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# Biomass sorghum production and components under different irrigation/tillage systems for the southeastern U.S.

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ABSTRACT

Renewable energy sources are necessary to reduce the U.S. dependence on foreign oil. Sorghum (*Sorghum bicolor* L.) may be a reasonable alternative as an energy crop in the southern U.S. because it could easily fit into existing production systems, it is drought resistant, and it has large biomass production potential. An experiment was conducted to evaluate several types of sorghum as bioenergy crops in Alabama: grain sorghum – NK300 (GS), forage sorghum – SS 506 (FS), and photoperiod sensitive forage sorghum – 1990 (PS). These sorghum crops were compared to forage corn (*Zea mays* L.) – Pioneer 31G65 in 2008 and 2009 with and without irrigation, and under conventional (total disked area, 0.15 m deep) and conservation tillage (in-row subsoiling, 0.30 m deep) in a strip-split-plot design. The parameters evaluated were: plant population (PP), plant height (PH), sorghum/corn aboveground dry matter (ADM), biomass moisture content (ABMC), and biomass quality (holocellulose, lignin, and ash). Sorghum had greater ADM than corn; however, corn had lower ABMC than sorghum. Lodging was observed in PS and FS, probably due to high plant populations (>370,000 plants $ha^{-1}$). Irrigation affected ADM positively in both years, but conservation systems improved ADM production only in 2009. Holocellulose, lignin, and ash variation differed significantly among crops but were lower than 8.3%, 2.0% and 1.9%, respectively, for both years and considered minor. Under conditions of this study, PS was considered the best variety for ADM production as it yielded 26.0 and 30.1 Mg $ha^{-1}$ at 18 and 24 weeks after planting (WAP).

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## 1. Introduction

The world energy demand of fossil fuels is of concern, because those energy sources are non-renewable and new discoveries lag behind increases in consumption. Future shortages can be expected, likely resulting in economic and political stresses within energy-deficient nations. The U.S. imported 682 billion L of crude oil in 2010 (U.S. EIA, 2011), and was thus dependent on other countries to supply its primary energy demand. Consequently, there is an increasing need to develop alternative energy supplies that can release the U.S. from foreign oil dependence, especially liquid fuels for transportation.

Among the alternatives for replacing fossil fuels in the transportation sector, biofuel is the most promising. Biofuel is defined as a liquid or gaseous fuel that is predominantly produced from biomass (Demirbas, 2008). The Renewable Fuel Standard 2 established four different biofuel categories, including (1) renewable biofuel, (2) advanced biofuel, (3) biomass-based diesel, and (4) cellulosic biofuel (U.S. EPA, 2011). Cellulosic biofuel has the most positive impact on GHG emissions and should be considered as the preferable alternative for bioenergy production which could assist with achieving U.S. energy independence.

Energy crops must produce large quantities of biomass and high quality lignocellulosic materials (Sanderson and Wolf, 1995). Principal components of plant tissue considered and quantified for bioethanol production are holocellulose (i.e., cellulose and hemicellulose), lignin, and carbohydrates. Cellulosic biomass has an optimal holocellulose conversion to ethanol when lignin is absent (low content or decomposed) (Weng et al., 2008). Furthermore, cellulosic biomass is a versatile feedstock for producing bioenergy, because it can be used not only in liquid fuel production but also in direct combustion for heat and electrical power. Feedstock for direct combustion needs to have high heating value (which is found in cellulosic biomass) with minimum concentration of ash and moisture (Cassida et al., 2005). Thus, high ash content decreases

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efficiency of combustion conversion due to diminished heat transfer (Burner et al., 2009; Sanderson et al., 1996).

Much emphasis has been placed on perennial crops for cellulosic material production. Switchgrass (*Panicum virgatum* L.) is a reference for comparisons and one of the most probable feedstocks for bioenergy (U.S. DOE, 2005). Negative impacts on food production may occur if conventional crops are replaced with perennial energy crops (Peters and Thielmann, 2008). Conversely, conventional crops and annual energy crops can be alternated on the same agricultural land to produce both food and bioenergy feedstock. Annual crops, which have largely been ignored for bioenergy production in the southeastern U.S., could provide a major source of biomass for cellulosic bioenergy production. For these reasons, sorghum (*Sorghum bicolor* L.) may be an alternative energy crop in this region, because large amounts of biomass can be produced in water-limited conditions (Amaducci et al., 2000; Habyarimana et al., 2004a,b). However, drought resistance of sorghum varies according to development stage through the growing season. Studies by Mastrorilli et al. (1999) indicated that sorghum's drought resistance tended to change according to development stages. Sorghum was more sensitive to drought stress in early 'leaf' stages where biomass productivity decreased substantially if water was restricted. Results from Mastrorilli et al. (1999) showed that stomata closure beings after sorghum reached the wilting point (−0.4 MPa). Therefore, irrigation should be used in early growth stages and any time soil water falls below the wilting point.

Sorghum could be integrated in a conservation system as part of a crop rotation with cash crops, such as peanuts (*Arachis hypogaea* L.) and cotton (*Gossipyum hirsutum* L.), where part of its biomass would be used as soil cover and any additional biomass would be harvested for biofuel production. In addition, tillage impacts on biomass production must be also evaluated. Conservation systems, such as in-row subsoiling combined with a winter cover crop are considered an alternative to increase crop productivity in southeast U.S. conditions (Hunt et al., 2004).

The objectives of our study were therefore: (1) to compare sorghum and corn (*Zea mays* L.) biomass quantity and quality for biofuel production, (2) to determine the effect of irrigation on biomass production, and (3) to determine the effect of conservation and conventional tillage on sorghum and corn for biomass production.

## 2. Materials and methods

### 2.1. Site description

A study was initiated in November of 2007 and conducted for 2 years at the E.V. Smith Research Center–Field Crop Unit, Shorter, AL (85°53′50″ W, 32°25′22″ N). The location had been cropped previously with cotton for 8 years in a conservation tillage system. The soil type was Marvyn Loamy sand (fine-loamy, kaolinitic, thermic, typic Kanhapludult). In order to maximize the amount of biomass produced and provide ground cover during the winter months, the entire field was planted with a rye (*Secale cereale* L.) cover crop before planting corn and sorghum.

### 2.2. Cultural practices and treatments

Rye was planted at 100 kg ha$^{-1}$, in early November each year using a no-till drill (Great Plains Mfg. Inc., Salina, KS) following typical conservation cultural practices for the region. In early April each year, the rye cover crop was terminated with glyphosate [N-(phosphonomethyl) glycine].

