{-1} lower. However, for giant reed soil extractable P and K were 121 and 30 kg ha^{-1} higher than for adjacent bahiagrass, respectively.

These apparent differences in soil impacts of the three perennial cellulosic energy crops evaluated in this study are likely related to differences among these species in morphology, physiology and association with beneficial microorganisms. For example, 80% of switchgrass roots are located in the topsoil (Bransby et al., 1998) and giant reed accumulates extremely large amounts of biomass in rhizomes, which are also located in the topsoil (Huang and Bransby, 2010). However, since mimosa is a woody species, its roots are likely distributed more evenly in the soil profile. In addition, mimosa appears to shed a much larger amount of senesced leaf material (Table 3-2) in late summer compared to giant reed and switchgrass. Finally, since mimosa is a legume it would be expected to fix N, while giant reed and switchgrass are known to have associations with beneficial microorganisms (Xu, 2011).

3.4 CONCLUSIONS

Data collected in this study suggest that the following conclusions can be drawn:

- long term biomass yields of mimosa and giant reed appear to be considerably higher than that of Alamo switchgrass;
- if managed according to procedures followed in this study, mimosa and switchgrass stands in the southeastern US should remain productive for 20 years or more, and giant reed for 13 years or more;
- unlike yield of traditional summer row crops such as corn, cotton and soybeans, biomass yield of the three perennial cellulosic energy crops evaluated in this study were affected very little by drought; and
- preliminary soil data collected in this study suggest that detailed research on nutrient cycling for giant reed, switchgrass and mimosa is needed to develop soil management practices that will ensure sustainable long term biomass production.

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Table 3-1 Soil pH and P, K, Mg and Ca content for giant reed, switchgrass, mimosa and adjacent bahiagrass in 2012.

Treatments	Soil pH	Phosphorous	Potassium	Magnesium	Calcium
		kg ha^{-1}			
Giant reed	4.6 (0.2) b	242 (25) a	219 (37) a	93 (20) a	326 (100) b
Adjacent bahiagrass	6.1 (0.1) a	121 (12) b	189 (37) a	114 (20) a	679 (12) a
Switchgrass	5.8 (0.2) a	47 (8) b	32 (2) b	65 (9) b	340 (48) b
Adjacent bahiagrass	6.1 (0.1) a	121 (12) a	189 (37) a	114 (20) a	679 (12) a
Mimosa	6.7 (0.1) a	25 (6) a	89 (7) b	280 (10) a	1404 (85) a
Adjacent bahiagrass	6.5 (0.1) a	40 (6) a	160 (10) a	600 (174) a	2035 (551) a

Values in parentheses are standard errors.

Means within each perennial energy crop species and each column with different letters differ (P<0.05).

Table 3-2 Yield and N content of leaf material shed by mimosa during the growing season in 2009, 2010 and 2011.

Year	Residue biomass yield (Mg ha^{-1})	Nitrogen content (%)	Nitrogen addition by residue (kg N ha^{-1})
2009	1.30 (0.13)	2.26 (0.09)	29.38
2010	1.37 (0.19)	2.38 (0.18)	32.61
2011	2.30 (0.65)	2.17 (0.10)	49.91
Average	1.66	2.27	37.3

Values in parentheses are standard deviations.

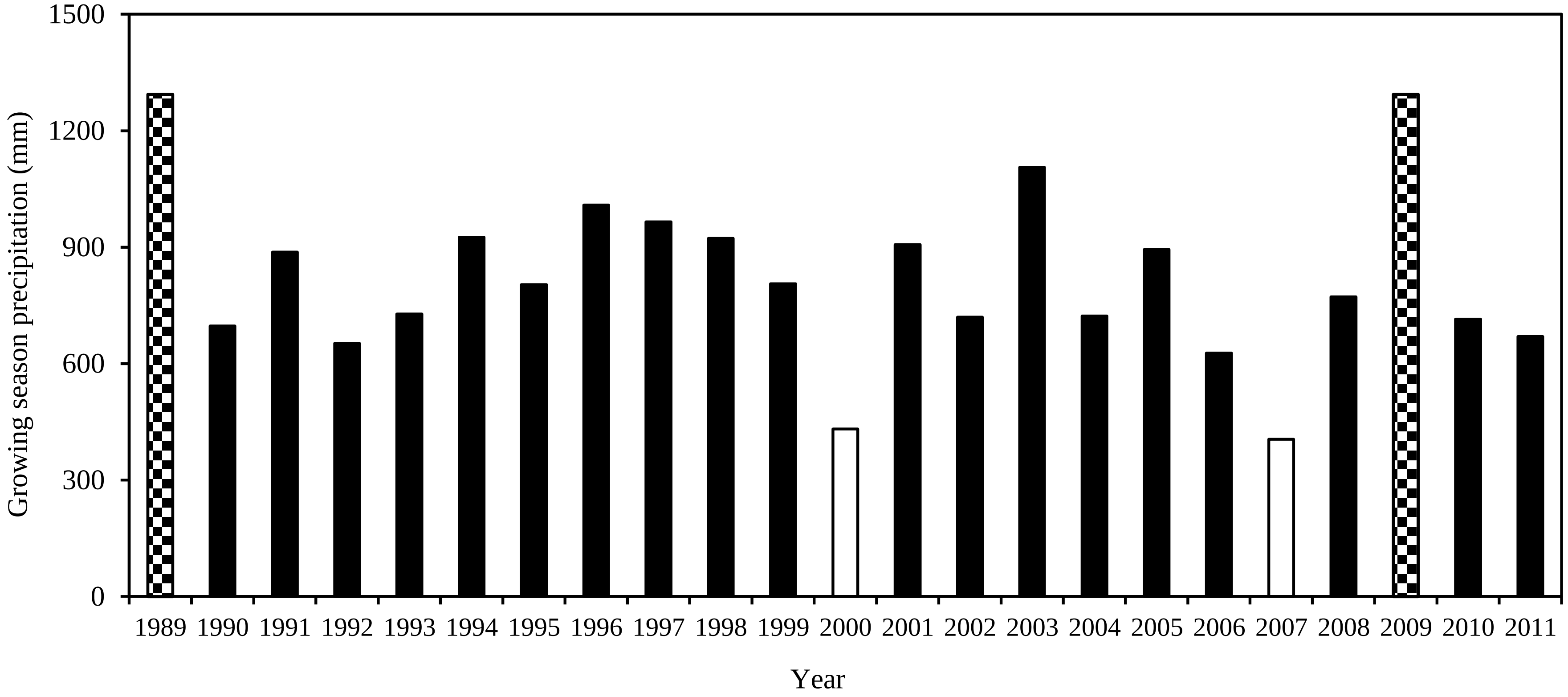


Figure 3-1 Growing season (March to October) precipitation from 1989 to 2011.

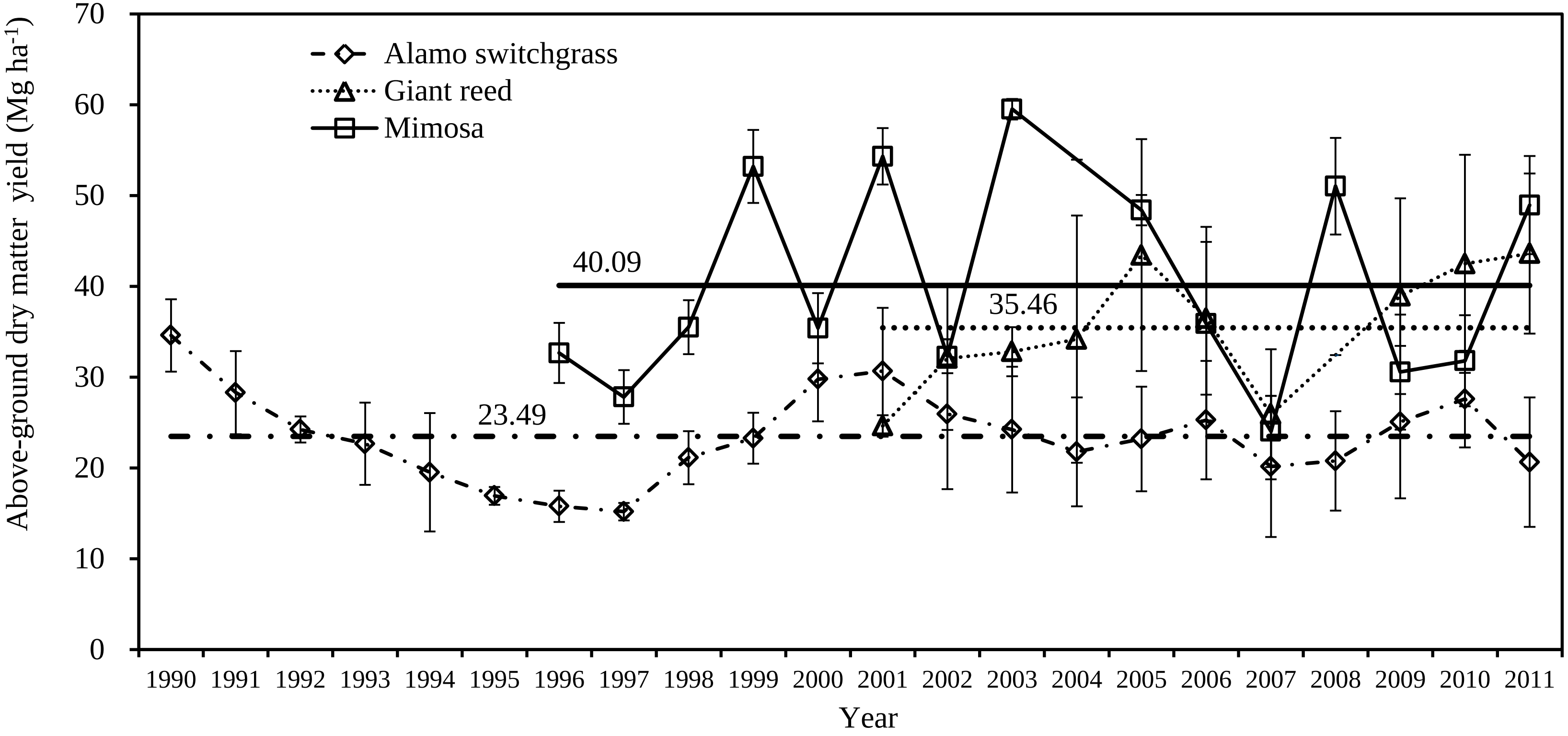


Figure 3-2 Annual biomass yield of mimosa from the eighth year to 2011, giant reed and switchgrass from the third year to 2011, with the long term mean indicated as a horizontal line.

Vertical bars represent the standard deviation.

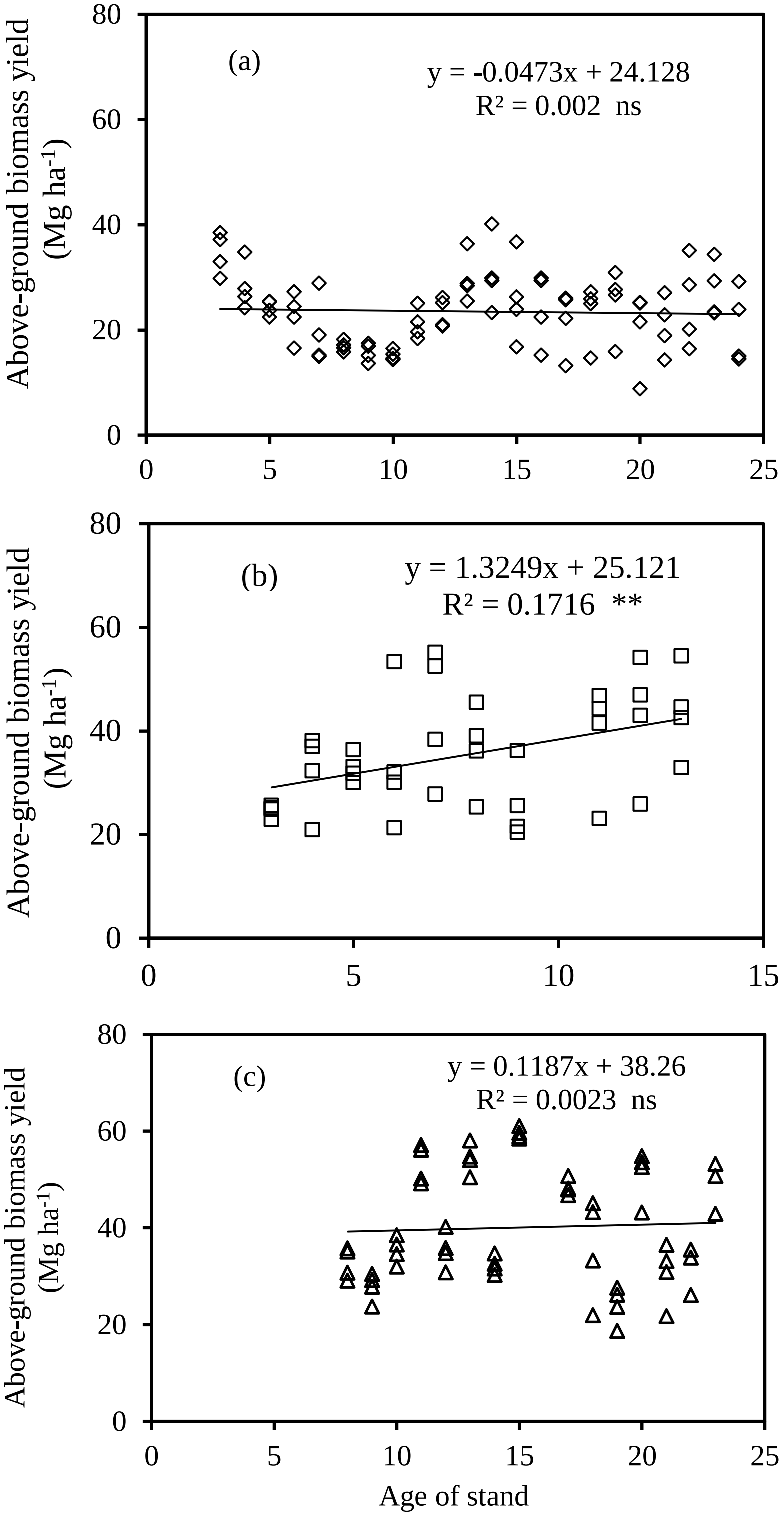


Figure 3-3 Effect of stand age (x) on yield (y) of switchgrass (a), giant reed (b) and mimosa (c).

ns = non-significant. ** Significant at the 0.01 probability level.

