A New Spin on an Old Crop for Bioenergy: Sorghum

by

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Abstract

According to Renewable Fuels Standard (RFS) – Energy Policy Act of 2005, the U.S. must reduce foreign oil dependence, where the target is to produce 36 billion gallons of oil equivalent in 2022 (RFA, 2010). Cellulosic material is considered an alternative source for bioenergy production, because it is renewable and environmentally friendly (Peters and Thielman, 2008). Annual crops, such as sorghum *(Sorghum bicolor L.)* can be cultivated in current row-crop production systems, which could provide grain and cellulosic feedstock production in Southeastern U.S. However, the impacts of removing cellulosic biomass on agricultural soils must not be ignored, and sorghum biomass has relatively high moisture content which should be dried before transported to reduce costs. Different experiments were established at the E.V. Smith Research Station, Shorter, AL to evaluate quantity and quality of sorghum biomass production, to monitor soil impacts due to biomass production/removal, and determine the best approach to drying sorghum biomass. Three types of sorghum: grain sorghum – NK300 (GS), high biomass forage sorghum – SS 506 (FS), and photoperiod sensitive forage sorghum - 1990 (PS) and a forage corn *(Zea mays L.)* – Pioneer 31G65 were grown for two consecutive years (2008 and 2009) under irrigated and non-irrigated treatments, and under two different tillage systems: conventional (total disked area, 0.15 m depth) and conservation tillage (in-row subsoiling, 0.30 m depth). The results indicated that irrigation affected aboveground dry matter (ADM) positively in both years, but conservation system improved ADM production only in 2009. Holocellulose, lignin and ash content differences among crops for both evaluated years were lower than 8.3%, 2.0% and 1.9 % respectively, and they were considered minor. PS was considered the best crop for ADM production, respectively, 26.04 and 30.13 Mg ha^{-1} at 18 and 24 weeks after planting in 2008. ADM production in 2009 decreased due to leaf losses caused by Anthracnose *(Colletotrichum graminicola)* disease which affected all sorghum varieties. Furthermore, changes in soil characteristics were detected after 2 years of cropping. Soil organic carbon (SOC) increased near soil surface (0.10 – 0.15 m), but it decreased from 0.40 – 0.45 m. SOC losses were higher in conventional than conservation tillage. Total nitrogen in soil (N) drastically increased in deep layers due to percolation. Additionally, bulk density (Bd) values increased at all evaluated depths. Irrigated plots had higher Bd than non-irrigated plots at both 0.05 – 0.10 and 0.20 – 0.25 m soil layers. And cone index (CI) values showed restrictive layers at depths of 0.15 m for conventional plots. Therefore, conservation tillage and photoperiod sensitive sorghum (1990) – PS were recommended. In another experiment, sorghum-sudan hybrid was harvested with two different headers on a self-propelled windrower: a Massey Ferguson 9145 (sickle) and a Massey Ferguson 9185 (disc). The disc header was comprised of two pairs (rear/front) of metal conditioner rollers which used three different pressures (0, 3500, and 7000 kPa), and two different gaps (0 and 0.02 m). Sorghum-sudan biomass moisture content (%) was evaluated daily until it remained constant. Results revealed that the higher pressures and smaller gaps resulted in faster drying of biomass. The best settings for the disc header were “7000 kPa – 0 m” or “7000 kPa – 0.02 m” which showed, respectively, moisture content levels of 13.6 % and 16.8 % after 14 days. These results indicate that proper setting of the disc header including properly setting the pressures and gaps are important to achieve optimum drying of sorghum biomass.

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LITERATURE REVIEW

1. Fossil fuels shortage and biofuels as an alternative source

Fossil fuels such as coal, petroleum and natural gas are considered primary energy sources, accounting for over 85% of the world energy demand. Petroleum is the largest share of these energy sources, accounting for 40% of the world's consumption. Oil demand is projected to increase by 1.7% per year from 2000 to 2030, when consumption will be about 2.4×10^9 L of oil equivalents. This continuous increment of oil demand is due to the economic growth that drives developing countries to become more motorized (IEA, 2002).