Three sorghum hybrids are used in the study: (1) NK300 (grain sorghum; GS), (2) Sucrosorgo506 (forage sorghum; FS) and (3) 1990 (photoperiod-sensitive sorghum; PS) (Sorghum Partners Inc., 2011). GS is highly qualified for dairy silage production, due to high grain to forage ratio (15–20%), with an average plant height of 2 m (6–7 feet), excellent standability, very good drought tolerance, average stalk sweetness (sugar content) and medium early maturity. GS is therefore important for both greenchop (harvesting without allowing the biomass to dry) and stalk grazing (Sorghum Partners Inc., 2011). In contrast, FS is described as a late maturing sorghum, with a mean plant height of 3.5 m, very good standability, high tonnage yield performance and high stalk sweetness (sugar content). FS has limited use for greenchop, but it can be used for bioethanol production if biomass is dry harvested (Sorghum Partners Inc., 2008a). Finally, PS is a photoperiod sensitive sorghum (headless), which needs less than 12 h and 20 min of daylight to produce a grain head. It is described as having mean plant height of 3.5 m, good standability, very high tonnage yield performance and average stalk sweetness (sugar content) (Sorghum Partners Inc., 2008b). Additionally, Pioneer 31G65 hybrid corn (Pioneer, 2011) which is commonly cultivated in the southeast U.S. was also included in this study as a point of reference. Pioneer 31G65 is described as suitable for producing large amounts of crop residue. The end-use segments for this variety are high total fermentables (dry-grind ethanol) with high extractable starch (wet milling) and yellow food corn. Therefore, this variety is considered a good choice both for grain and cellulosic biomass production.

In late April 2008 and 2009, starter fertilizer was applied at a rate of 14, 4, 14, and 5 kg ha$^{-1}$ of nitrogen (N), phosphorus (P), potassium (K), and sulfur (S), respectively according to the Alabama Cooperative Extension System soil test recommendations (Adams and Mitchell, 2000). An additional 110 kg N ha$^{-1}$ of UAN (34%) was side dressed with a tractor-mounted liquid applicator in row middles during the growing season of each year.

Two tillage systems (conservation and conventional) were implemented shortly after fertilization. Conservation plots received in-row subsoiling with a narrow-shanked subsoiler (KMC, Kelley Manufacturing Co., Tifton, GA) to a depth of 0.35–0.40 m. Conventional plots were disked and leveled using a tractor-mounted tandem disk harrow to a depth of 0.15 m. The four bioenergy crops, including GS, FS, PS, and corn were seeded in rows spaced at 0.92 m. Seeding rates were based on company recommendations, which were 407,700 seeds ha$^{-1}$ for FS, GS, and PS (Sorghum Partners Inc., 2008a,b, 2011). Corn was seeded at 78,300 seeds ha$^{-1}$ (Pioneer, 2011). Tillage and planting were performed with a tractor equipped with a Trimble AgGPS Autopilot automatic steering system (Trimble, Sunnyvale, CA), with centimeter level precision. Premergence herbicides application to all bioenergy crops in both years were 1.6 kg a.i. ha$^{-1}$ of S-metolachlor [2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl) acetamide] with 0.82 kg a.i. ha$^{-1}$ of glyphosate using a boom sprayer mounted on a tractor at recommended carrier and adjuvant concentrations.

The irrigation plots were managed with two different regimes: non-irrigated (rainfed) and irrigated. The irrigation treatment consisted of applying water in appropriate timing and amounts to provide plants with adequate water availability during the growing season. Irrigated plots received a water increment of 131 mm in 2008 distributed in 6 different days, such as 17 (12 mm), 31 (8 mm), 50 (24 mm), 63 (32 mm), 77 (30 mm), and 91 (25 mm) days after planting. However, due to high rainfall the irrigated plots received a water increment of 58 mm distributed in 3 days during 2009 season, such as 1 day before planting (14 mm), 21 (19 mm) and 30 (25 mm) days after planting. Irrigation was terminated at 16 weeks after planting in both years. Alabama Cooperative Extension System recommendations were used to apply all insecticides (Flanders et al., 2011).

Grain from NK300 and corn were harvested in late August of each year using a Gleaner G combine (AGCO Company, Duluth, GA). SS506 and 1990 were harvested in late October of each year.

### 2.3. Data collection

#### 2.3.1. Weather data

Cumulative precipitation for 2008–2009 and were collected at E.V. Smith Research Center (AWIS, 2011). In addition, cumulative precipitation was monitored during each growing season. Eight ECH2O Rain gauges – Model ECRN (Decagon Devices, Pullman, WA) were installed during each growing season (from planting to 14 WAP). Rain gauges were paired in four sets. Each set had two rain gauges and an ECH2O logger – Model Em5 (Decagon Devices, Pullman, WA). These four sets were placed in different field locations where one rain gauge was installed in an irrigated plot and the other one installed in non-irrigated plot. All rain gauges were located 0.6 m from two middle rows.

Cumulative in-season growing degree-days (CGDUs) were calculated based on daily air temperature collected at E.V. Smith Alabama Agricultural Station (AWIS, 2011). Growing degrees units were calculated using base temperature of 10 °C for all bioenergy crops. Maximum temperature of 29.4 and 38 °C were used for corn and sorghum, respectively.

#### 2.3.2. Rye cover crop

Rye dry matter samples were collected 1 week prior to planting sorghum for both years. A 0.25 $m^2$ frame was used to sample two rye subsamples from each experimental unit. Samples were oven-dried at 55 °C until constant weight to determine aboveground biomass dry biomass yield. In 2008, rye aboveground samples were collected for all experimental units because rye was cropped across the entire experimental area. However, rye was just cropped in conservation plots in 2009 where aboveground samples were collected.

#### 2.3.3. Plant population

Sorghum and corn populations were calculated from the number of plants in 1.5 m transects on both middle rows of each plot. Plant populations were determined 6 weeks after planting (growing season) and 14 weeks after planting (at harvest).

#### 2.3.4. Plant height

Five plant height measurements were made each year. Measurements occurred at 6, 9, 14, and 24 weeks after planting in both years. However, in 2008, the fourth time period was performed at 18 weeks while in 2009, these data were collected at 20 weeks after planting due to rainfall that occurred during the 18th week after planting.

Ten different plants in the two middle rows of each plot were randomly selected, and those plants were measured extending the uppermost leaves. Mean height of the 10 plants was used for statistical analysis.

#### 2.3.5. Aboveground dry matter and biomass moisture content

Aboveground biomass was harvested three times per year. It was sampled 14, 18, and 24 weeks after planting in 2008 and at 14, 20, and 24 weeks after planting in 2009. The harvest at 20 WAP in 2009 rather than at 18 WAP (delay in two weeks) was caused by high precipitation. Aboveground biomass samples for corn and GS were not collected at the 24th week in 2008 and 2009, because those crops were terminated at 18 weeks after planting.

The aboveground biomass samples were collected in a 1.5 m section in each of the two middle rows of all experimental plots. Grains, cobs, and husks were separated from leaves (lamina and sheath) and stems.