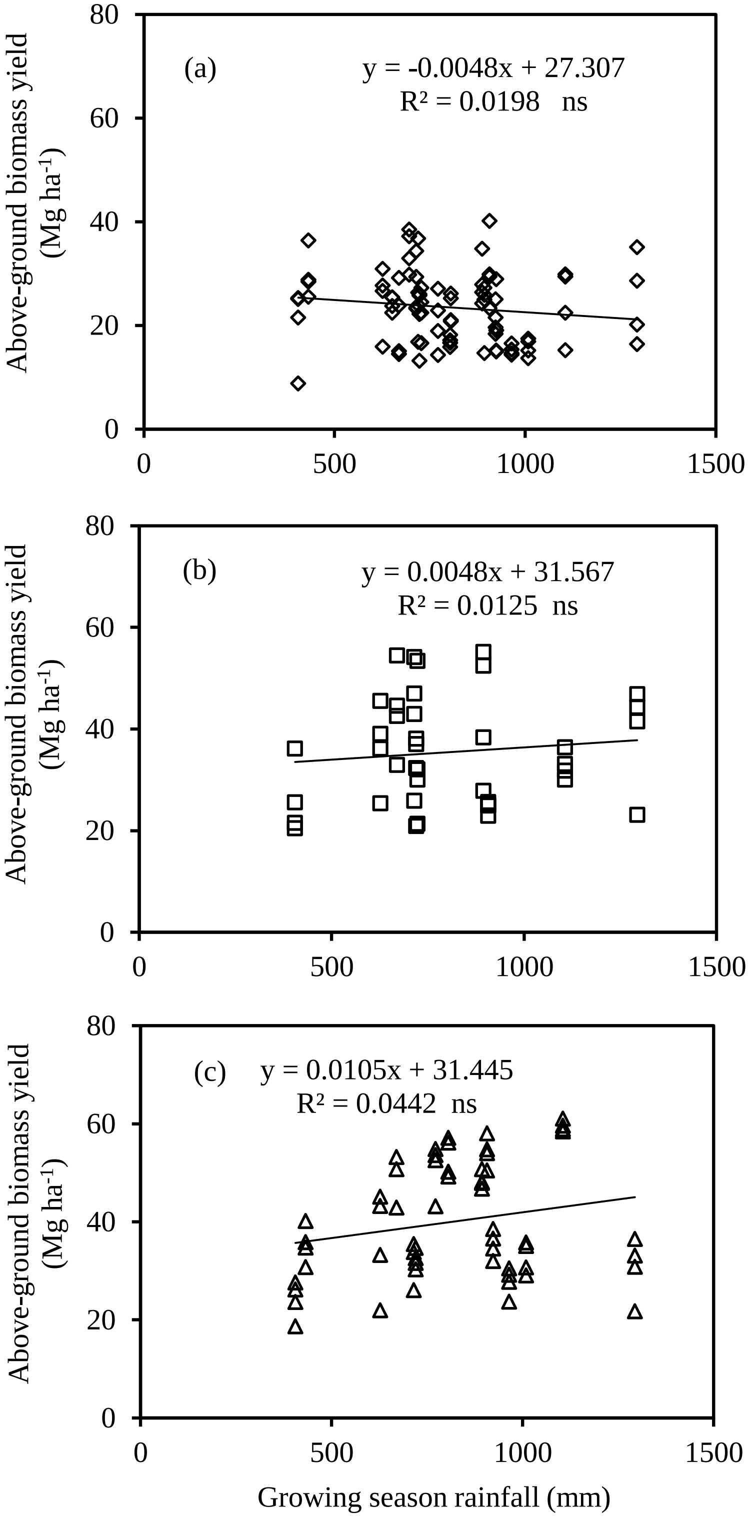
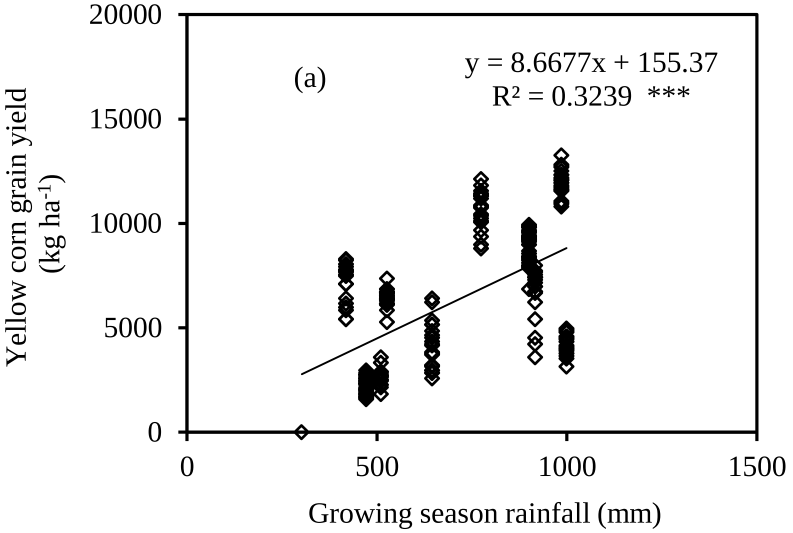


Figure 3-4 Effect of growing season rainfall (March to October) (x) on biomass yield (y) of switchgrass (a), giant reed (b) and mimosa (c).

ns = non-significant.



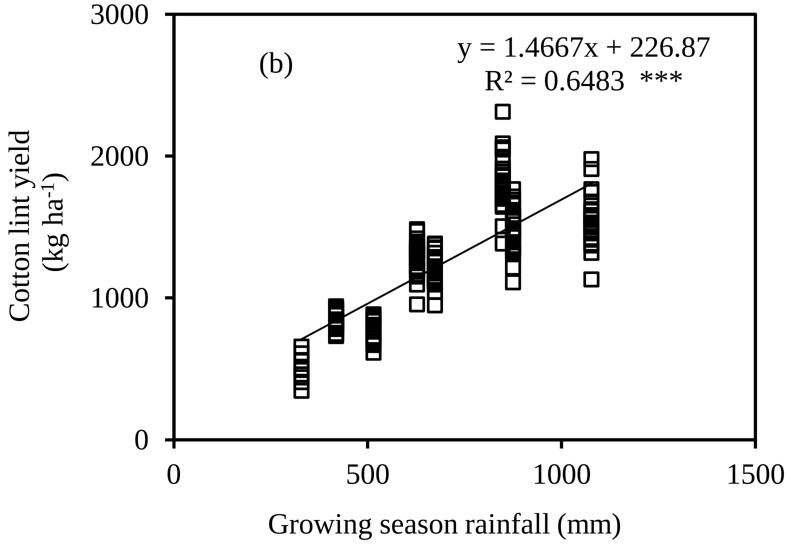


Figure 3-5 Effect of growing season rainfall (March to September) (x) on grain yield (y) of yellow corn (a) and cotton lint yield (y) (b) grown in central Alabama during the 2000-2011period.

*, **, *** Significant at the 0.05, 0.01 and 0.001 probability level, respectively.

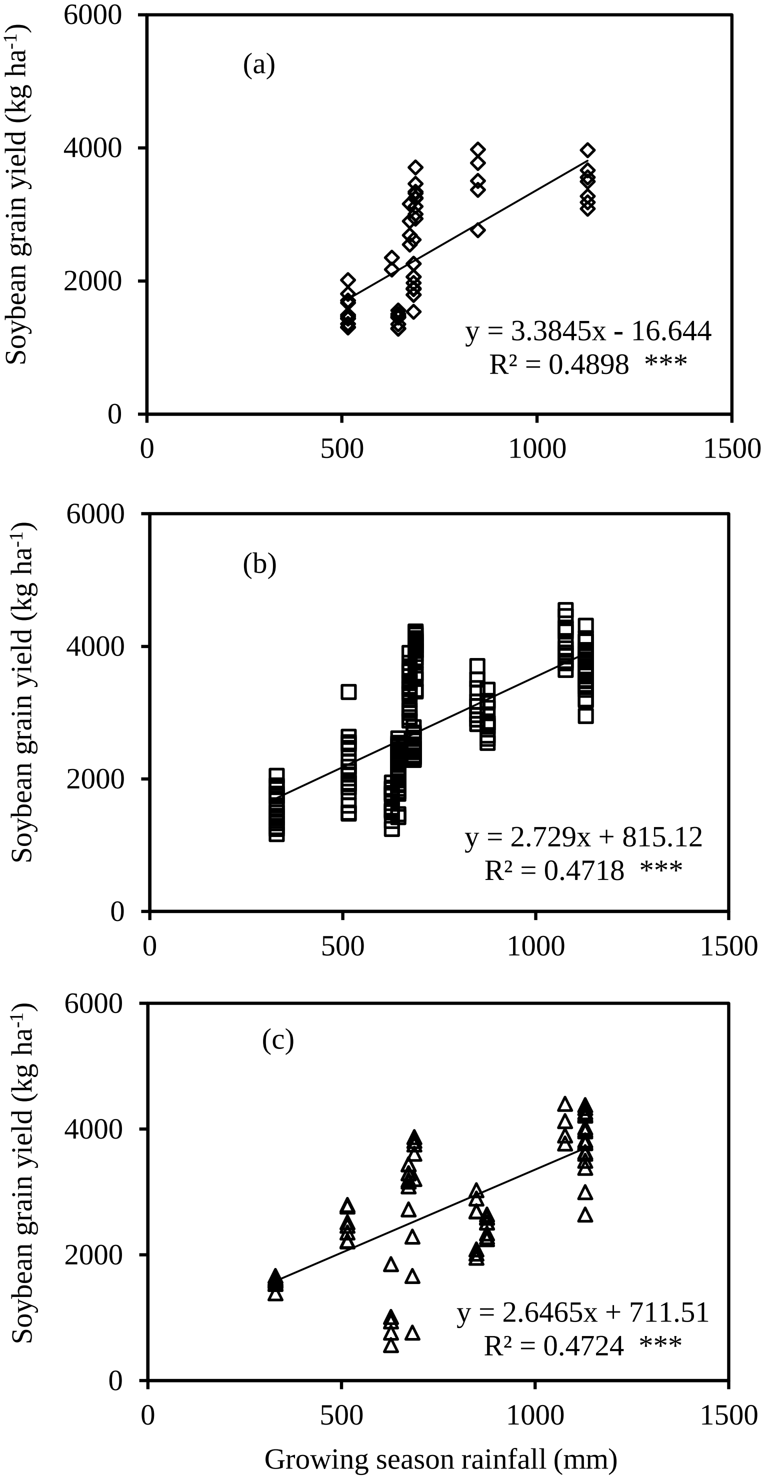


Figure 3-6 Relationship between rainfall (March to September) (x) and grain yield (y) of soybean cultivars in maturity group IV (a), V (b), and VI (c) grown in central Alabama during the 2000-2011 period.

*, **, *** Significant at the 0.05, 0.01 and 0.001 probability level.

Plate 3-1 Mimosa leaf residue collection at the end of the 2009 growing season.

CHAPTER 4 EFFECTS OF NITROGEN FERTILIZATION AND SUBSOILING ON BIOMASS YIELD OF ESTABLISHED SWITCHGRASS

ABSTRACT

Switchgrass (*Panicum virgatum* L.) has been extensively evaluated in the US as a potential cellulosic energy crop, and ‘Alamo’ is one of the highest yielding switchgrass cultivars in Southeast. Several studies indicated a positive response in biomass yield of Alamo switchgrass to added nitrogen fertilizer, but this response varies greatly, depending on climate and site. Moreover, information is not available on possible benefits of subsoiling compacted soil (which is common in the Southeast) under established switchgrass stands with a subsoiling plough. Therefore, the objectives of this study were to evaluate the effects of N rate and subsoiling on biomass yield of established Alamo switchgrass in central Alabama. A declining positive response was observed for biomass yield as N rate increased from 0 to 112 kg N ha^{-1}, but there was no yield response to subsoiling. Average biomass yields for 0, 56 and 112 kg N ha^{-1} over a three-year period were 4.85, 7.80 and 9.45 Mg ha^{-1}, respectively. Assuming a biomass price of at least \$44.1 Mg^{-1}, application of N fertilizer was economically viable.

Keywords: ‘Alamo’ switchgrass, nitrogen fertilizer, subsoiling, biomass yield.

4.1 INTRODUCTION

Switchgrass (*Panicum virgatum* L.) is a native, warm-season perennial grass that has been extensively evaluated as a cellulosic energy crop in the US. It is popular because of its wide geographic adaptation, high biomass yield, desirable fuel characteristics, and compatibility with conventional farm practices (Sanderson et al., 1996; McLaughlin and Walsh, 1998; Bransby et al., 1999; Schmer, M. R., et al. 2006; Lemus et al., 2008).

There are two ecotypes of switchgrass that facilitate its wide geographic adaptation: lowland ecotypes are heat and drought tolerant, and suitable for the Mid-west and southeastern US, whereas upland ecotypes are more cold tolerant, and suitable for the northern US, but are less productive (Bransby et al., 1999; Cassida et al., 2005 (a) and (b)). Currently, many commercial switchgrass cultivars are available, including two lowland types, ‘Alamo’ and ‘Kanlow’, and six upland types, ‘Cave-in-Rock’, ‘Blackwell’, ‘Summer’, ‘Trailblazer’, ‘Pathfinder’, and “Kansas-Native’.

Switchgrass cultivars differ greatly in biomass yield. Sanderson et al. (1996 and 1999) found that biomass yields of lowland cultivars including Alamo switchgrass are better than upland yields in Texas and Virginia. “Alamo” switchgrass was also identified by Ocumpaugh et al. (2003) as the best variety in long-term studies in Texas. Furthermore, the results from a long-term cultivar trial of eight cultivars of switchgrass in Alabama listed above also demonstrated that lowland cultivars provided substantially higher biomass yields than upland cultivars: in this experiment, Alamo switchgrass was the best cultivar with highest average biomass yield of 23.4 Mg ha^{-1}over a 20-year period and yield, was not influenced by rainfall and plot age (Crider, 2009; Huang, 2010). For these reasons, Alamo switchgrass has received more research attention than other cultivars for production of cellulosic biomass in the southeastern US.

Muir et al. (2001) found that biomass production of Alamo switchgrass grown without N fertilizer tended to decline over time in Texas. Several other studies indicated a positive response of Alamo switchgrass yield to added N fertilizer in Texas and Tennessee, but based on results from these studies, different N rates were recommended (Reed et al., 1995; Muir et al., 2001; Charles et al., 2011). Reed et al. found that biomass yield of Alamo switchgrass was maximized at about 224 kg N ha^{-1} in Beeville, Texas on a Wind thorst fine sandy loam soil, whereas Muir et al. reported a maximum yield of 22.5 Mg ha^{-1} with 168 kg N ha^{-1} at Stephenville on the same soil type. This reflects variation in response of Alamo yield to N fertilization across different climates and sites. Furthermore, N fertilization must be optimized to balance the cost of fertilizer application and the revenues obtained from improved biomass yield. A projected economic optimum N fertilization level for Alamo switchgrass was about 120 kg N ha^{-1} even if maximum yield was observed at higher rates, since biomass yield responses are typically quadratic when high rates of N are tested (Ocumpaugh et al., 2003).

Many soils in the Southeast are prone to compaction, suggesting that subsoiling might improve crop production. For instance, Izumi et al. (2009) found in a no-till wheat-soybean rotation, wheat grain yield increased after subsoiling Since switchgrass is a perennial it is possible that soil compaction could be more limiting to growth than for annual crops due to complete elimination of tillage, and this suggests that subsoiling might increase biomass yield of established switchgrass stands. However, no information on this topic is available.