Therefore, the world energy demand based on fossil fuels is becoming troublesome, because those energy sources are non-renewable. Future shortages can be expected, resulting in economical and political issues among nations. The United States imported 582×10^6 L of crude oil in 2007 (EIA, 2010b), and was dependent on other countries to supply its primary energy demand. However, the interest in alternative energy supplies that can release the United States from oil dependence is increasing with research being focused on developing other energy source options that are able to replace fossil fuels, especially oil.

Among the alternatives to replace fossil fuels in the transportation sector, biofuels are an alternative source that should be carefully analyzed. Production of biofuel results in increased security of the U.S. energy supply and diminishes the effects of climate change which are two primary U.S. government policies (Peters and Thielman, 2008). The US government established the Energy Independence and Security Act of 2007 amending the Renewable Fuels Standard (RFS) – Energy Policy Act of 2005, in order to reduce foreign oil dependence, greenhouse gas emissions and provide meaningful economic opportunity in the U.S. The RFS target for the US is to produce 36 billion gallons in 2022 (RFA, 2010).

Biofuel is defined as a liquid or gaseous fuel for the transportation sector that is predominantly produced from biomass (Demirbas, 2008). The Renewable Fuels Standard (RFS) set different definitions according to biofuel types, such as conventional biofuel, advanced biofuel, cellulosic biofuel and biomass-based diesel. Conventional biofuel is ethanol derived from corn starch and reduces greenhouse gas (GHG) emissions by 20% (RFA, 2010). Advanced biofuel is any renewable fuel that is derived from renewable biomass and reduces GHG emissions by 50%. Cellulosic biofuel is renewable fuel from cellulose, hemicellulose or lignin derived from renewable biomass that reduces GHG emissions by 60% (RFA, 2010). Projections for 2022 predict corn *(Zea mays* L.*)* ethanol will be the largest biofuel produced, making 56.8×10^9 L available, with cellulosic ethanol contributing an additional 27.3×10^9 L (EIA, 2010a).

Alternative fuel sources should not only have similar performance as oil, but also be renewable and environmentally friendly. Among renewable fuels, ethanol appears as a superior alternative. The Renewable fuels Association – RFA (2010) compared ethanol engine performance with a 113 octane rate against 87 for unleaded gasoline. The studies revealed that ethanol reduced carbon dioxide emissions by 29%. Blending ethanol and gasoline is an option to decrease petroleum dependence and Agarwal (2007) concluded that ethanol used as an additive to unleaded gasoline improved engine performance and exhaust emissions by decreasing CO and HC , however CO_2 emissions increased marginally.

The main ethanol producers in 2005 were Brazil, US, and China, which produced, respectively, 16,500, 16,214 and 3,800 million ethanol liters and showed growth rates of 7.1, 21.2 and 4.1% (Walter et al., 2007). In the US, the main producers are located in the Midwest (Iowa, Illinois, South Dakota and Minnesota). The produced ethanol is sold as octane enhancer or oxygenate blended with petrol covering up to 3% of the USA gasoline demand (RFA, 2006). The Energy Information Administration (EIA, 2010a) listed two different uses of ethanol in U. S. transportation sector: E85 (fuel mixture of 85% ethanol and 15% gasoline) and Ethanol – gasoline blending. The projections assume that the E85 consumption will start with 127 quadrillions of kJ per year in 2015, reaching 928 quadrillions of kJ per year in 2030, where the annual growth will be 33.5% during the period from 2006 to 2030. Therefore, the ethanol-gasoline blending is already being consumed, with 496 quadrillions of kJ being used in 2006. Ethanol is projected to have an annual growth rate of 3.7% reaching 1,192 quadrillions of kJ per year in 2030.

For these reasons, new paths for ethanol production should be developed in order to supply future demand, diminish international oil dependence and reduce GHG emissions.