The wet biomass weights of leaves and stems were recorded. Sub-samples were collected, ground, weighed, and dried at 55 °C until constant weight and then used to estimate aboveground dry matter (ADM) and aboveground biomass moisture content (ABMC).

#### 2.3.6. Aboveground biomass quality

Dry aboveground samples were ground using a Wiley (Thomas Scientific, Swedesboro, NJ) sample mill to pass a 1 mm screen. Neutral detergent fiber (NDF), which represents the insoluble matrix of plant cell wall (holocellulose and lignin) (Robbins et al., 1975), was analyzed using Robertson and Van (1977) procedures. A 0.5 g sub-sample was treated in 100 mL of neutral-detergent solution, and in 1–2 mL of amylase enzyme solution. The sample was then filtered, washed, filtered under vacuum, and dried in a forced air oven at 105 °C for 8 h. Cell wall residues were weighed for calculations.

Acid-detergent fiber (ADF), which is a rough partition of the insoluble cell wall into acid-detergent soluble hemicellulose and the insoluble lignin and cellulose, was determined using the Association of Official Analytical Chemists method (AOAC, 1975). A 1.0 g sample of ground tissue was dissolved in 100 mL of acid-detergent solution, and boiled to keep particles in suspension and refluxed for 1 h. The suspended particles were then filtered, washed, and filtered under vacuum. ADF yield was determined in the same manner as NDF.

Klason lignin was used to determine lignin content (AOAC, 1975). ADF material was treated with 24 N sulfuric acid for 3 h, filtered, rinsed, and oven dried at 105 °C. Acid detergent lignin (ADL) residues were weighed and ashed at 450 °C. The acid insoluble ash residues were weighed and subtracted from ADL to provide ash-free lignin estimate.

To estimate ash content, a 1 g sample was placed into a crucible and oven-dried at 105 °C. The residues were weighed to estimate 100% dry biomass content and ashed at 450 °C. The ash residue was weighed to calculate ash content (AOAC, 1975).

Hemicellulose was estimated as the difference between NDF and ADF. Cellulose was estimated as the difference between ADF and Klason lignin. Holocellulose was estimated as the sum of cellulose and hemicellulose.

### 2.4. Experimental design and statistical analysis

Bioenergy crops, irrigation, and tillage practices were evaluated in a strip-split plot design. The four crop varieties were horizontal treatments. Two irrigation regimes were vertical plots, and two tillage systems were sub-plots.

The experimental area (84 m long by 60 m) was divided into 4 replications. Each replication was divided into 4 areas which were separated by borders 9.1 m long by 3.7 m wide in order to evaluate the bioenergy crops: PS, FS, GS, and corn. Plots were divided into two different irrigation regimes (irrigated, non-irrigated), which were also separated by borders 9.1 m long by 3.7 m wide. Irrigation regime plots were also divided in two different tillage systems (conservation and conventional) which resulted in 64 experimental units 9.1 m long by 3.7 m wide. Experimental units were composed of 4. All measurements were collected from the two middle rows of each experimental unit.

All data were analyzed using the appropriate strip-split-plot design with PROC MIXED of SAS (Littell et al., 1996). Replication and its interactions with bioenergy crops (crops) and irrigation regimes were considered random effects, and their interactions were considered fixed. Data were analyzed and discussed considering both years, except when significant year × treatment interaction occurred. In this case, data were analyzed by year. Treatment means were separated by the LSMEANS procedure (SAS Inst.

**Table 1**
In-season cumulative growing degree units (GDUs) and precipitation for different biomass sampling periods and precipitation[a] near Shorter, AL.

| Biomass sampling/precipitation | 2008 | 2009 | 15-years normal |
|---|---|---|---|
| *GDU* | | | |
| Sorghum crops[b] | | | |
| 14 WAP[c] | 1503.3 | 1589.7 | 1529.4 |
| 18/20 WAP[c,d] | 1865.3 | 2284.4 | 1841.8/2299.9 |
| 24 WAP[c] | 2617.2 | 2585.0 | 2601.4 |
| Corn crop[e] | | | |
| 14 WAP[c] | 1357.7 | 1456.2 | 1410.8 |
| 18/20 WAP[c] | 1681.8 | 2115.2 | 1686.9/2104.6 |
| 24 WAP[c] | 2392.7 | 2407.2 | 2404.7 |
| *Water inputs* (mm) | | | |
| Non-irrigated plots | 337 | 573 | 318 ± 38 |
| Irrigated plots[f] | 468 | 631 | – |

[a] Growing season considered from planting to 14 weeks after planting (first biomass sampling period).
[b] 1990 – photoperiod sensitive sorghum, SS506 – forage sorghum, and NK300 – grain sorghum.
[c] Weeks after planting (WAP).
[d] Samples collected at 18 and 20 weeks after planting in 2008 and 2009, respectively.
[e] Pioneer31G65.
[f] Sum of irrigation and natural rainfall.

Inc., Cary, NC) when protected by *F*-tests significant at $\alpha$ of 0.10, and are reported as least squares means ± SE.

## 3. Results and discussion

### 3.1. Environmental conditions

Cumulative precipitation was greater in 2009 (573 mm) than in 2008 (337 mm) during the growing season (Table 1). Cumulative precipitation in 2008 was considered normal due to its small variance from the 15-year normal average (318 ± 38 mm). However, unusually high precipitation was observed in 2009 as compared to the 15-year average.

Cumulative growing degree units for sorghum crops had similar values among 2008, 2009, and 15-year normal average at first (14 WAP) and third (24 WAP) sampling period. However, CGDUs at second sampling period were higher in 2009 than in 2008. Corn had the same trend in CGDUs as described above for sorghum crops (Table 1). Precipitation during 18 and 19 WAP delayed the second harvest period in 2009 which allowed the bioenergy crops to accumulate more GDUs.

### 3.2. Rye cover crop

In 2008, rye biomass production was low (0.26 Mg ha$^{-1}$) and did not offer good soil cover because an average of 1.4 Mg ha$^{-1}$ of rye dry matter is required to effectively protect soil from erosion (Kessavalou and Walters, 1997). Rye dry matter collected for all experimental units before planting sorghum and corn showed that plots prepared for different crops were not significantly different from each other ($P$ = 0.34). In 2009, rye dry matter samples collected in conservation plots was 2.58 Mg ha$^{-1}$ and showed no significant differences in yields across treatments ($P$ = 0.72).