Therefore, the objective of this study was to evaluate the yield response of a 17-year old Alamo switchgrass stand to added N fertilizer and subsoiling in central Alabama.

4.2 MATERIALS AND METHODS

4.2.1 Treatments and experimental design

The experiment was conducted at the E.V. Smith Research Center, Field Crop Unit of the Alabama Agricultural Experiment Station near Shorter, Alabama. Soil at the site was classified as a Norfolk fine sandy loam (fine, loamy, siliceous, thermic Typic Kandiudult). In April 1992, Alamo switchgrass seed had been drilled 12 cm deep into plots in rows 20 cm apart at a seeding rate of 11.3 kg ha^{-1}. Plots were fertilized with 56 kg N ha^{-1} at planting, but after establishment received limited management and no fertilizer or irrigation for several years prior to the current experiment. The experiment was laid out in a randomized complete block factorial design with two treatments: subsoiling or no subsoiling, and one time application of 0, 56, or 112 kg N ha^{-1} each year over a three-year period starting in 2009. Plots measured 3 × 9 m, and were blocked according to pre-treatment yields that were obtained in fall of 2008. Plots were subsoiled to a depth of 25 cm in early March each year before switchgrass initiated growth by using a KMC subsoiler (Kelley Manufacturing Co., Tifton, Georgia) with blades set 60 cm apart (Plate 4-1). In early June 2009, 2010 and 2011, each N treatment plot received a single application of ammonium nitrate at its designated rate.

4.2.2 Data collection

At the end of each growing season (October) the center two rows of each plot were cut to a 5-cm stubble height with a sickle bar mower. Fresh biomass weight from the harvested area in each plot was measured using a hanging scale in the field. Biomass subsamples taken from each plot were dried at 60°C for 48 h for dry matter determination and border rows were harvested right after sampling.

4.2.3 Data analysis

Analysis of variance was conducted using SAS v9.2 PROC MIXED procedure. Block was considered as a random factor, while year was considered a fixed factor. The critical *P*-value of 0.10 was used as cutoff for testing fixed effects, and determination of differences in least-squares means was based on adjusted *P*-value obtained by using the option ADJUST=SIMULATE in the LSMEANS statement.

To determine the economic implications of N fertilization the N cost per additional Mg of biomass produced by N fertilization was calculated by dividing the cost of fertilizer per hectare by the difference in biomass yield between fertilized and unfertilized switchgrass for any particular fertilization level. Based on 2010 USDA data for fertilizer prices (USDA-ERS, 2010), a price of \$1.30 kg^{-1} N was assumed.

4.3 RESULTS AND DISCUSSIONS

4.3.1 Weather conditions

Rainfall was close to the long-term average in the 2010 and 2011 growing seasons, but very high in 2009 (Table 4-1). The summer (March to October) growing season rainfall of 2009 was 1293 mm, which is 366 mm higher than the average of past 10 years.

4.3.2 Biomass yield

Biomass yield increased with N rate in all three years (Figure 4-1), but this response varied by year, indicating an N rate × year interaction. In particular, the response to N fertilization increased with time (Figure 4-2). This trend was not positively related to rainfall (Table 4-1), but might have been a cumulative response to N as a result of all plots receiving no N fertilization for several years prior to initiation of this experiment. When compared to the control (0 kg N ha^{-1}), applying 56 kg N ha^{-1} increased biomass yield by a range of 34.6% to 72.8% in the three-year period, and applying 112 kg N ha^{-1} by a range of 44.5% to 146.7%. This positive response of Alamo biomass yield to added N fertilizer was consistent with the findings of Reed et al. in 1995 and Muir et al. in 2001 in Texas. In addition, a distinct change in leaf color from light green to dark green was also observed on fertilized plots 10 days after fertilization, suggesting that control plots were severely deficient in N (Plate 4-2).

Although subsoiling has been reported to increase yields in some traditional crops such as wheat and cotton (Izumi et al., 2009; Raper et al., 2007), it did not affect biomass yield of switchgrass in this experiment. A possible explanation for this is that subsoiling might have resulted in root damage of switchgrass. Although Alamo switchgrass has a well-developed deep root systems reaching to 3 m below the soil surface, more than 78% of roots are located at soil depth of 0-30 cm (Ma, 1999). Even though switchgrass was planted in rows in this experiment, individual plants spread outward between rows, making root damage by subsoiling possible.

The cost of N per additional Mg of biomass produced by N fertilization decreased substantially with time, and ranged between \$19.15 and \$65.00 (Table 4-2). Although N cost per Mg of switchgrass biomass produced was similar with the two N rates, a greater risk is assumed with the higher N rate. Therefore, the price of switchgrass biomass and the volatility of the market, would have a significant impact on the decision to use a higher N rate.

4.4 CONCLUSIONS

Results from this study allowed the following conclusions to be drawn:

- biomass yield of a previously unfertilized mature stand of Alamo switchgrass increased with N fertilization up to 112 kg N ha^{-1};
- this response increased over time, and was not related to precipitation;
- assuming that the response of biomass yield to N fertilization was cumulative, results from the second and third years of this study suggest that if sale price of biomass was above \$33.36 Mg^{-1}, fertilization with N was justified from an economic point of view; and
- subsoiling had no effect on biomass production.

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Table 4-1 Monthly and growing season precipitation 2007-2010.

Year	Precipitation (mm)								
	Month								Summer growing season
	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	
2009	244	109	262	100	75	192	148	164	1293
2010	124	32	176	56	128	122	46	31	716
2011	139	49	56	57	204	16	124	25	670
Average (1997-2006)	181	129	92	141	118	97	104	65	927

Table 4-2 Cost of N per additional Mg of biomass by year and level of N fertilization.

N rate (kg ha^{-1})	Cost of N per additional Mg of biomass ($)		
	2009	2010	2011
56	41.80	21.80	19.31
112	65.00	33.36	19.15

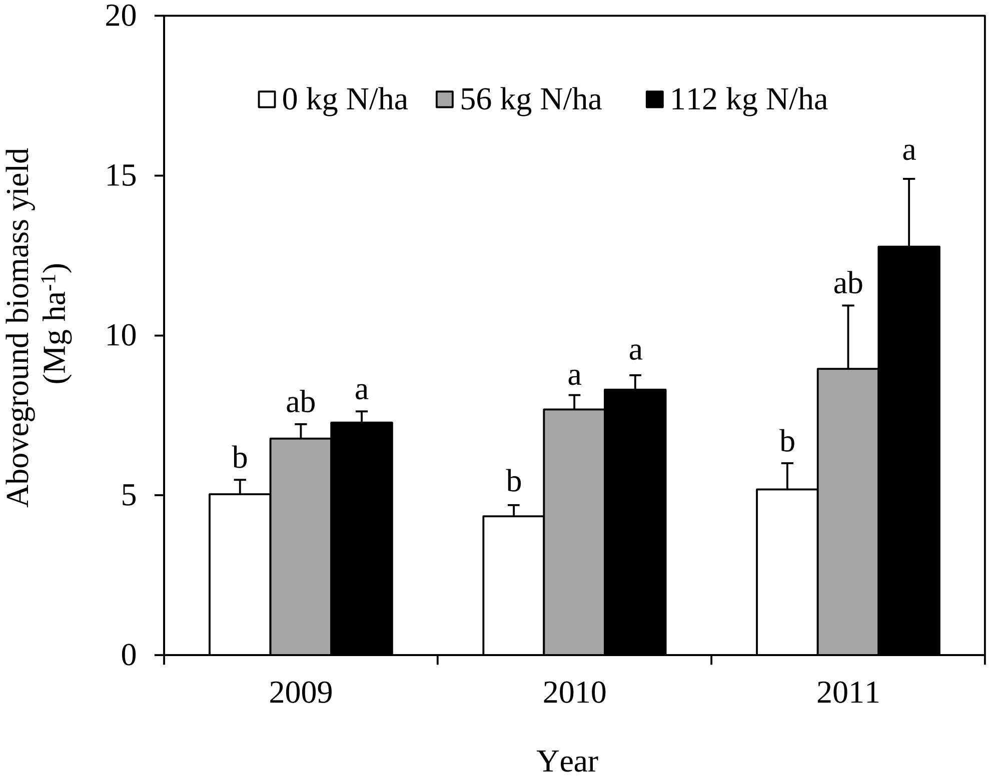

Figure 4-1 Biomass yield of Alamo switchgrass under different N rates across years. Different letters within each year indicate significant differences (*P*<0.10).

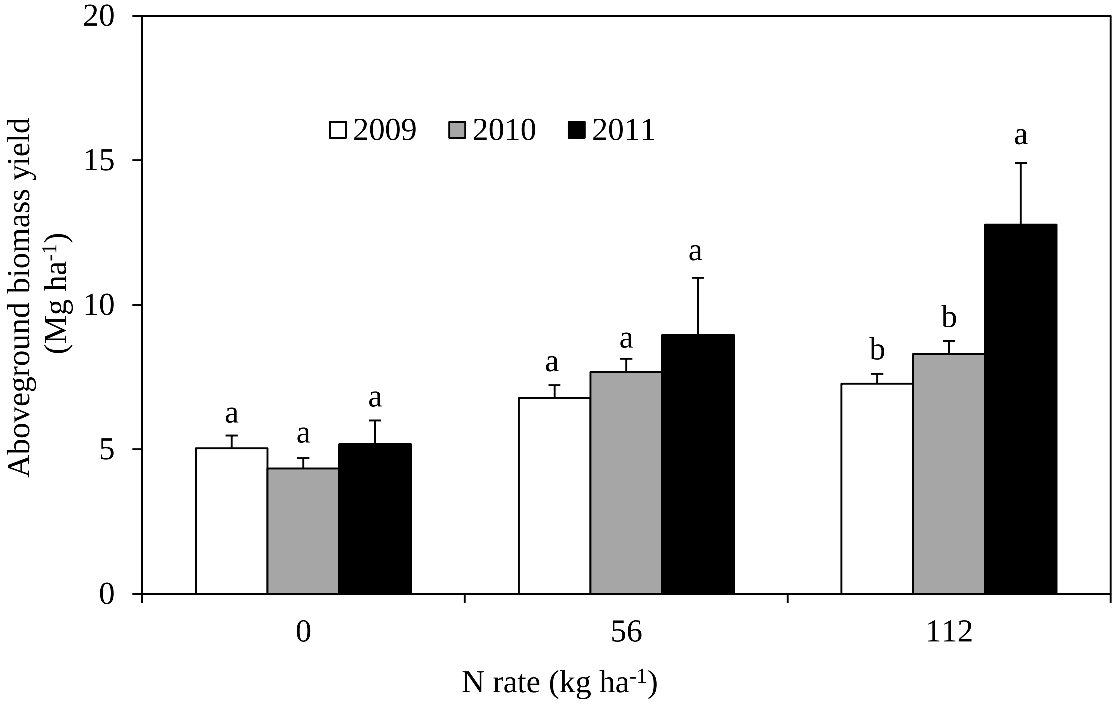

Figure 4-2 Biomass yield of Alamo switchgrass sunder the same nitrogen fertilizer treatment over time.

Different letters within each nitrogen treatment indicate differ (*P*<0.10).

(a) (b)

Plate 4-1 Alamo switchgrass with subsoiling (a) and without subsoiling (b) in June 2011.

Plate 4-2 Alamo switchgrass 10 days after applying N treatments in June 2011.

CHAPTER 5 EFFECTS OF NITROGEN FERTILIZATION AND INTERSEEDING CRIMSON CLOVER ON BIOMASS YIELD OF ESTABLISHED SWITCHGRASS

ABSTRACT

Switchgrass (*Panicum virgatum* L.) has been extensively evaluated in the US as a potential cellulosic energy crop. ‘Alamo’ is one of the best switchgrass cultivars in the southeastern region. Nitrogen fertilizer is recognized as an important management practice for optimizing biomass production of switchgrass. Several studies indicated a positive response in biomass yield of ‘Alamo’ switchgrass to added nitrogen fertilizer, but this response varied greatly depending on climate and site history. Moreover, information on the effect of replacing nitrogen fertilization with intercropping a winter legume on switchgrass biomass production is not available. Therefore, the objective of this study was to evaluate the effects of nitrogen fertilization and intercropping crimson clover on biomass yield of switchgrass in central Alabama. Biomass yield showed a declining, positive response with an increase of nitrogen rate from 0 to 224 kg N ha^{-1}. Average biomass yields for 0, 56 and 112 kg N ha^{-1} over a three-year period were 8.64, 13.32 and 16.14Mg ha^{-1}, respectively. Interseeding crimson clover (*Trifolium incarnatum* L.) did not increase biomass yield.

Keywords: ‘Alamo’ switchgrass, nitrogen, winter legume, biomass yield.

5.1 INTRODUCTION

Switchgrass (*Panicum virgatum* L.) is a native, warm-season perennial grass that has been selected as a model herbaceous energy crop in the US. It has wide geographic adaptation, high biomass yield potential, and is compatibility with conventional farm practices (Sanderson et al., 1996; McLaughlin and Walsh, 1998; Bransby et al., 1999).

There are two ecotypes of switchgrass: lowland ecotypes are heat and drought tolerant, and suitable for the Midwest and southeastern United States, whereas upland ecoptypes are cold tolerant, and suitable for the Northern US (Bransby et al., 1999; Cassida et al., 2005 (a) and (b)). Currently, many switchgrass cultivars are commercially available, including two lowland types, ‘Alamo’ and ‘Kanlow’, and six upland types, ‘Cave-in-Rock’, ‘Blackwell’, ‘Summer’, ‘Trailblazer’, ‘Pathfinder’, and “Kansas-Native’. In 1996 and 1999, Sanderson et al. found that biomass yields of lowland cultivars including Alamo switchgrass were better than upland yields in Texas and Virginia. Moreover, the results from a long-term cultivar trial in Alabama with the eight cultivars listed above also showed that lowland cultivars provided higher biomass yields than upland cultivars, and that Alamo switchgrass was the best cultivar with the highest average biomass yield of 23.4 Mg ha^{-1}over a 20-year period (Crider, 2009; Huang, 2010), and that Alamo yields were not affected by rainfall or plot age. Muir et al. (2001) found that biomass production of Alamo switchgrass without N applied tended to decline over time in Texas. Several studies indicated a positive response of Alamo switchgrass yield to added N fertilizer in Texas and Tennessee, but different N rates were recommended for maximum yield production (Reed et al., 1995; Muir et al., 2001; Charles et al., 2011). Reed et al. found that biomass yield of Alamo switchgrass was maximized at about 224 kg N ha^{-1} in Beeville, Texas on a Windthorst fine sandy loam soil, whereas Muir et al. reported a maximum yield of 22.5 Mg ha^{-1} at 168 kg N ha^{-1} at Stephenville on the same type of soil. This reflects variation in response of Alamo yield to climate and site.

The projected economic optimum N fertilizer level for Alamo switchgrass was about 120 kg N ha^{-1} even if maximum biomass yields occur at higher rates, since responses are typically quadratic when high rates are used (Ocumpaugh et al., 2003).