2. Bioethanol production

Bioethanol is the fuel derived from renewable sources of feedstock, such as wheat (*Ttriticum aestivum* L.*)*, sugar beet *(Beta vulgaris* L.*)*, corn, straw, cellulosic material, and others (Demirbas, 2008). Bioethanol production in the U.S. was 433 quadrillions of kJ in 2006, mostly from corn starch. In addition, projections are assuming that bioethanol from cellulose will be a new source by 2010, with a small contribution of 10.5 quadrillions of kJ, but it will reach 612 quadrillions of kJ in 2010 when the total ethanol source amount is projected to be 2,121 quadrillions of kJ (EIA, 2010a).

Bioethanol production from cellulose is a recent technology. The conversion includes two processes: hydrolysis of cellulose in lignocellulosic materials to fermentable reducing sugars, and fermentation of the sugars to ethanol (Sun and Cheng, 2002). Ethanol derived from cellulosic material tends to have two advantages; environmental (reduced GHGs emissions) and economics (more cost effective and greater energy ratio) (Solomon et al., 2007).

Any cellulosic material may be used to produce ethanol, including crop residues such as stover, straw, husks, etc., thus avoiding economic and social issues, e.g. food production shortage. Peters and Thielman (2008) concluded that biofuel production would have negative effects on living conditions due to increased land competition and implications for food market when land previously utilized for food production is redirected to fuel production.

Therefore, crop residues from common commercial crops should be evaluated in quantity and quality of cellulosic biomass produced. In order to determine their potential, Kadam and McMillan (2003) suggested that collecting the total amount of residue from fields may result in soil erosion and decreased organic matter. Consequently, the agricultural soil function diminishes. In this way, agricultural residues must be sustainably collected when part of the residues remains on site to conserve the soil. Kim and Dale (2004) listed tillage practice, topography, soil type and crop rotation as the factors that must be considered in order to determine the sustainable amount of residues that can be harvested.

The principal component of plant tissue considered and quantified are cellulose, hemicellulose, lignin and carbohydrates. For example, crop residues with low lignin content are desirable for bioethanol production. Lignocellulosic biomass has an optimal conversion to biofuels when lignin is absent (low content or decomposed) (Weng et al., 2008).

To evaluate crop residues from common commercial crops, several factors should be analyzed, not only to increase total amount of residue produced and exported from a field, but also to improve the crop residue quality. Among these factors, plant type/varieties, irrigation, tillage and plant composition are considered crucial and they will be discussed in detail.

3. Corn and sorghum cellulosic biomass to bioenergy production.

3.1. Corn

The U.S. produces 71% of the world corn crop, and is the top exporter. Corn is the largest crop in the U.S. in hectares produced and value (FAS, 2010). In 2007, $37{,}895\text{x}10^3$ ha of corn was planted ($93{,}600\text{x}10^3$ acres) and produced $332{,}077\text{x}10^3$ metric tons of grain ($13{,}073{,}893\text{x}10^3$ bushels). The top states of production are Iowa, Illinois and Nebraska. Alabama lags far behind with 137,593 ha planted that produced 562x10^3 metric tons (NASS, 2010).

Corn stover could be an income source for farmers because the residue could potentially be used in production of bioethanol. The amount of corn stover produced can be predicted from Lindstrom et al. (1981) where the ratio of stover aboveground : corn harvest is approximately 1 : 1. However, just 35% of these residues should be extracted under conventional tillage while 70% is available under no-till farming (Lindstrom et al, 1981). According to Kim and Dale (2004), conservation tillage requires at least 30% of ground cover, but 60% of ground cover should be considered due to uncertainties of locations.

In 2007, the U.S. corn stover production was estimated to be 282x10^6 metric tons of dry mass, considering 15% moisture content for the grain and using a 1 : 1 ratio of dry matter : corn grain. In addition, assuming a theoretical average of 41% of the produced corn residues could be collected from fields without prejudicial effects on environment (Kadam and McMillan, 2003), the cellulosic biomass produced from corn and available for ethanol production was estimated to be 113x10^6 metric tons of dry mass.