### 3.3. Plant population

No significant plant population differences among crops were found when comparing years ($P$ = 0.91). FS, GS, PS and corn showed an average of 380,325; 375,840; 359,470, and 78,694 plants ha$^{-1}$, respectively, at 6 WAP for both years. Those plant population results were similar to the company's seed planting density recommendations which were between 271,800 and 407,700 plants ha$^{-1}$ for FS,

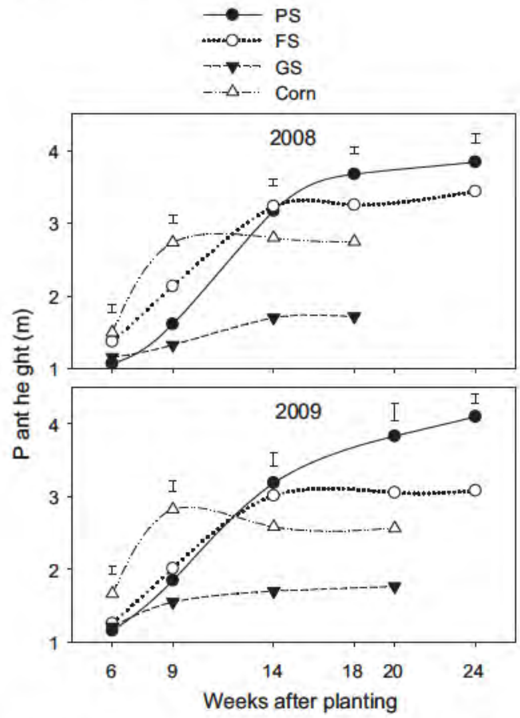


**Fig. 1.** Plant height measurements for all sampling periods in 2008 and 2009 near Shorter, AL. Vertical error bars denote significant differences – L.S. means$_{0.1}$ separation between bioenergy crops within same sampling periods (WAP) and years.

GS and PS (Sorghum Partners Inc., 2008a,b, 2011). Corn recommendations cited that the optimum plant population for this hybrid was 78,300 plants ha$^{-1}$ (Pioneer, 2011).

Significant differences in plant population occurred at 6 and 14 WAP within each crop in 2008 and 2009. FS and GS had significant population decreases between these sampling times for both years. FS had a population reduction of 8.15% (356,106 vs. 327,012 plants ha$^{-1}$) and 28.7% (362,834 vs. 258,558 plants ha$^{-1}$) in 2008 and 2009, respectively ($P \leq 0.01$). GS had a population reduction of 5.4% (376,064 vs. 355,882 plants ha$^{-1}$) and 22.9% (375,616 vs. 289,729 plants ha$^{-1}$) in 2008 and 2009, respectively ($P \leq 0.01$).

### 3.4. Plant height

Corn was the tallest entry at 6 WAP in 2008 and 2009 (Fig. 1). Sorghum varieties were not significantly different in plant height from each other, but they were significantly different from corn ($P$ = 0.01). High precipitation at 6 WAP could have increased height of GS and PS in 2009. Mastrorilli et al. (1999) concluded that most sorghum plants had high water demand during the first weeks, and irrigation should be emphasized in early stages and any time in which soil water is below wilting point.

At 9 WAP, PS surpassed GS in height in both years. In 2008, corn was taller than FS, PS, and GS ($P \leq 0.01$). The same trend was observed in 2009 ($P \leq 0.01$). Additionally, PS and FS showed no significant plant height differences at 14 WAP for both years. Corn reached anthesis during this period, resulting in similar height as 9 WAP. At 18 WAP in 2008, PS (3.67 m) was significantly higher than FS (3.25 m, $P \leq 0.01$) because FS reached anthesis at 18 WAP which decreased vertical plant growth. The same results were found at 20 WAP in 2009. Finally, PS was continuously growing at 24 weeks after planting for both years reaching 3.84 m (2008), and 4.09 m (2009). This result might confirm the hypothesis that PS has a longer vegetative phase than FS and GS which might result in more dry matter production over longer periods.

Irrigation significantly affected plant height in both years for all periods (data not shown). Plants in irrigated plots were significantly taller than non-irrigated plants, except at 6 WAP in 2009. Carmi et al. (2006) found similar results for forage sorghum varieties, and Sakellariou-Makrantonaki et al. (2007) also concluded that irrigation resulted in taller sorghum plants. However, no significant differences between irrigation (180 mm vs. 250 mm) were found between two different silage sorghums (Yosef et al., 2009). Additionally, plants in non-irrigated plots (1.36 m) were slightly taller than in irrigated plots (1.28 m) at 6 WAP in 2009, because no irrigation was needed during the first 6 weeks during 2009 season due to 378 mm of rainfall.

Significant crop × irrigation interactions were found at 14 and 18 WAP in 2008; and at 14 WAP in 2009. Those interactions suggested that irrigated GS and corn were shorter than FS and PS (data not shown). Irrigation did not improve GS and corn plant height after 14 WAP, since both varieties were mature while PS and FS were still growing (vegetative stage).

Plants in conservation tillage were still growing vegetatively for both years during all periods, except 24 WAP (data not shown). Omer and Elamin (1997) suggested that in-row subsoiling (vertical soil disruption) improved soil aeratoin and infiltration resulting in taller sorghum plants.

Significant crop × tillage interactions were found at 6 and 9 WAP in 2008 (data not shown). Corn was the only crop that was taller in conservation plots at 6 WAP in 2008. However, conservation tillage improved plant height for PS, FS, and corn, except GS at 8 WAP. In 2009, crops × tillage interactions were found at 20 WAP in 2009. Results suggested that tillage treatments were not significantly different for both PS and FS. Similar results were found at 24 WAP for both years.

### 3.5. Aboveground dry matter

Due to higher precipitation in 2009 than 2008 (Table 1), significant ADM differences among crops were found when comparing years ($P \leq 0.01$). Therefore, the results of ADM were analyzed by year. Yields from conservation plots (18.47 Mg ha$^{-1}$) and conventional plots (18.39 Mg ha$^{-1}$) did not differ in ADM in 2008 ($P = 0.87$; Fig. 2). Similar results were found by Shirani et al. (2002) and Angers et al. (1997). All sorghum varieties showed higher ADM production than corn for both years which was similar to results reported by Cogle et al. (1997) who reported no differences among different tillage systems, but also reported sorghum biomass yield higher than corn. In 2009, conservation plots (12.26 Mg ha$^{-1}$) showed higher ADM production than conventional plots (11.02 Mg ha$^{-1}$; $P = 0.01$). Several factors could have influenced these ADM differences between tillage treatments in 2009, including increased amounts of rye cover crop that were produced that could have resulted in better growing conditions for biomass production under conservation tillage. Conservation tillage was considered more suitable for soils which had good drainage (Al-Kaisi et al., 2005), and Marvyn soils were described as well drained, and moderately permeable (OSD, 2011). Furthermore, conservation tillage has been noted for enhanced plant growth due to increased root proliferation and water infiltration than conventional tillage systems (Reeves and Touchton, 1986).