Over-application of N fertilizer can cause environmental problems such as pollution of soil and water. These negative effects of N fertilizer might be avoided by inter-seeding a winter legume to supply the required N. However, no information on this possibility is available. Therefore, the objective of this experiment was to evaluate the yield response of a 2-year old 'Alamo' switchgrass stand to added N fertilizer and inter-seeded crimson clover (*Trifolium incarnatum* L.) in central Alabama.

5.2 MATERIALS AND METHODS

5.2.1 Treatments and experimental design

This experiment was located at the E.V. Smith Research Center, Plant Breeding Unit of the Alabama Agricultural Experiment Station near Tallassee, Alabama. Soil at the site was classified as a Wickham sandy loam (fine-loam, mixed, semiactive, thermic Typic Hapludult). The field was fallowed in the year prior to the planting of Alamo switchgrass. In July 2007, Alamo seed was drilled into plots in rows 20 cm apart at a seeding rate of 11.3 kg ha^{-1}. Plots had received no fertilizer or irrigation prior to the experiment which was laid out in a randomized complete block design with three treatments in 2009 (0, 56, and 112 kg N ha^{-1}), four treatments in 2010 (0, 56, and 112 kg

N ha^{-1}, and interseeded crimson clover) and six treatments in 2011 (0, 56,112, 168 and 224 kg N ha^{-1}, and interseeded crimson clover). Blocks and plots were separated by 1 m and 2 m wide alleys, respectively. Plots were 1.5 m wide and 9.0 m long. In early June 2009, 2010 and 2011, each N treatment plot received a single application of ammonium nitrate at its assigned rate. Crimson clover was planted between switchgrass rows in separate plots in late November 2009 and 2010 after removing aboveground biomass, and received no N fertilizer.

5.2.2 Data collection

At the end of each growing season (October), biomass was harvested from the central two rows of each plot to a 5-cm stubble height with a sickle bar mower. Fresh biomass weight from the harvested area in each plot was measured using a hanging scale in the field. Biomass subsamples taken from each plot were dried at 60°C for 48 h for dry matter determination. Border rows were harvested right after sampling.

5.2.3 Data analysis

Analysis of variance was conducted using SAS v9.2 PROC MIXED. Block was considered a random factor, while year was considered a fixed factor. The critical *P*-value of 0.10 was used as cutoff for testing fixed effects, and determination of differences in least-squares means was based on adjusted *P*-value obtained by using the option ADJUST=SIMULATE in the LSMEANS statement. Regression analysis of biomass yield in 2011 against N rate was performed by using the SAS v9.2 PROC REG procedure.

To determine the economic implications of N fertilization the N cost per additional Mg of biomass produced by N fertilization was calculated by dividing the cost of fertilizer per hectare by the difference in biomass yield between fertilized and unfertilized switchgrass for any particular fertilization level. Based on 2010 USDA data for fertilizer prices (USDA-ERS, 2010), a price of \$1.30 kg^{-1} N was assumed. Maximum economic yield (MEY) of Alamo switchgrass for nitrogen rates in 2011 was calculated when assuming biomass price at \$65 and \$100 Mg^{-1}.

5.3 RESULTS AND DISCUSSIONS

5.3.1 Weather conditions

Rainfall was close to the long-term average in the 2010 and 2011 growing seasons, but very high in 2009 (Table 5-1). The summer (March to October) growing season rainfall of 2009 was 1293 mm, which is 366 mm higher than the average of past 10 years.

5.3.2 Biomass yield

Biomass yield increased with level of N fertilizer in each of the three years of the study, but the relative effect of N fertilization varied by year, indicating a year x N level interaction ($P<0.10$) (Figures 5-1 and 5- 2). Differences in biomass response to N fertilization among years did not seem to be related to total growing season rainfall (Table 5-1). In 2011, when the two additional levels of N fertilization were added, biomass yield increased quadratically with increasing N, and maximum yield of 14.9 Mg ha^{-1} was observed at an N rate of 168 kg N ha^{-1} (Figure 5-3). Maximum economic yields were achieved at 167 and 189 kg N ha^{-1} when biomass prices were set at \$65 and \$100 Mg^{-1}, respectively (Table 5-2). In addition, a difference in leaf color from light green to dark green was also observed 10 days after N fertilization as N rates increased from 0 to 50 kg N ha^{-1} (Plate 5-1), suggesting that plots that received no N fertilization were severely deficient in N.

Interseeding crimson clover decreased biomass yield of Alamo switchgrass by 30.2% in 2010, but this difference was smaller in 2011 (Figure 5-4). Possible reasons for this is that crimson clover may compete with switchgrass in the early part of the season (Plate 5-2), and/or drilling the crimson clover seed might have damaged the root system of the switchgrass. This suggests that investigation of the effects of a wider switchgrass row spacing and/or harvesting crimson clover prior to initiation of switchgrass growth in the spring may be justified.

The cost of N per additional Mg of biomass produced by N fertilization decreased slightly from 2009 to 2010, but increased in 2011, and ranged between \$11.65 and \$24.19 (Table 5-3).

5.4 CONCLUSIONS

Results from this study allowed the following conclusions to be drawn:

- biomass yield of switchgrass increased with level of N fertilization, but the relative increase varied by year, was not related to rainfall or time, and was different from another study conducted at the same time and location, but on a different soil type;

- results suggest that if sale price of biomass was above \$24.19 Mg^{-1}, fertilization with N was justified from an economic point of view; and
- interseeding crimson clover decreased biomass yield of switchgrass relative to the 0 kg N ha^{-1} control.

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Table 5-1 Monthly and growing season precipitation 2007-2010.

Year	Precipitation (mm)								
	Month								Summer growing season
	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	
2009	244	109	262	100	75	192	148	164	1293
2010	124	32	176	56	128	122	46	31	716
2011	139	49	56	57	204	16	124	25	670
Average (1997-2006)	181	129	92	141	118	97	104	65	927

Table 5-2 Regression equations, pseudo R^2, and maximum economic yield (MEY) of Alamo switchgrass for nitrogen treatments.

Year	Biomass price ($ $\mathrm{Mg^{-1}}$)	Regression equation	R^2	MEY for nitrogen treatment (kg N $\mathrm{ha^{-1}}$)
2011	65	$y=428.6428+3.6434x-0.0109x^2$	0.48	167
2011	100	$y=659.4504+6.3052x-0.0167x^2$	0.60	189

Table 5-3 Cost of N per additional Mg of biomass by year and level of N fertilization.

N rate (kg ha^{-1})	Cost of N per additional Mg of biomass ($)		
	2009	2010	2011
56	15.93	11.65	22.82
112	19.28	16.30	24.19

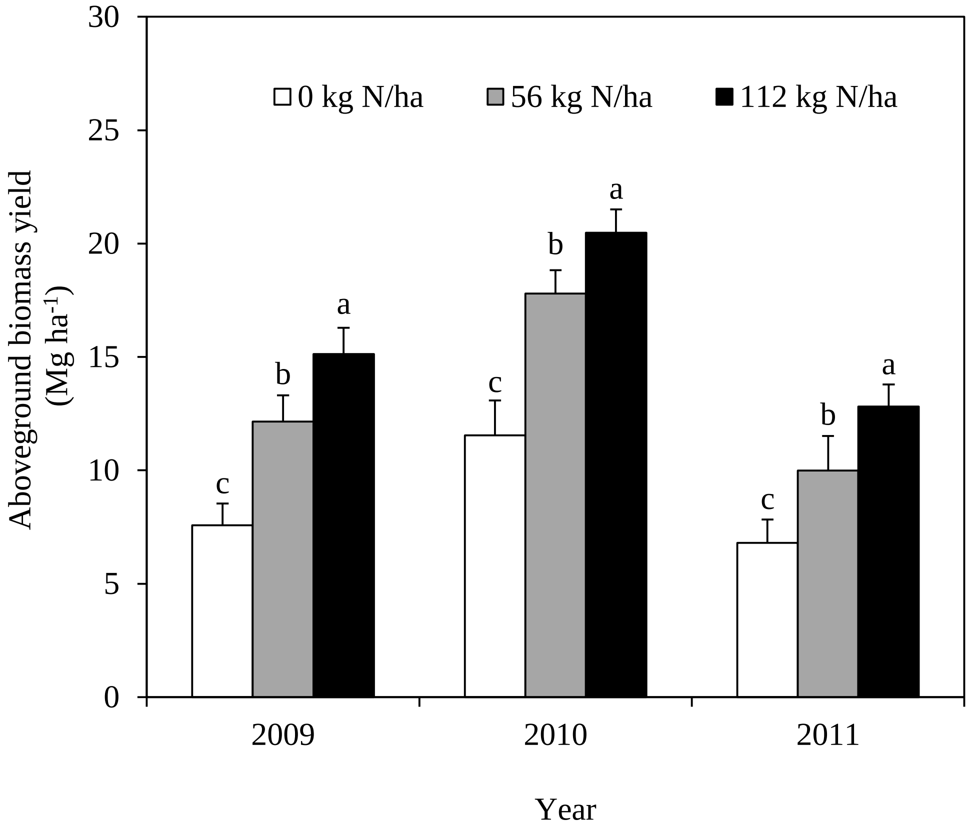

Figure 5-1 Biomass yield of Alamo switchgrass under different nitrogen rates by year. Different letters within each year indicate that treatments differ (*P*<0.10).

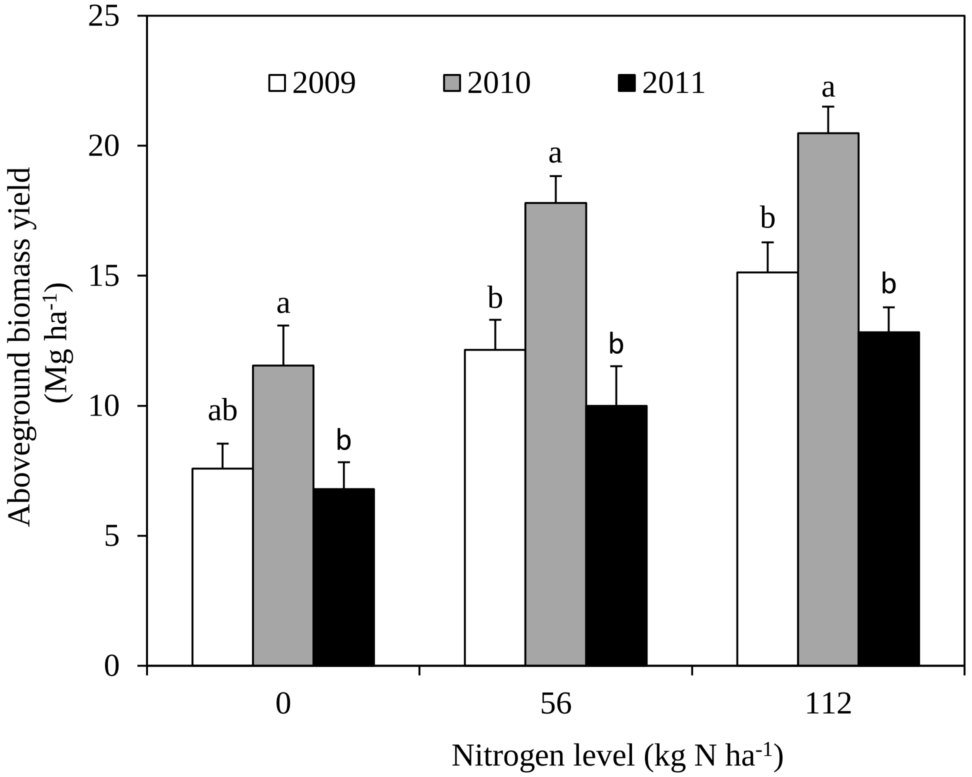

Figure 5-2 Biomass yield of Alamo switchgrass over time by N rate.

Yields with different letters in different years within each N rate differ (*P*<0.10).

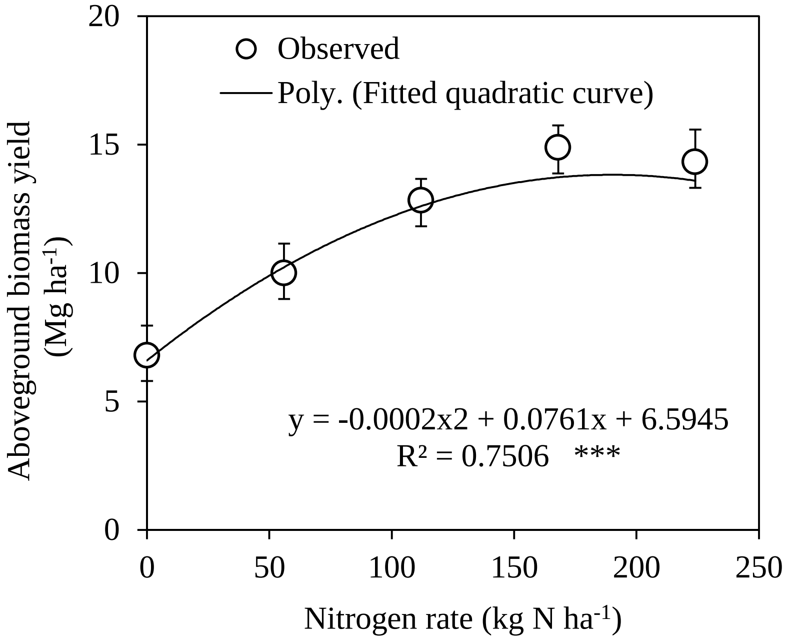

Figure 5-3 Effect of fertilizer N rate on aboveground biomass yield of Alamo switchgrass in 2011.

Vertical bars represent standard errors.
*** Significant at the 0.001 probability level.

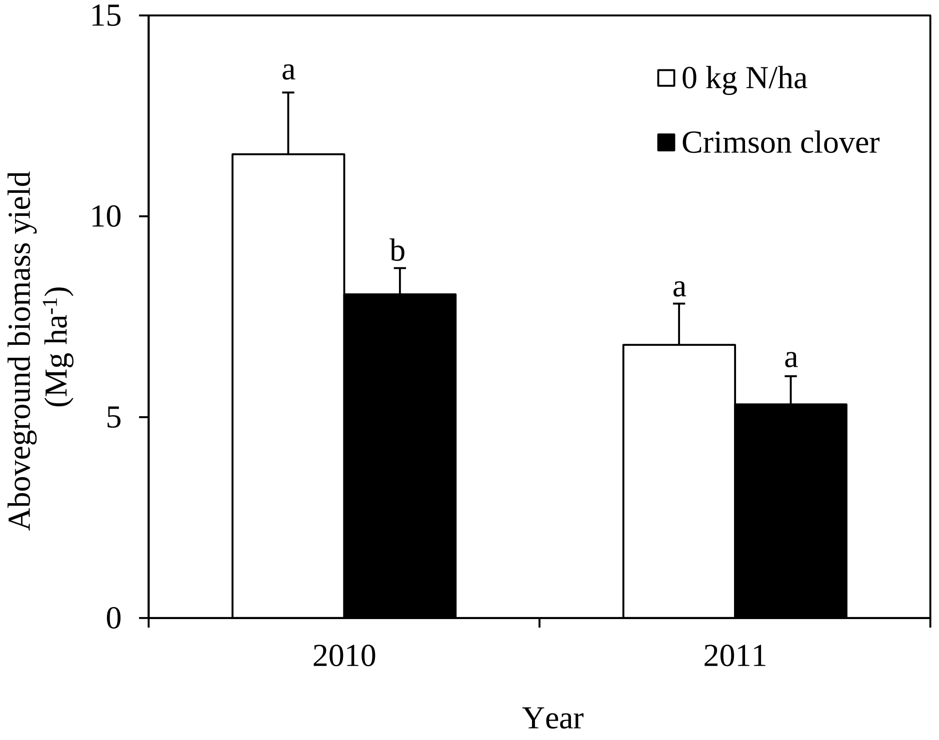

Figure 5-4 Biomass yield of Alamo switchgrass in 2010 and 2011 with no N fertilization and with or without interseeded crimson clover.

Treatments within each year with different letters differ (P<0.10).

Plate 5-1 Alamo switchgrass 10 days after applying N treatments in June 2011.

Plate 5-2 Alamo switchgrass with and without interseeded crimson clover in April 2011.

CHAPTER 6 EFFECTS OF HARVEST TIME AND FREQUENCY AND APPLICATION OF BROILER LITTER ON BIOMASS AND RHIZOME YIELD OF GIANT REED IN ALABAMA

ABSTRACT

Giant Reed (*Arundo donax* L.), a perennial rhizomatous grass native to East Asia, has been extensively evaluated as a dedicated cellulosic energy crop in southern Europe. Besides producing large quantities of shoot biomass, giant reed also sequesters a large amount of carbon below the ground in its rhizomes and roots. Studies on giant reed indicated an inconsistent response in biomass yield to added nitrogen fertilizer, which probably reflects variation in yield response to climate and site. Moreover, no information is available on yield response of giant reed to harvest frequency. Therefore, the objective of this study was to evaluate the biomass yield response of giant reed to harvest frequency and fertilization with broiler litter, and its potential for soil carbon sequestration in rhizomes in central Alabama. Broiler litter application reduced biomass yield. Annual and biennial harvesting in winter provided higher biomass and rhizome yield than harvesting in summer every year, and in summer and winter every year. Annual biomass yield for annual and biennial harvesting in winter did not differ but biennial harvesting in winter will likely result in lower cost Mg^{-1}. Biennial harvesting in winter sequestered 50 Mg ha^{-1} of carbon, and

apparently resulted in higher soil extractable P and K than adjacent areas in which bahiagrass (*Paspalum notatum* Flugge) was growing.

Keywords: cellulosic energy crop; giant reed; aboveground biomass yield; rhizome yield; harvest frequency; application of broiler litter; carbon sequestration

6.1 INTRODCUTION

Giant Reed (*Arundo donax* L.) is a perennial rhizomatous C_3 grass native to East Asia (Polunin and Huxley, 1987) which is grown in both grasslands and wetlands, and is especially well adapted to Mediterranean environments. Since giant reed is sterile, it must be propagated vegetatively from stem cuttings or rhizome pieces, or by micro-propagation. It has been extensively evaluated as a dedicated cellulosic energy crop in southern Europe (Vecchiet et al., 1996; Merlo et al., 1998; Hidalgo and Fernandez, 2001; Lewandowski et al., 2003). Most perennial grasses have poor yields during the year of establishment, but giant reed may be an exception: a first-year yield of over 16 Mg ha^{-1} was reported by Angelini et al. (2005) at a planting density of 20,000 plants ha^{-1}. Biomass yields are typically 20-40 Mg ha^{-1} yr^{-1} without any fertilization after establishment (Angelini et al., 2005; Cosentino et al., 2005; Angelini et al., 2009). Calorific value of mature giant reed biomass is about 18 MJ kg^{-1} (Angelini et al., 2005). The average energy input is approximately 2% of the average energy output over a 12-year period (Angelini et al., 2009). Unlike most other grasses, giant reed possesses a lignin content of 25%, which is similar to that of wood (Faix et al., 1989). This makes giant reed a desirable cellulosic energy crop for solid biofuel production. Giant reed can also help mitigate carbon dioxide (CO_2) emissions from fossil fuels because rhizomes sequester carbon into the soil, although very little quantitative information on below-ground carbon sequestration by giant reed is available.

Because of its favorable characteristics, efforts to commercialize giant reed are being increased in Italy, Greece, France, Spain and Portugal. However, irresponsible attempts to use the crop for erosion control in riparian sites in the US, such as in southern California and along the Rio Grande in Texas, have led to the plant getting out of control in these watersheds. Consequently, it is listed as an invasive weed in California, Hawaii, Maryland, Tennessee and Texas (Bell, 1997). This has created apparently exaggerated perceptions in the US that there is a high risk involved in developing the crop for commercial cellulosic biomass production even if it is propagated outside riparian areas. However, research conducted in South Australia (Williams and Biswas, 2009) refutes this perception.

In Italy Angelini et al. (2005) found that the optimum time for annual harvesting of giant reed is immediately prior to emergence of growth in spring, but no information is available on the combined effects of both harvest time and frequency. Responses of giant reed to N fertilization have been variable: in Greece Christou et al. (2001) observed no response, while in Italy Angelini et al. (2005) recorded a positive response in young stands. Therefore, the objective of this study was to determine the effect of fertilization with broiler litter on biomass yield of giant reed, and the response of biomass and rhizome yield to harvest time and frequency.

6.2 MATERIALS AND METHODS

6.2.1 Treatments and experimental design

The experiment was conducted at the E.V. Smith Research Center, Plant Breeding Unit of the Alabama Agricultural Experiment Station near Tallassee, Alabama on a Wickham sandy loam (fine-loam, mixed, semiactive, thermic Typic Hapludult). The site was fallow prior to planting giant reed. In the spring of 1999, plots were disked and leveled, and 1-m stem segments of a Californian accession of giant reed were hand-placed end-to-end in four furrows 75 cm apart, and completely covered with 5-7.5 cm of soil in each plot. Plots were 3 m wide and 9 m long. All plots were fertilized with ammonium nitrate at a rate of 112 kg N ha^{-1} in May 2000. After establishment, broiler litter was applied to designated plots in May, 2001 and 2003 at a rate of 112 kg N ha^{-1}, based on measured N content of the litter. In 2004 and 2005, plots were harvested annually but did not receive fertilizer. From 2006 to 2011 four harvest frequency treatments were applied: summer every year, winter every second year, winter every year, and summer & winter every year. The experimental design was a completely randomized design (CRD) with subsamplings for broiler litter trial, and an un-replicated CRD with subsamplings for harvest time and frequency trial.

6.2.2 Data collection

Biomass harvests were carried out in late October of 2001, 2002 and 2003 for the broiler litter experiment. For the time and frequency of harvest experiment from 2006 to 2011, summer harvests were conducted in early August, and winter harvests were conducted in late October. Plants in a 1-m^2 area within each plot were harvested by cutting 5 cm above ground level and harvested material was weighed to determine fresh weight. In November 2009, rhizomes in a 1-m^2 area were removed from each plot and weighed to determine fresh weight. Subsamples of biomass and rhizomes from each plot were dried at 60°C for 72 h for dry matter determination, and ground to 1mm for analysis of carbon content using a CNS Analyzer (LECO CNS-2000 Macro Analyzer; LECO Corp., St. Joseph, Michigan). In October 2012, soil samples were collected from each plot, and also from adjacent sites on which bahiagrass was growing. These samples were then analyzed for pH, P, K, Ca and Mg to determine harvest treatment effects on these soil variables.

6.2.3 Data analysis

Statistical analysis of data from both fertilization and harvest time and frequency experiments were conducted using SAS v9.2 PROC MIXED. In order to analyze the harvest time and frequency data, an upper bound of 0.5 was placed for the intraclass correlation coefficient (ICC) by looking at current data and plugged into test statistic equations, and error degrees of freedom for testing the differences among harvest time and frequency treatments was based on the amount of within-treatment subsampling (Perrett and Higgins, 2006). The critical *P*-value of 0.10 was used as cutoff for testing fixed effects, and determination of differences in least-squares means was based on adjusted *P*-value obtained by using the option ADJUST=SIMULATE in the LSMEANS statement.

6.3 RESULTS AND DISCUSSIONS

6.3.1 Weather conditions

Summer growing season (March to October) rainfall was close to the long term average except for 2003 and 2009 in which it was very high, and 2000 and 2007 in which severe droughts occurred (Table 6-1). Monthly maximum and minimum air temperatures were close to long term averages in all years except in 2000, 2002 and 2007: air temperatures over 40 ℃ were recorded in the summer of 2000 and 2007, and a minimum air temperature of -12 ℃ was recorded in the winter of 2002 (Figure 6-1). Mean minimum air temperature in winter was -8.8 ℃ and mean maximum air temperature in summer was 37.5 ℃.

6.3.2 Biomass yield

By the time this experiment started in 2001 giant reed plants had filled in the spaces between the rows in which the cane had been planted in 1999. Biomass yield for the broiler litter treatment was not different from the unfertilized control in the first year of the study, but by the third year it was actually lower (Figure 6-2). This result was different from experiments involving chemical N fertilizer in which

Christou et al. (2001) observed no response to N in Greece, and in which Angelini et al. (2005) recorded an increase in yield in Italy. These differences might be due, in part, to soil and climate differences across experimental sites. The average biomass yield of the control treatment in 2001 and 2003 was 31.31 Mg ha^{-1}. This high biomass yield achieved without N fertilizer suggests that there might be endophytes and beneficial soil microorganisms involved. Xu et al. (2011) found that several strains of bacteria isolated from giant reed exhibited strong N-fixing capability.

There was no difference among harvest treatments in biomass yield after the first two years, but differences developed after four years and persisted through the sixth year of the study (Figure 6-3), suggesting that treatments had a cumulative effect (Figure 6-4). In the fourth and sixth years of the study (Figure 6-3) harvesting in winter every year and every second year provided higher annual biomass yields than harvesting in summer or in summer and winter every year., In addition, a severe infestation with brambles was also observed on all summer harvest plots, whereas there were virtually no weeds in plots that were harvested in winter (Plate 6-1). Clearly, even if giant reed is harvested only once a year, harvesting in summer reduced yield. This is likely due partly to the plant not being able to replenish energy and nutrients extracted from rhizomes in the first phase of the growing season under summer harvesting regimes. Also of importance is that there was no difference in annual biomass yield of giant reed when it was harvested once a year or once every two years in winter. This result suggests that giant reed would offer considerable flexibility in harvest management of commercial plantations. For example, if for any reason biomass produced in a particular year cannot be used in a commercial operation, it can be stored in the field with little or no loss, and harvested in the subsequent year. Alternatively, harvesting every second year might be justified as a standard practice because it should have harvesting cost advantages over annual harvesting.

6.3.3 Rhizome yield

Besides providing higher biomass yield, harvesting in winter every year and every second year also provided two to three times higher rhizome yields than harvesting in summer or summer and winter every year (Figure 6-5). While the general difference among treatments was the same for biomass and rhizome yields, the relative difference in rhizome yields was considerably greater than the difference in biomass yields. Again, this suggests that summer harvests reduce biomass yield largely because they restrict replenishment of rhizomes. Over an 11-year period, rhizome biomass yields for harvests in winter every second year and every year were 117.10 Mg ha^{-1} and 93.59 Mg ha^{-1}, respectively. Since carbon content of rhizomes was 42.93%, this translated into sequestration of 50.3 and 40.2 Mg ha^{-1} of C, respectively, which is 6 to 8 times higher than that observed by Ma (1999) for C sequestration by the roots of switchgrass. Recognizing that these data reflect C sequestered only in rhizomes, if C contained in roots was also added, estimates of total below-ground C sequestration by giant reed in this study would have been even higher. It follows that these high levels of below-ground C sequestration could have significant economic implications in regions where C trading is active.

Soil analyses suggest that production of giant reed over a 13-year experimental period decreased soil Ca and Mg, and therefore, soil pH, relative to adjacent bahiagrass, while P and K were increased by production of this crop (Table 6-2). In addition, the relative differences in these variables among treatments appear to be related to biomass and rhizome yield. In particular, data suggest that Ca and Mg are removed in harvested biomass, while P and K are absorbed by roots from deep in the soil profile and subsequently accumulate in the rhizomes, even though some of these nutrients would also be removed in harvested biomass. These trends have important soil management implications and, therefore, suggest that more detailed research on this topic is justified.

6.4 CONCLUSIONS

Conclusions that can be drawn from this study include the following:

- over a 3-year period, fertilization with broiler litter decreased the yield of giant reed relative to the unfertilized control;
- harvesting giant reed once a year or once every two years in winter provided higher biomass yield and rhizome accumulation than harvesting once a year in summer or in summer and winter every year;
- rhizome accumulation after 11 years was 117.1 and 93.6 Mg ha^{-1} when giant reed was harvested every year or every two years in winter,

respectively, and the related soil carbon sequestration could have significant economic implications if carbon trading was active; and

- trends in soil nutrients associated with production of biomass from giant reed suggest that further detailed research on this topic is justified.

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Table 6-1 Monthly and summer growing season precipitation 1998-2011.

Year	Precipitation (mm)												
	Month												Summer growing season
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	
1998											28	35	
1999	164	67	115	43	104	217	131	37	65	95	52	77	806
2000	123	37	97	47	45	33	46	52	99	13	156	121	432
2001	83	81	333	130	92	155	66	65	37	30	77	68	907
2002	92	71	158	66	77	124	47	39	117	92	112	104	720
2003	61	134	153	226	136	147	187	120	109	27	107	77	1106
2004	51	110	19	73	96	178	62	99	147	49	134	55	723
2005	54	113	255	185	32	39	215	87	37	45	86	77	894
2006	112	116	80	44	78	18	93	99	103	111	150	62	627
2007	150	75	78	51	12	29	21	83	56	75	55	94	405
2008	111	102	77	101	64	50	126	252	19	83	93	82	772
2009	52	105	244	109	262	100	75	192	148	164	154	276	1294
2010	152	76	124	32	176	56	128	122	46	31	52	59	715
2011	57	100	139	49	56	57	204	16	124	25			670

Table 6-2 Soil nutrient content data by harvest treatment.

Treatments	Soil pH	Phosphorous	Potassium	Magnesium	Calcium
		kg ha^{-1}			
Summer every year	6.4 (0.1) a	109 (12) b	301 (37) ab	181 (20) a	717 (67) ab
Winter every second year	4.6 (0.2) c	240 (25) a	227 (22) b	87 (11) b	341 (67) c
Winter every year	4.6 (0.2) c	242 (25) a	219 (37) ab	93 (20) b	326 (100) c
Summer & winter every year	5.8 (0.1) b	127 (12) b	324 (22) a	128 (11) a	479 (67) bc
Fallow bahiagrass	6.1 (0.1) ab	121 (12) b	189 (37) b	114 (20) a	679 (12) a

Values in parentheses are standard errors.