ADM differed with year and WAP (Fig. 3). In 2008, ADM differences among crops were found when comparing LS means calculated from all tillage and irrigation treatments. FS showed the highest ADM production at 14 WAP, followed by PS, GS and corn. However, PS surpassed FS at 18 WAP followed by GS and corn. At 24 WAP, PS showed higher yields than FS with, respectively, 30.13 Mg ha$^{-1}$ and 24.00 Mg ha$^{-1}$. Thus, PS was the only variety that showed significantly higher ADM production at 24 WAP than at other sampling periods. Results indicated that PS had high biomass production potential over long periods (from 18 WAP). On the other hand, FS showed no significant differences between 18 and 24 WAP which were just significantly higher than 14 WAP. GS and corn showed the same yields in both 14 and 18 WAP ($P \leq 0.01$).

Additionally, irrigated plots had higher ADM yields than non-irrigated plots in 2008 (Fig. 2; $P = 0.01$). Because irrigation was

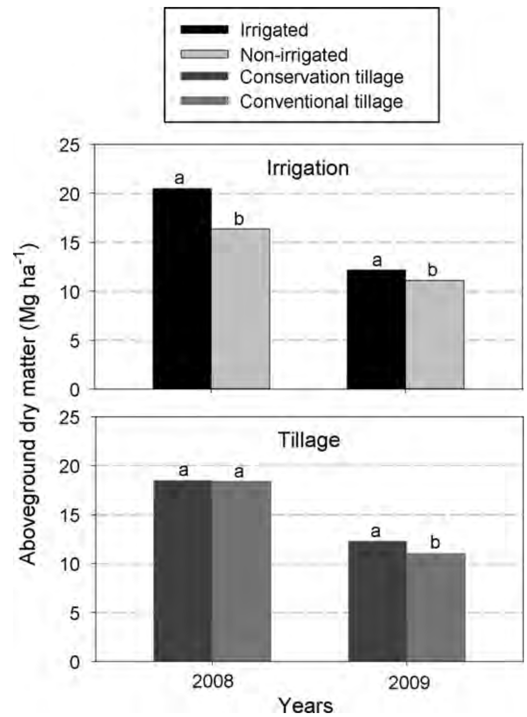


**Fig. 2.** Irrigation and tillage effects on aboveground dry matter production for all sampling periods in 2008 and 2009 near Shorter, AL. Different letters denote significant differences (L.S. means$_{0.1}$) between treatments within years.

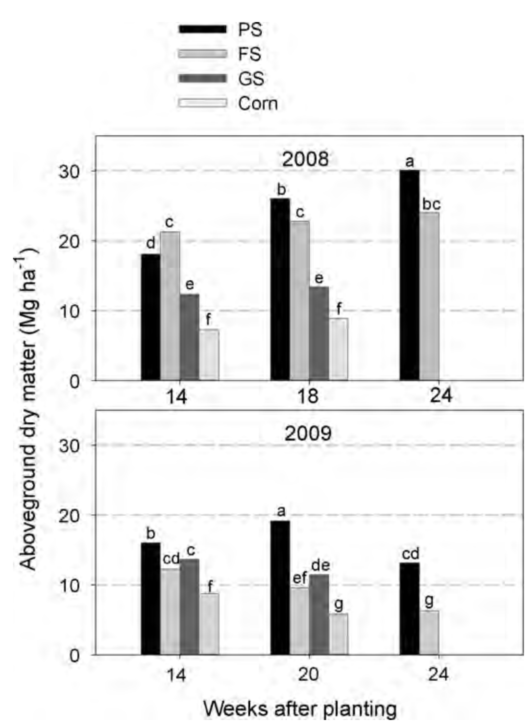


**Fig. 3.** Aboveground dry matter production in 2008 and 2009 near Shorter, AL. Different letters denote significant differences (L.S. means$_{0.1}$) between bioenergy crops and sampling periods (WAP) within years.

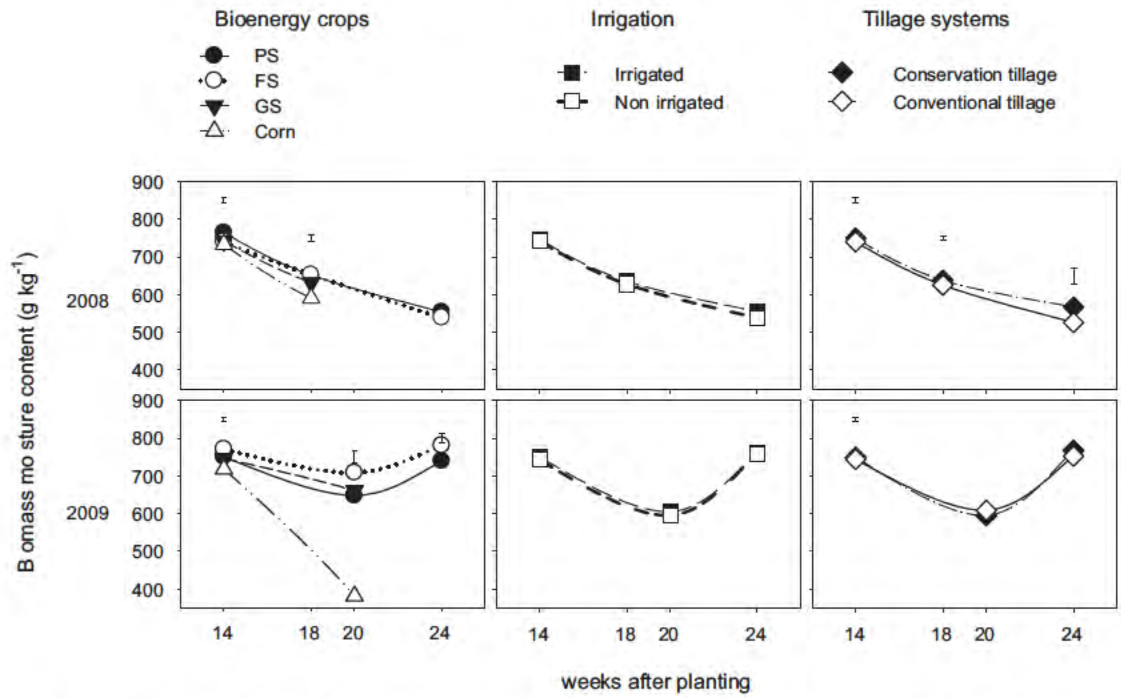


**Fig. 4.** Bioenergy crops, irrigation, and tillage effects on aboveground biomass moisture content in 2008 and 2009 near Shorter, AL. Vertical error bars denote significant differences (L.S. means$_{0.1}$) between treatments within sampling periods (WAP) and years.

terminated at 16 WAP, crops × irrigation interaction showed that PS had no ADM differences between irrigation treatments at 18 and 24 WAP. Thus, irrigated FS was not significantly different for any period in 2008, but non-irrigated FS had higher ADM yields at 24 than 14 WAP ($P = 0.02$).