Means within each column with different letters differ ($P<0.10$).

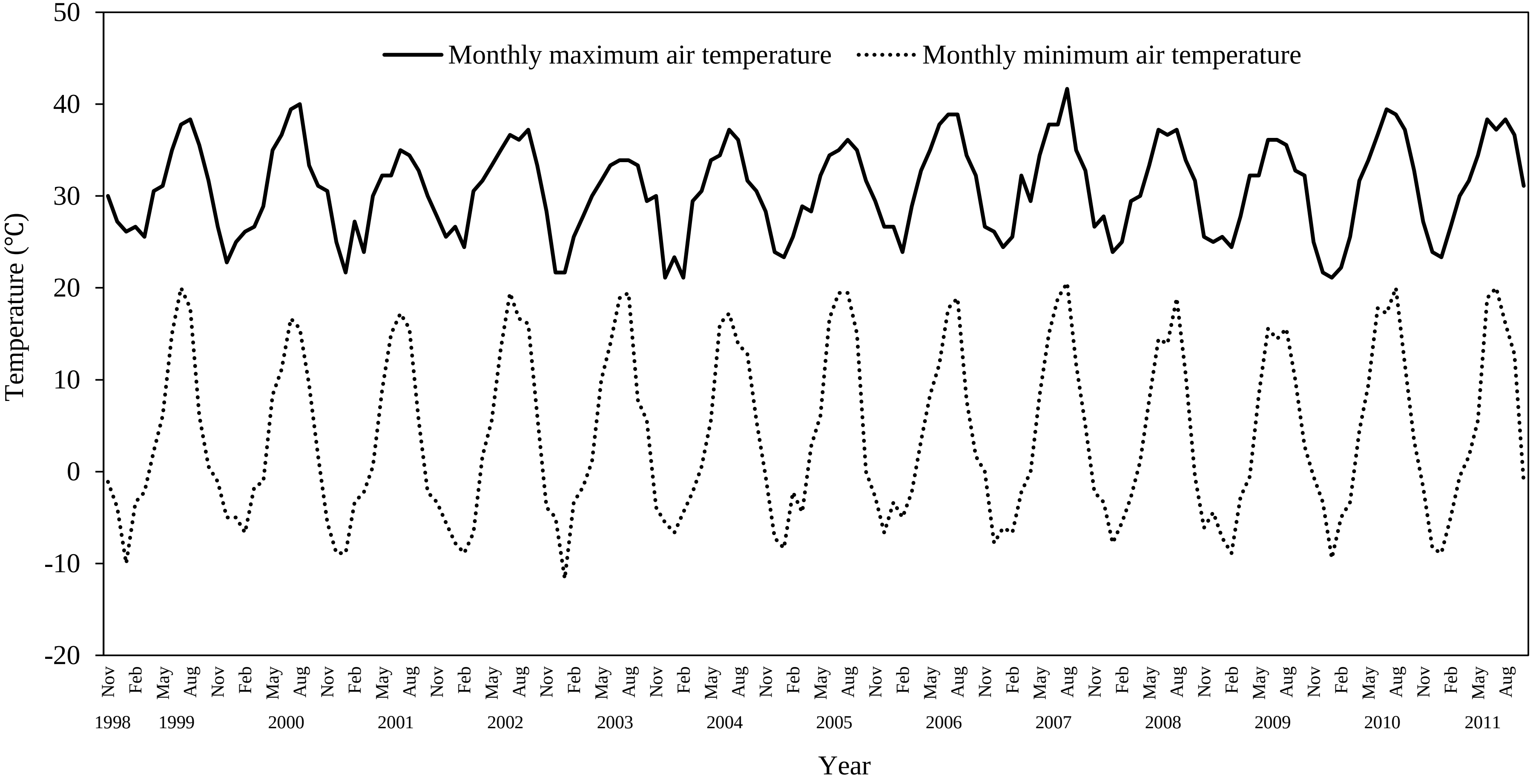


Figure 6-1 Monthly minimum and maximum temperatures from November 1998 to October 2011.

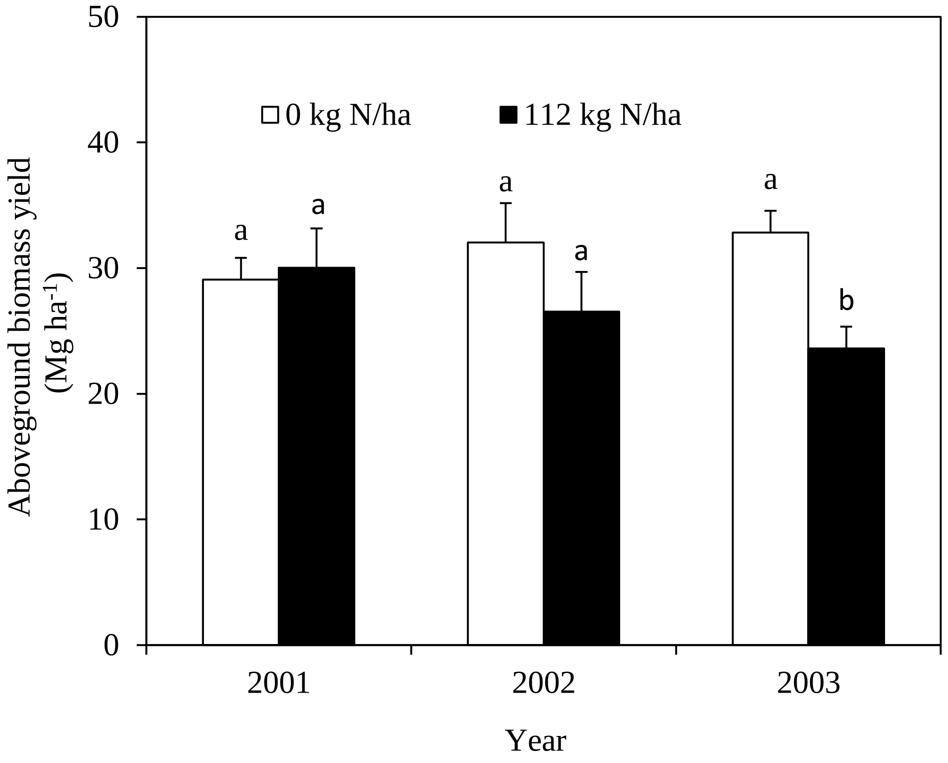


Figure 6-2 Annual biomass yield of giant reed with or without application of broiler litter by year.

Means within each year with different superscripts differ (*P*<0.10).

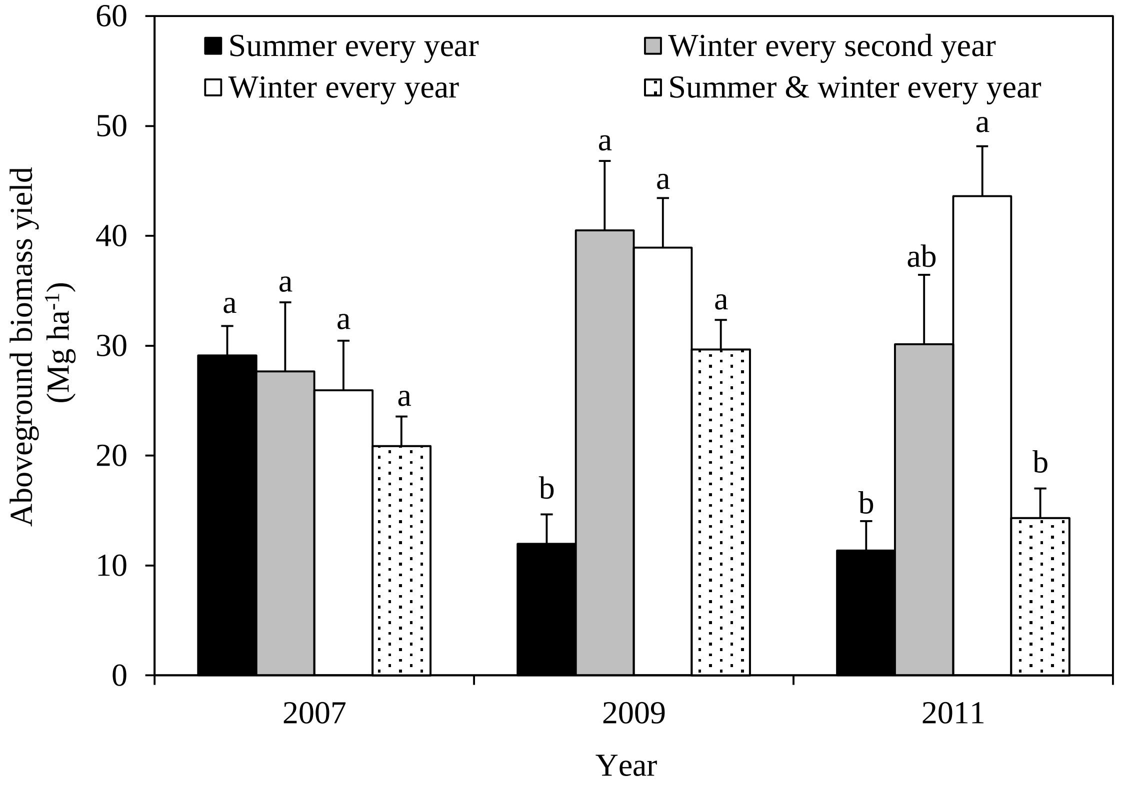


Figure 6-3 Annual biomass yield of giant reed under different harvesting regimes across years.

Means within each year with different superscripts differ (*P*<0.05).

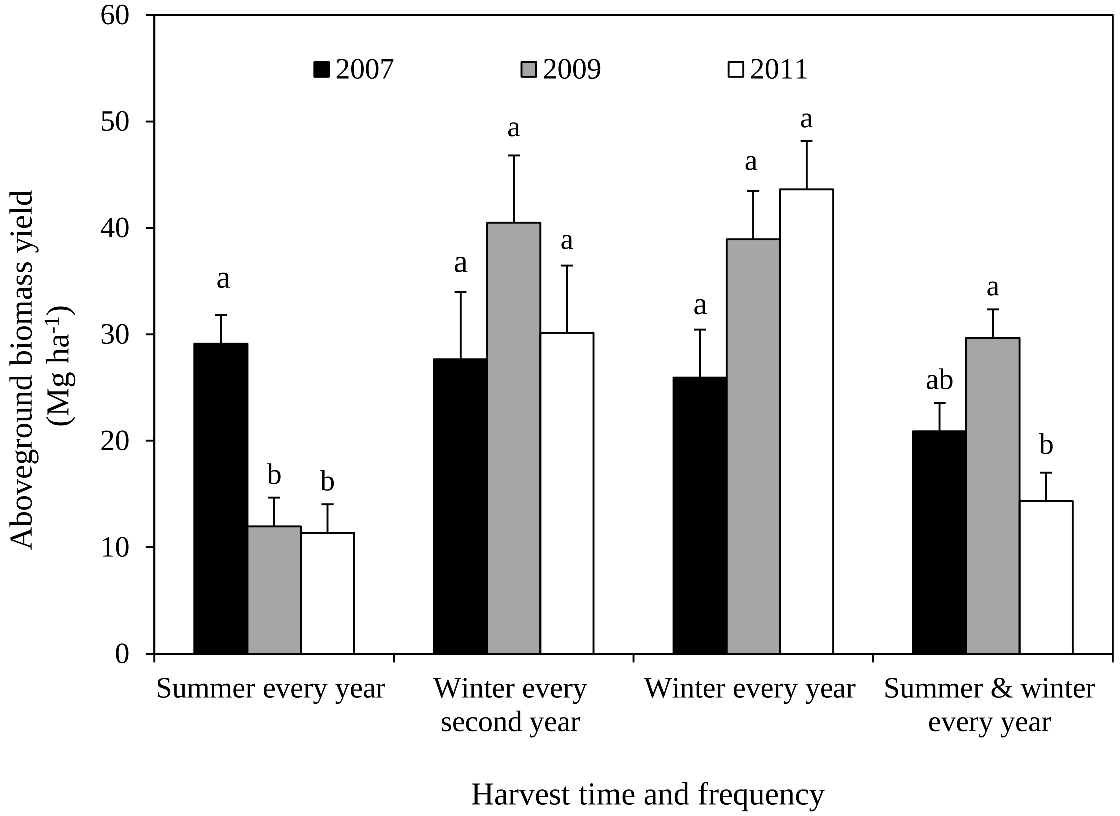


Figure 6-4 Annual biomass yield of giant reed over time and harvest treatment.

Means within each harvest frequency with different superscripts differ ($P<0.05$).