The overall ADM yield was 37.7% lower in 2009 (11.49 Mg ha$^{-1}$) than 2008 (18.44 Mg ha$^{-1}$) ($P \leq 0.01$). Excessive water, sorghum athracnose (*Colletotrichum graminicola*), and southern corn leaf blight – SCLB (*Bipolaris maydis*) in corn probably decreased ADM yields in 2009. Anthracnose was reported as the major sorghum disease which reduced sorghum yields in hot and humid conditions (Metha et al., 2005). High severity of anthracnose disease in sorghum varieties, such as >75% area diseased in FS at 24 WAP (data not shown) was related to lack of crop rotation. Moore et al. (2009) concluded that successive sorghum crops at same location resulted in lower yields due to high incidence of anthracnose and rice, soybeans, and corn planted before sorghum improved sorghum yields. Furthermore, corn plants were affected by SCLB with ear leaf damage reaching 21–30% at 15 WAP (data not shown) which could be related to decrease in ADM at 20 WAP.

### 3.6. Aboveground biomass moisture content

Overall ABMC was significantly higher in 2009 than in 2008 ($P \leq 0.01$; Fig. 4). This can be partly explained by greater volumetric soil moisture (0.24 m$^3$ m$^{-3}$) in 2009 at 15 WAP as compared to soil moisture of 0.17 m$^3$ m$^{-3}$ in 2008 at 16 WAP (data not shown). This higher soil water content in 2009 could result in higher soil water availability and uptake by the bioenergy crops. No significant differences in ABMC were found between irrigation treatments, because irrigation was terminated at least 1 week before 14 WAP in both years. However, significant ABMC differences between tillage systems were found at 14 WAP ($P = 0.01$), 18 WAP ($P = 0.05$) and 24 WAP ($P = 0.02$) in 2008 where conservation systems had higher ABMC than conventional system. Nevertheless, significant ABMC differences between tillage systems in 2009 were just found at 24 WAP ($P = 0.03$) where conservation system was greater than conventional.

PS had significantly higher ABMC than GS, FS, and corn ($P = 0.01$) at 14 WAP in 2008. However, FS had the highest ABMC at 14 WAP in 2009 which was significantly different from PS, GS, and corn ($P = 0.01$); thus PS and GS were significantly higher than corn in this harvest period. At 18 WAP, FS, PS and GS were significantly higher in ABMC than corn ($P = 0.01$) in 2008. FS, PS and GS were also higher in ABMC than corn ($P \leq 0.01$) at 20 WAP in 2009, but PS had significantly higher ABMC than PS and GS. Corn showed the lowest ABMC values for all sampling periods in both years, because the corn plants were drier than the sorghum bioenergy crops. In both years at 20 WAP, the corn plants appeared to be completely dry. At 24 WAP in 2008, ABMC for PS and FS did not differ ($P = 0.47$). Conversely, FS had significantly higher ABMC than PS ($P = 0.03$) at 24 WAP in 2009. During 2009, anthracnose disease incidence at 24 WAP was more severe in FS (>75% of leaf diseased) than in PS (45–59% of leaf area diseased) (data not shown) which resulted in a greater leaf blighting levels of FS plants, therefore a higher proportion of stems in FS ADM than in PS might result in higher ABMC for FS. Additionally, ABMC tended to decrease in late sampling periods (visual comparisons only); except for 24 WAP in 2009. According to AWIS (2011), total precipitation of 121 mm was observed from 2 to 4 days before 24 WAP sampling period in 2009 which probably resulted in significant PS and FS moisture uptake. Finally, Wilcke et al. (1999) recommended that moisture content of biomass samples fall between 150 g kg$^{-1}$ and 200 g kg$^{-1}$ for storage; therefore ADM conditioning of all bioenergy crops might be necessary because the lowest ABMC value found among all sampling periods in both years was corn at 20 WAP.

### 3.7. Aboveground biomass quality

#### 3.7.1. Holocellulose and lignin concentration

Holocellulose is the desirable portion of cellulosic biomass, because it can be converted to carbohydrates (xylose, mannose,