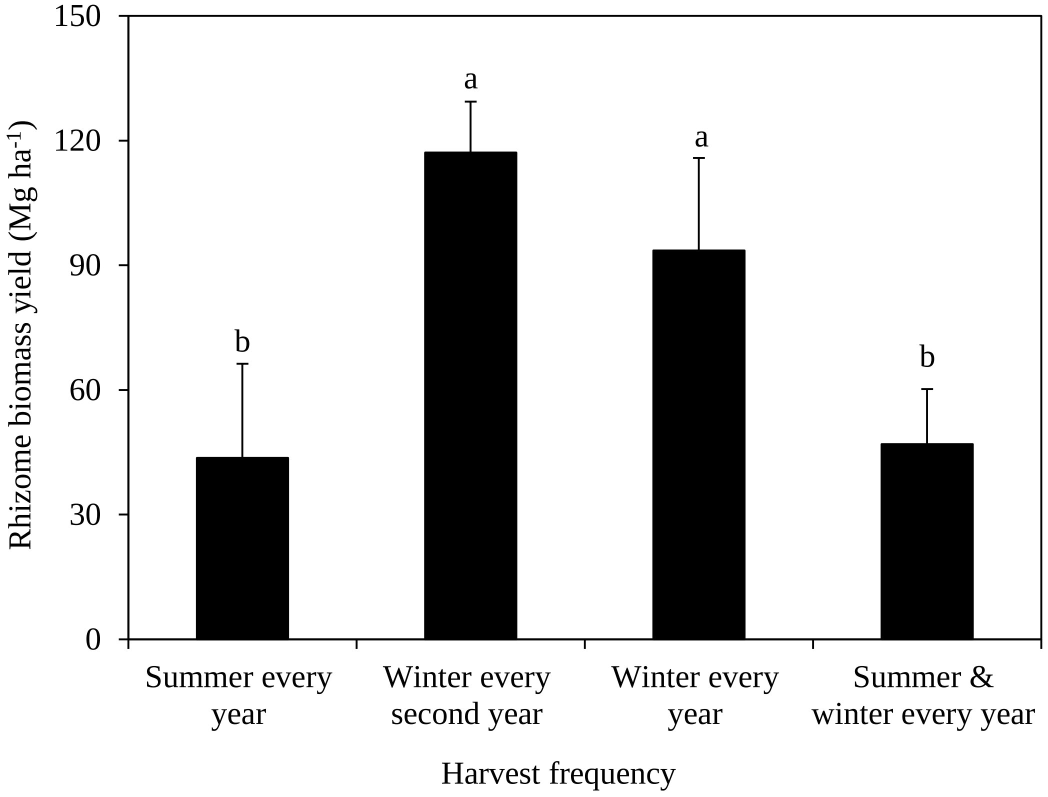
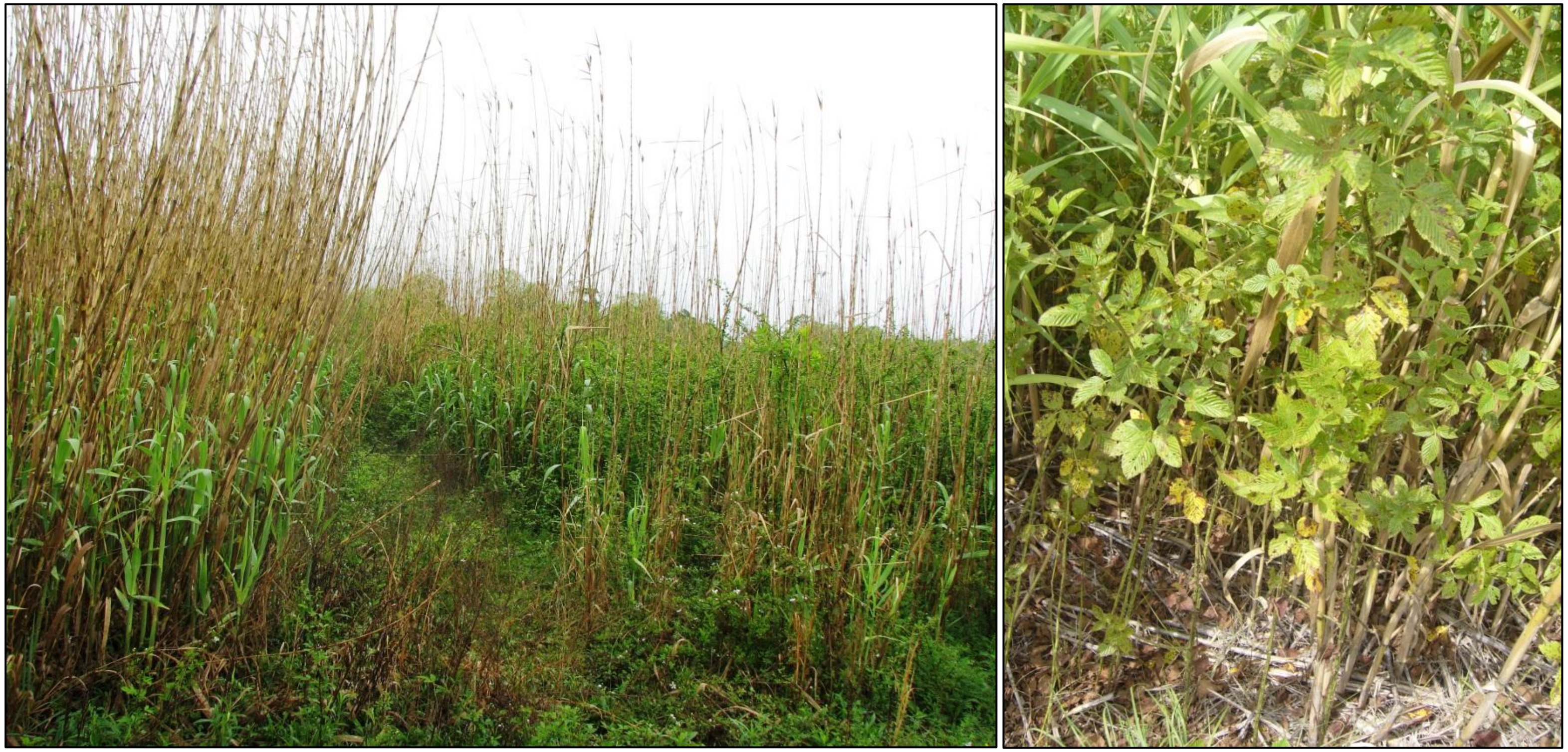


Figure 6-5 Biomass yield of giant reed rhizomes under different harvesting regimes in 2009. Means with different letters differ (*P*<0.10).



(a) (b)

Plate 6-1 Giant reed in spring 2012 showing (a) infestation with brambles under summer harvesting (right) and no infestation for winter harvesting (left), and (b) a closer view of brambles.

CHAPTER 7 SEASONAL GROWTH PATTERNS OF GIANT REED IN ALABAMA

ABSTRACT

Giant reed (*Arundo donax*) has been extensively evaluated for biomass production in southern Europe, with an emphasis on management practices, development of new cultivars, and determining differences among existing cultivars. Even though detailed information on the growth patterns of giant reed would assist in development of improved management practices, this information is not available. Therefore, the objective of this study was to describe the seasonal growth pattern of giant reed in Alabama. Changes in both plant height and biomass yield of giant reed with time were well described by a Gompertz function. The fastest growing period occurred at approximately 66 d after initiation of regrowth (mid-May), when the absolute maximum growth rate was of 0.045 m d^{-1} and 0.516 Mg ha^{-1} d^{-1}. After mid-May, the rate of growth decreased until maturation at approximately 200 d after initiation of regrowth (mid- to late September). The observed maximum average plant height and biomass yield were 5.28 m and 48.56 Mg ha^{-1}, respectively. Yield decreased following maturation up to 278 d after initiation (early to mid-December) of growth in spring, partly as a result of leaf loss, and was relatively stable thereafter.

Keywords: giant reed; cellulosic energy crop; growth curve; Gompertz function; plant height; aboveground biomass yield

7.1 INTRODUCTION

Giant reed (*Arundo donax* L.) is a perennial rhizomatous C_3 grass native to East Asia (Polunin and Huxley, 1987). It grows in both grasslands and wetlands, and occurs widely in Mediterranean environments. The crop is sterile, so it must be propagated vegetatively, either from stem cuttings or rhizome pieces, or by means of micro-propagation. Giant reed has been extensively evaluated as a dedicated cellulosic energy crop in southern Europe (Vecchiet et al., 1996; Merlo et al., 1998; Hidalgo and Fernandez, 2001; Lewandowski et al., 2003). Biomass yields are typically 20-40 Mg ha^{-1} year^{-1} without any fertilization after establishment (Angelini et al., 2005; Cosentino et al., 2005; Angelini et al., 2009). Even though detailed information on the growth patterns of giant reed would assist in development of improved management practices, this information is not available in the southeastern US. Therefore, the objective of this study was to describe the seasonal growth pattern of giant reed in Alabama.

7.2 MATERIALS AND METHODS

7.2.1 Treatments and experimental design

A small plot experiment was conducted at the E.V. Smith Research Center, Plant Breeding Unit of the Alabama Agricultural Experiment Station near Tallassee, Alabama on a

Wickham sandy loam (fine-loam, mixed, semiactive, thermic Typic Hapludult). The experimental site was fallow prior to the planting of giant reed. In the spring of 1999, 1-m stem segments of a giant reed accession from California were hand-placed end-to-end in furrows 75 cm apart and covered with 5-7.5 cm of soil in prepared plots that were 3 m wide and 9 m long. Plots were fertilized with ammonium nitrate at a rate of 112 kg N ha^{-1} in May 2000, but received no fertilizer in subsequent years. Biomass was harvested annually each winter before this study began, and rhizomes had completely filled in the spaces between rows to form a solid stand.

7.2.2 Data collection

Giant reed emerged in mid- and early March in 2010 and 2011, respectively. Biomass was harvested by hand from a 1-m^2 quadrat within each of four plots at approximate 30 d intervals from April 2010 to February 2012, with all material from plots being harvested in late February of each year. Cutting height was 5 cm above ground. More harvest date information is presented in Table 7-2. In the second growing season, each harvest was conducted on a different area within each plot from the quadrats that had been harvested in the previous season, to avoid any impact of cutting date in the previous season on second season results. All harvested plant material was weighed immediately after harvesting to determine fresh weight in the field by using a hanging scale. Five randomly identified plants from each plot were used for determination of plant height, which was measured from the base of the stem to the collar of the highest leaf. Subsamples taken from the harvested material from each plot at each harvest date were dried at 60°C for 72 h for dry matter determination.

7.2.3 Data analysis

Analysis of variance for biomass yield data was performed by using the SAS v9.2 PROC MIXED procedure. This analysis was conducted by year since harvest dates were slightly different between years. Determination of differences in least-squares means was based on adjusted *P*-value obtained by using the option ADJUST=SIMULATE in the LSMEANS statement.

Scatter diagrams of plant height and biomass yield against time were drawn for each year to help determine the most appropriate function to describe the data. Generalized logistic, Gompertz and logistic functions were tested for describing changes in plant height and yield with time in the first part of the year starting in March, because the scatter diagrams suggested a sigmoid-shaped curve during this phase of growth. In the latter part of the year yield decreased steadily with time, so this suggested use of a linear function.

Model fitting and parameter estimation of generalized logistic, Gompertz and logistic functions were performed by using the SAS v9.2 PROC NLIN procedure. Selection of the best fitting function was done based on the mean square error (MSE) rather than the residual sum of squares (RSS,) since the MSE also takes into account the number of parameters in the models.

7.3 RESULTS AND DISCUSSIONS

Precipitation and temperature data are presented in Table 7-1 and Figure 7-1, respectively. Growing season rainfall (March to October) in both years was slightly below the average growing season rainfall from 1990 to 2009. Mean minimum air temperature in mid-winter was -8.8 ℃ and mean maximum air temperature in mid-summer was 37.5 ℃.

Recognizing that experimental plots received no fertilizer and that giant reed is a C3 species, growth rates and yields recorded for giant reed in this study were remarkably high: maximum yield was 47.11 Mg ha^{-1} and 48.56 Mg ha^{-1} in September of 2010 and 2011, respectively. In contrast, yields of unfertilized Alamo switchgrass during the same period and at the same location were 11.55 and 6.80 Mg ha^{-1} in 2010 and 2011, respectively. Biomass yield for consecutive harvests differed in the first three months of each year, but this difference was reduced or eliminated as maturity was reached and as yield declined in the latter part of the year (Table 7-2).

A Gompertz function provided the best fit for changes in plant height with time, probably because the data were distinctly asymmetrical. Since no difference was detected between years, data from the two years were pooled. The resultant model is presented in Figure 7-2, based on model parameters as follows:

$$y = 5.0918 * e^{-e^{(1.4675-0.0238*x)}} \qquad 0 < x \leq 202\ d$$

According to this model, an absolute maximum growth rate of 0.045 m d^{-1} or 0.32 m $week^{-1}$ occurred 62 d after initiation of growth (mid-May) and at a plant height of 1.89 m (Figure 7-3). The rate of growth then started to decrease over time until maturity approximately 200 d after emergence (mid- to late September).

Other studies have shown that growth of many annuals, such as corn and wheat are better described by a logistical curve than by a Gompertz curve (Katsadonis et al., 1997; Karadavut et al., 2008), indicating that the data were distinctly symmetrical. Unlike these annual crops, but in agreement with the findings of another study on giant reed and miscanthus conducted in central Italy (Nassi o Di Nasso et al., 2011), a Gompertz function provided the best description of changes in biomass yield of giant reed with time until maturity in this study, and thereafter a linear function was used to describe the subsequent decline in yield. Again, since no difference was detected between years, data from the two years were pooled. The resultant model is presented in Figure 7-4, based on model parameters as follows:

$$y = \begin{array}{ll} 47.8698 * e^{-e^{(1.9240-0.0293*x)}} & 0 < x \leq 200\ d; \\ 68.3698 - 0.1069 * x & 200 < x \leq 350\ d. \end{array}$$

According to this model, inflection point was predicted on day 66 (mid-May) after initiation of growth, when biomass yield was 17.78 Mg ha^{-1} (Figure 7-5). At this inflection point, relative growth rate for biomass yield was 0.0293 Mg ha^{-1} d^{-1}, which is very close to the findings by Nassi o Di Na in central Italy (Nassi o Di Nasso et al., 2011), and absolute maximum growth rate was 0.516 Mg ha^{-1} d^{-1} or 3.61 Mg $week^{-1}$. The rate of growth subsequently decreased over time until maturation at approximately 200 d after emergence (mid- to late September) when a maximum yield of 46.94 Mg ha^{-1} was reached. After this point yield decreased steadily at a rate of 0.1069 Mg ha^{-1} d^{-1}, or 0.75 Mg $ha^{-1}week^{-1}$, probably due mainly to leaf loss (Plate 7-1) and possibly translocation of nutrients from shoots to rhizomes.

The asymmetrical nature of the growth curve of giant reed reflects extremely rapid growth following emergence, and attainment of the maximum growth rate within a third (66 d) of the time it takes to reach maximum yield (200 d). This pattern is probably due to existence of an extensive permanent root system, and stored energy and nutrients in the very large rhizomes of giant reed, which facilitate rapid growth in the early part of the season. Therefore, while results from this study indicate that maximum yield is attained in mid- to late September, annual harvesting at this time might reduce long-term yields. Results from a companion study support this view by demonstrating that yield of giant reed is sensitive to time of harvest. Consequently, unless additional research indicates otherwise, harvesting giant reed after it reaches dormancy (November or December) will likely ensure the highest sustainable yields, even though this will result in approximately 6 to 9% reduction in short-term yield when compared to harvesting in mid- to late September.

7.4 CONCLUSIONS

The following conclusions can be drawn from this study:

- recognizing that no fertilizer was applied to giant reed plots in this study, recorded growth rates and yields were extremely high;
- the growth pattern of giant reed in Alabama is distinctly asymmetrical;
- maximum growth rate is achieved approximately 60 d after emergence (mid-May);
- maximum yield is attained approximately 200 day after emergence (mid- to late September); and
- harvesting giant reed after initiation of dormancy in November or December will probably be the best strategy to ensure sustainable long-term yields, even though this will result in a 6-9% reduction in short term yield compared to harvesting in mid- to late September, but further research is needed to verify this projection.

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Table 7-1 Monthly and growing season (March to October) precipitation 2009-2011.

Year	Precipitation (mm)												
	Month												Growing season
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	
2009											154	276	
2010	152	76	124	32	176	56	128	122	46	31	52	59	716
2011	57	100	139	49	56	57	204	16	124	25			670
Average (1990-2009)	119	120	169	106	85	109	126	103	91	85	115	146	875

Table 7-2 Biomass yield of giant reed at different harvest times in 2010 and 2011 growing seasons.