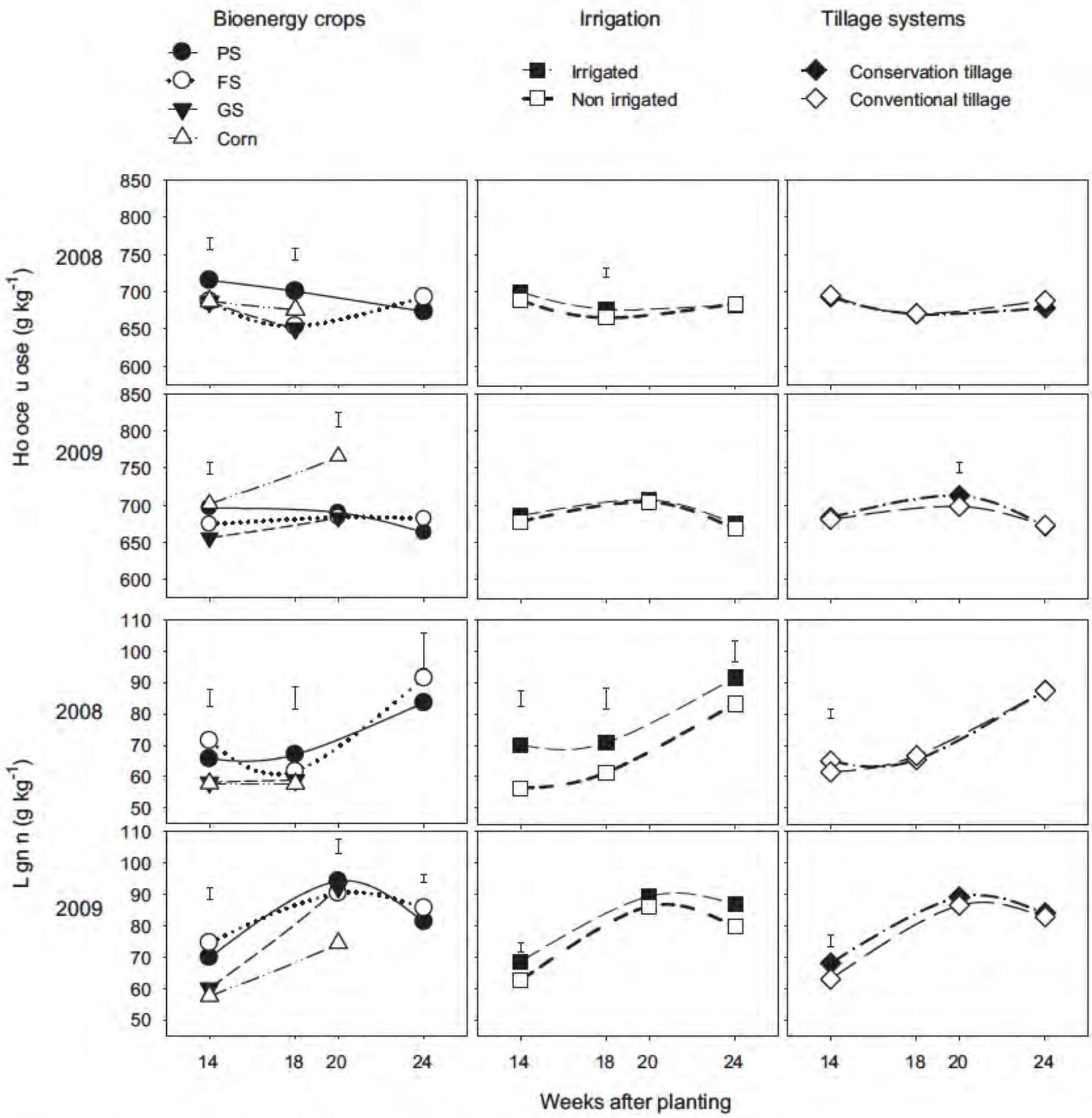


**Fig. 5.** Bioenergy crops, irrigation, and tillage effects on aboveground biomass holocellulose and lignin concentration for 2008 and 2009 near Shorter, AL. Vertical error bars denote significant differences (L.S. $means_{0.1}$) between treatments within sampling periods (WAP) and years.

galactose, and glucose). Consequently, those carbohydrates can be used for ethanol production.

Holocellulose concentration (HC) was significantly higher in 2009 than in 2008 ($P = 0.01$; Fig. 5). High precipitation and high incidence of anthracnose disease in 2009 could have decreased HC. Due to these differences, the data were analyzed by years.

Significant differences were found at 14 weeks after planting (WAP) in 2008. During this period, PS had significantly higher HC than corn, GS, and FS at 14 WAP ($P = 0.02$). However, crops × irrigation effect ($P = 0.02$) at 14 WAP indicated that PS had significantly higher HC than the other crops when irrigated (data not shown), but there were no significant differences among crops under non-irrigated conditions. At 18 WAP ($P = 0.01$), PS showed significantly higher HC values than corn, FS and GS, but FS were not significantly different from GS. At 24 WAP, FS and PS showed no significant HC differences.

In 2009, corn and PS had greater HC than FS and GS at 14 WAP ($P = 0.01$). However, corn had significantly higher HC than PS, FS and GS at 20 WAP ($P \leq 0.01$). Furthermore, FS had no HC significant differences from PS at 24 WAP. A reasonable explanation for corn having higher HC than PS in 2009 is that high anthracnose incidence on PS plants resulted in leaf losses. Leaves could have higher HC than stems, therefore lower HC in PS ADM could be related to leaf losses.

Irrigated plots only had higher HC than non-irrigated plots at 18 WAP in 2008 ($P = 0.08$). At this sampling period, irrigated treatments showed higher HC than non-irrigated treatments. Tillage treatments showed no significant HC differences in 2008. Conversely, conservation treatments had higher HC than conventional treatments at 18 WAP ($P = 0.01$) in 2009 (Fig. 5). Statistical differences in tillage and irrigation treatments are considered minor because they are smaller than 2 and 4.6%, respectively.

The U.S. Department of energy (DOE) cited switchgrass as the most probable cellulosic energy crop (U.S. DOE, 2005). McLaughlin et al. (1999) cited switchgrass HC ranging from 540 to 670 g $kg^{-1}$. However, all tested crops showed higher or equal HC than switchgrass. PS, FS, GS, and corn showed ranges of 663–715 g $kg^{-1}$, 654–693 g $kg^{-1}$, 651–686 g $kg^{-1}$, and 676–766 g $kg^{-1}$, respectively.

Lignin is the undesirable portion of biomass when considering bioethanol production, because it cannot be converted into carbohydrates, and it has a recalcitrant effect. In other words, lignin masks holocellulose (cellulose and hemicellulose) which reduces

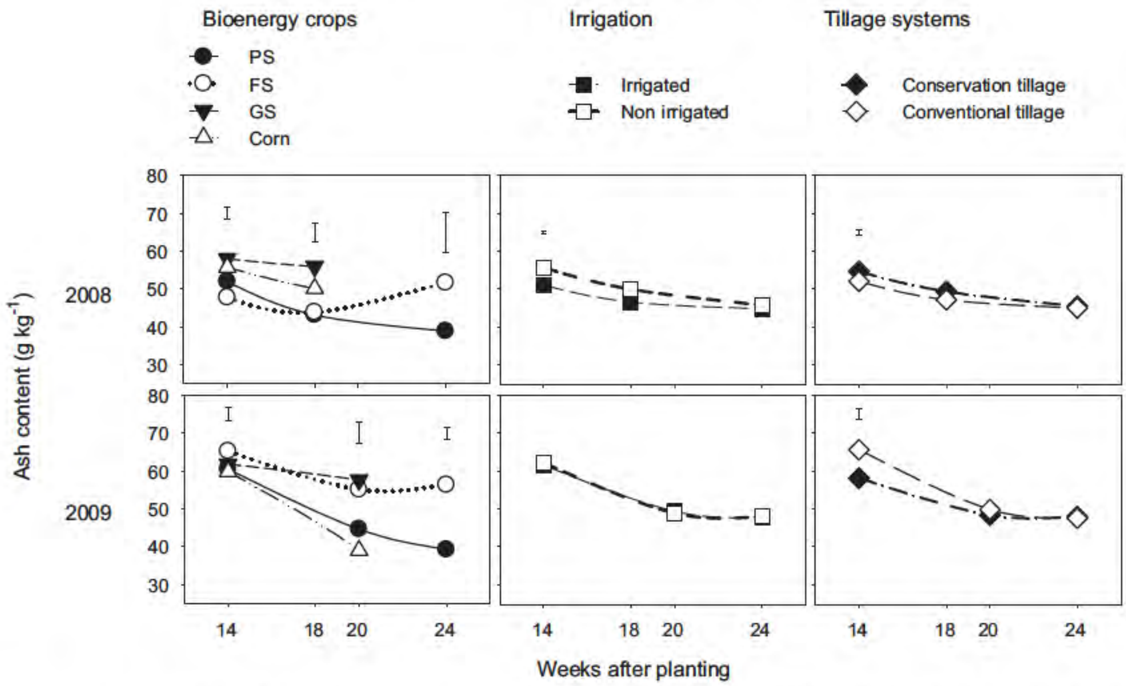


**Fig. 6.** Bioenergy crops, irrigation, and tillage effects on aboveground biomass ash concentration for 2008 and 2009 near Shorter, AL. Vertical error bars denote significant differences (L.S. means$_{0.1}$) between treatments within sampling periods (WAP) and years.

carbohydrate conversion. Therefore, low lignin concentration (LC) is desired in cellulosic materials in order to enhance bioethanol production (Weng et al., 2008).

LC was significantly different between years ($P \leq 0.01$). Higher LC was found in 2009 than in 2008. Those differences could be related to higher precipitation in 2009, because better water status could increase lignin content on different forage species, such as sorghum (Amaducci et al., 2000). Furthermore, anthracnose disease in sorghum plants and SCLB disease in corn plants resulted in leaf losses. Because leaves had lower lignin content than stems (Carmi et al., 2006), high LC could be expected in 2009 season for all crops.

Crops were significantly different in LC for both years. In 2008, FS had the highest LC which was significantly different from PS, GS and corn at 14 WAP ($P \leq 0.01$). However, at 18 WAP ($P \leq 0.01$), PS showed significantly higher LC than FS, GS and corn. Thus, PS and FS were significantly different in LC for all sampling periods, where FS were significantly higher in LC than PS at 24 WAP ($P = 0.06$). However, GS and corn always showed no significant differences in LC at 18 WAP.

In 2009, FS and PS had significantly higher LC than GS and corn at 14 WAP ($P \leq 0.01$). However, at 20 WAP, all sorghum varieties (PS, GS, and FS) showed significantly higher LC than corn. Additionally, FS showed higher LC than PS at 24 WAP, $P = 0.02$ (Fig. 5).

Irrigated plots showed higher LC than non-irrigated plots at 14 ($P = 0.01$), 18 ($P = 0.01$) and 24 WAP ($P = 0.01$) in 2008. In 2009, irrigated treatments had higher LC than non-irrigated treatments ($P = 0.01$). Carmi et al. (2006) found similar results, indicating that irrigation increased lignin content for different forage sorghum species. No LC differences were found at 20 and 24 WAP.

In both years, conservation tillage had significantly higher LC than conventional tillage at 14 WAP. Tillage treatments had no significant LC differences at other sampling periods for both years.

Switchgrass LC was cited as 190 g kg$^{-1}$ (Lee et al., 2007). However, all tested crops showed lower LC than switchgrass. PS, FS, GS and corn showed ranges of 66–94 g kg$^{-1}$, 61–91 g kg$^{-1}$, 58–92 g kg$^{-1}$, and 58–74 g kg$^{-1}$, respectively.

### 3.7.2. *Ash concentration*

Ash concentration (AC) in cellulosic materials is relevant information for thermal and biochemical technologies which produce electricity and fuel. Low AC increases conversion efficiency and decreases slagging (Sanderson et al., 1996). Slagging is defined as ash and inorganic deposits on boilers walls which decreases heat transfer and can make a power plant inoperable (Burner et al., 2009). Therefore, low AC is desirable to produce bioenergy.

Crops were significantly different in AC for both years. In 2008, GS and corn were higher in AC than PS and FS at 14 WAP, but only GS were significantly different from FS at 14 WAP ($P = 0.01$). The same trend was observed at 18 WAP ($P = 0.03$). FS showed significantly higher AC than PS at 24 WAP (Fig. 6), but those differences were valid just under irrigated treatments (crops × irrigation interaction; $P = 0.10$).

In 2009, no significant AC differences were found among crops at 14 WAP. GS and FS showed significantly higher AC than PS and corn at 20 WAP ($P = 0.01$). And, FS showed higher AC than PS at 24 WAP ($P = 0.01$; Fig. 6). McLaughlin et al. (1999) cited switchgrass AC ranging from 45 to 58 g kg$^{-1}$. However, all tested crops showed similar AC. PS, FS, GS and corn showed ranges of 38–60 g kg$^{-1}$, 44–65 g kg$^{-1}$, 56–62 g kg$^{-1}$, and 50–60 g kg$^{-1}$, respectively.

Significant differences between years were found when comparing AC as shown in Fig. 6. AC was greater in 2009 than in 2008 ($P \leq 0.01$).

Irrigation treatments were not significantly different in AC for both years, except at 14 WAP in 2008 where the non-irrigated treatment had higher AC than the irrigated treatment.

Tillage treatments were significantly different in AC for both years at 14 WAP. Conservation tillage was significantly higher in AC than conventional tillage in 2008 ($P = 0.01$). Conversely, conventional tillage showed higher AC than conservation tillage in 2009 ($P = 0.01$). Furthermore, irrigation × tillage interaction ($P = 0.01$) in 2008 indicated that conventional tillage had higher AC just in non-irrigated conditions, where tillage treatments were not significantly different in AC under irrigated conditions.

## 4. Conclusions

Sorghum bioenergy crops yielded more ADM than corn during all sampling periods in both years; and they yielded more than corn with irrigation and conservation tillage. In some production scenarios, then, sorghum may be superior to corn for cellulosic biomass. Most yield parameters exhibited significant environmental variation. Higher cellulosic biomass production reported in 2008 than 2009 season was related to the presence of anthracnose and southern corn leaf blight diseases in sorghum and corn crops, respectively. Thus, crop rotation may be recommended. Lodging which affected PS, FS and GS sorghum varieties could be related to high plant population. Therefore, sorghum plant populations for biomass production in the southeastern U.S. should be reevaluated.

Irrigation positively affected cellulosic biomass production in both years. Higher cellulosic biomass production was noted for conservation than conventional tillage in 2009. Better rye soil cover found in 2009 (2.57 Mg ha$^{-1}$) than 2008 (0.26 Mg ha$^{-1}$) was attributed to increased rye dry matter production in 2009 caused by better spring weather conditions.

Biomass moisture content were higher for sorghum bioenergy crops than corn; however all bioenergy crops, including corn, need to be conditioned to reduce moisture content before storage. Cellulosic biomass quality parameters were only slightly significantly different among crops for all sampling periods. Variation in holocellulose, lignin, and ash concentration among crops was less than 8.3, 2.0, and 1.9%, respectively. Therefore, total cellulosic biomass production was more important that cellulosic biomass quality for selecting the best crop.

PS was considered the best tested crop to produce maximum amounts of cellulosic biomass (ADM) which produced 26.04 and 30.13 Mg ha$^{-1}$ at 18 and 24 WAP. However, FS can be a reasonable alternative if a shorter growing season is desired and harvesting occurs at 14 weeks after planting (21.27 Mg ha$^{-1}$). Plant height readings clarified that PS had slower development than other crops. However, its' prolonged vegetative stage in the southeastern U.S. photoperiod resulted in high cellulosic biomass production in late harvests.

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