Harvest date	Day after emergence	Biomass yield (Mg ha^{-1})	Harvest date	Day after emergence	Biomass yield (Mg ha^{-1})
04/15/2010	36	3.81 ± 1.71^{d}	04/15/2011	44	4.09 ± 0.99^{e}
05/14/2010	65	21.10 ± 1.71^{c}	05/19/2011	78	24.98 ± 0.99^{d}
06/14/2010	96	31.07 ± 1.71^{b}	06/15/2011	105	32.01 ± 0.99^{c}
07/15/2010	127	40.78 ± 3.44^{ab}	07/18/2011	138	41.94 ± 0.99^{b}
08/16/2010	159	44.25 ± 5.94^{ab}	08/15/2011	166	46.80 ± 2.93^{ab}
09/15/2010	189	47.11 ± 5.94^{ab}	09/20/2011	202	48.56 ± 0.99^{a}
10/20/2010	224	42.48 ± 5.84^{ab}	10/21/2011	233	43.62 ± 4.41^{abc}
11/15/2010	250	41.95 ± 1.71^{a}	12/14/2011	287	38.62 ± 2.93^{abc}
12/03/2010	268	38.19 ± 3.44^{ab}	01/25/2012	329	32.74 ± 2.93^{bcd}
01/21/2011	317	34.60 ± 3.44^{ab}			
02/18/2011	345	32.10 ± 3.44^{ab}			

^{abcde} means within each column with different superscripts differ significantly ($P<0.05$).

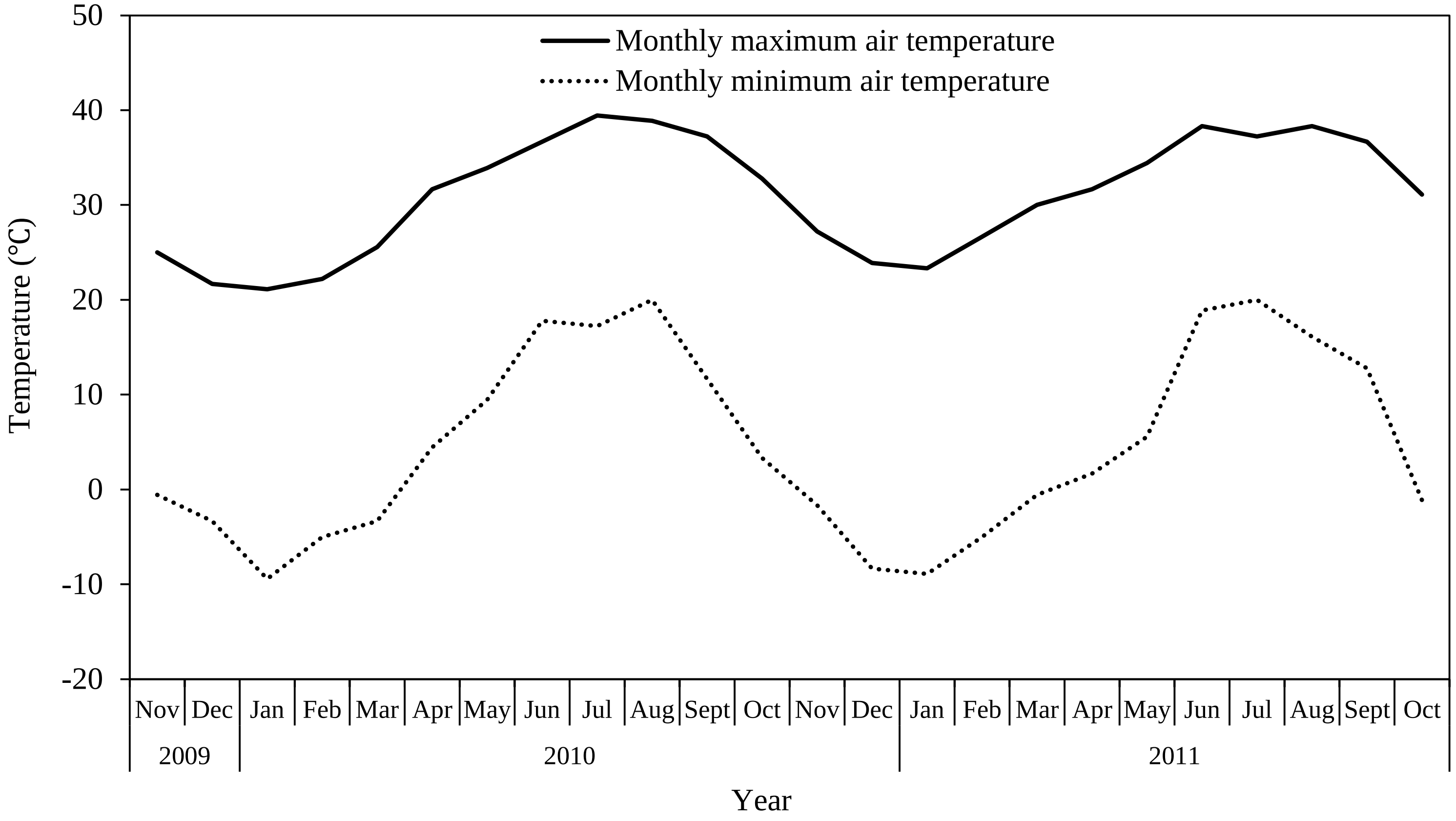

Figure 7-1 Monthly maximum and minimum air temperatures from November 2009 to October 2011.

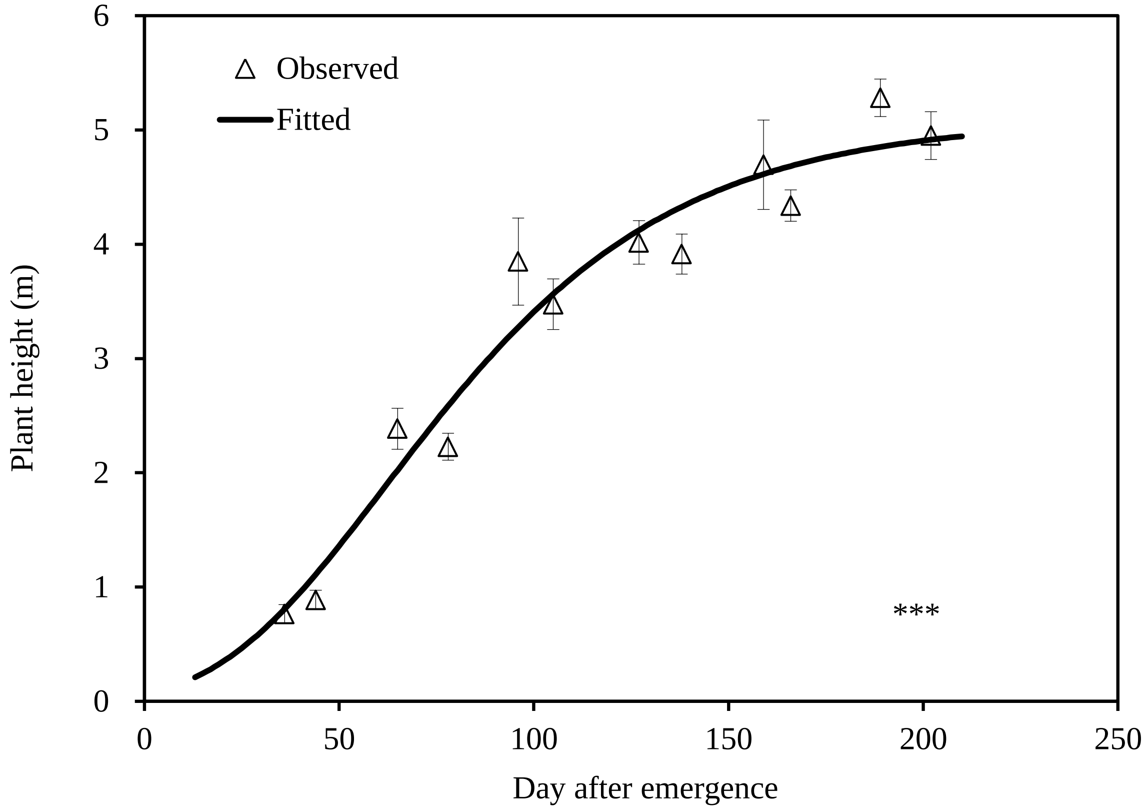

Figure 7-2 Change in plant height of giant reed with time.

Vertical bars represent standard errors.
*** Significant at the 0.001 probability level.

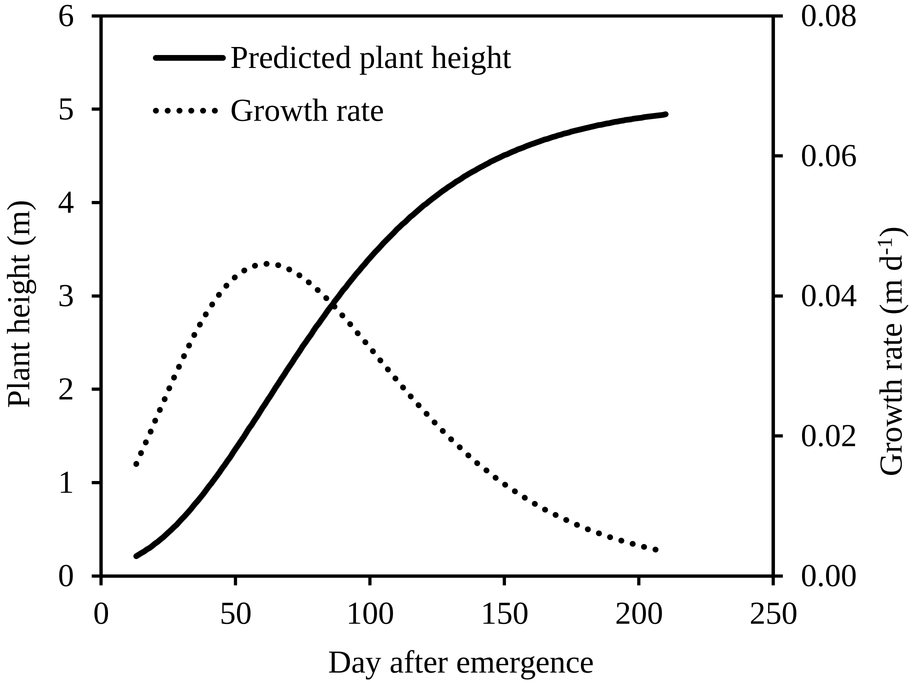

Figure 7-3 Changes in plant height and growth rate of giant reed with time.

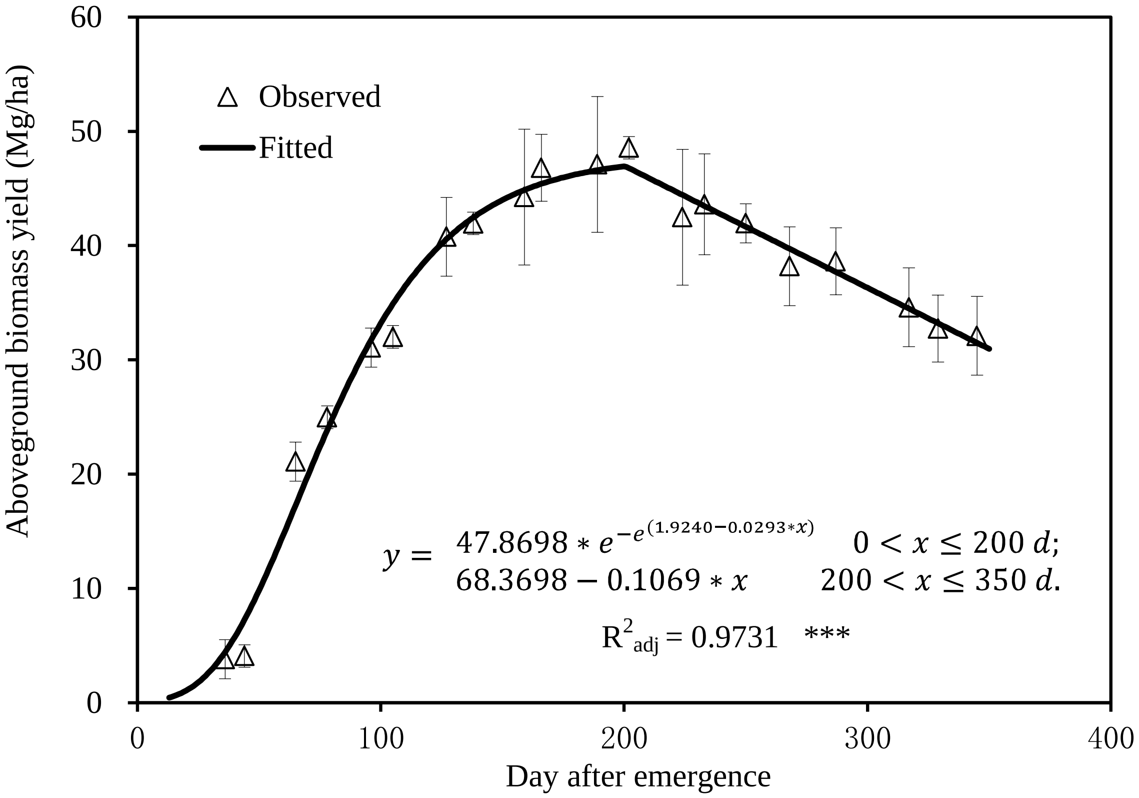

Figure 7-4 Change in biomass yield of giant reed with time.

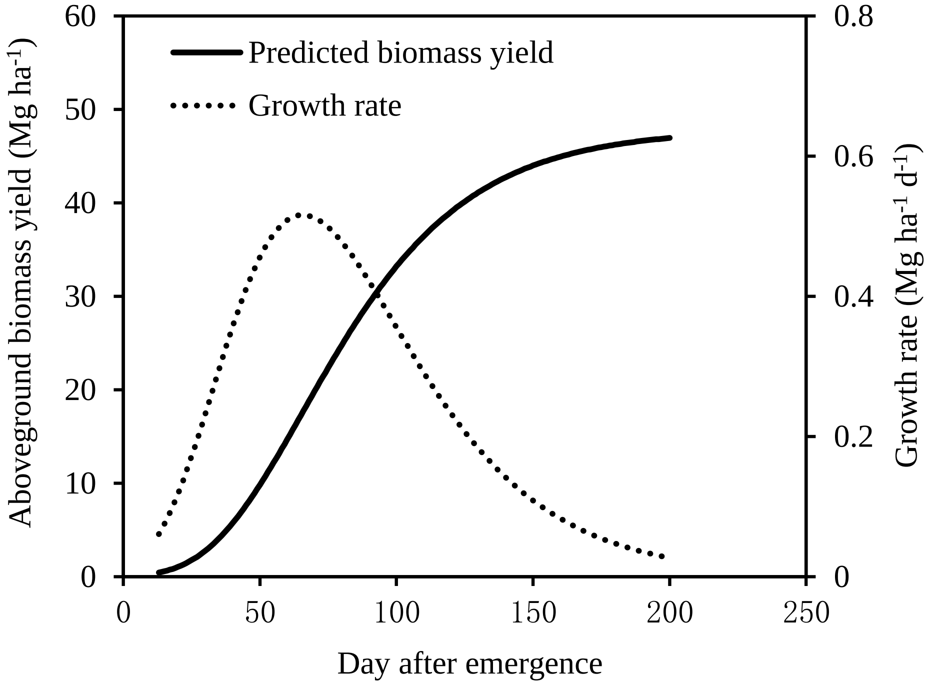

Figure 7-5 Changes in biomass yield and growth rate of giant reed with time.

(a) (b)

Plate 7-1 Giant reed on October 8th, 2010 (a) and November 18th, 2010 (b).