Kim and Dale (2004) listed the composition of corn grain and corn stover as follows: grain corn had 86.2% of dry matter, containing 0.60% lignin and 73.70% carbohydrates, against 78.5% of dry matter to corn stover, with 18.69% lignin and 58.96% carbohydrates. Corn stover obviously has much higher lignin content than corn starch. For this reason, the theoretical ethanol yield for corn stover was approximately 290 L dry ton^{-1} , which was lower than the theoretical ethanol yield for corn starch (460 L dry ton^{-1}) (Kim and Dale, 2004). Therefore, the potential ethanol that could be produced in 2007 from corn cellulosic biomass was estimated as 32,741,580x10^{3} L.

To produce both grain and stover that can be harvested for ethanol production, the selected corn variety should have the characteristics that provide good grain yield and high production of cellulosic biomass. However, varieties are developed for specific regions due to different climate and soil conditions in each region. In southeastern U.S., the corn variety “Pioneer 31G65” is common, where Pioneer Hi-Bred International Inc. (2010) describes this variety as suitable to produce large amounts of crop residue. This variety has a plant height of “8” and a drought tolerance of “8” on the scale of “1” to “9” with “1” being poor and “9” being outstanding. And 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, the variety “Pioneer 31G65” is considered a good choice both for grain and cellulosic biomass production.

3.2. Sorghum

The United States is considered the world’s top sorghum producer. In 2007, 3,123x10^{3} ha were planted with 2,754x10^{3} ha being harvested for grain, and the remainder being harvested for silage, producing, respectively, 12x10^{3} tons of grain and 6,206x10^{3} metric tons of biomass. The top states for sorghum grain production were Kansas (5.4x10^{3} metric tons), Texas (4.1x10^{3} metric tons), and Louisiana (602 metric tons). Additionally, Kansas was considered the top producer for sorghum silage (1,120x10^{3} metric tons), followed by Arizona (408x10^{3} metric tons) and California

($391x10^3$ metric tons). Alabama only produced $3x10^3$ metric tons of sorghum silage (NASS, 2010).

Sorghum is considered an important crop for biomass production, and consequently, is an interesting source for bioethanol production from cellulose, where it is capable of producing total maximum dry matter yield of 27.33 tons ha^{-1}in a short time (120 days) with a maximum mean daily growth rate of 22 g m^{-2}. In contrast, corn showed lower values of total maximum dry matter yield, with 22.42 tons ha^{-1} but it had higher maximum mean daily growth rate (23 g m^{-2}), reaching 51 g m^{-2} when fields were planted with higher densities (Loomis and Williams, 1963). In contrast, sorghum may not increase the maximum mean daily growth rate, because increased plant densities gave equivalent dry matter yields, and probably equivalent maximum mean daily growth rates (Habyarimana et al., 2004a).

Ethanol yield from sorghum stover was considered to be 270 L dry ton^{-1}, which is 20 L dry ton^{-1} lower than corn stover ethanol yield (290 L dry ton^{-1}) (Kim and Dale, 2004). The lower conversion rate is due to higher contents of lignin (8%) and cellulose (42.4%) in sorghum residues compared to corn (7.3% of lignin and 38% of cellulose). Hemicellulose content was higher in corn (27.4%) than in sorghum (26%) (Amaducci et al., 2000). However, sorghum had higher dry matter production (26.1 tons ha^{-1}) than corn (18.3 tons ha^{-1}), especially when water was restricted (rainfed condition) (Farre and Faci, 2006; Singh and Singh, 1995; Amaducci et al., 2000). Therefore, sorghum and corn residues should produce, respectively, 7,047 L ha^{-1} and 5,307 L ha^{-1} of ethanol, where sorghum ethanol production could be 32.78% higher than corn.

Many different commercial sorghum varieties and hybrids are available to farmers. Those different plants are basically separated into two groups: grain sorghum and forage sorghum. In order to reach high dry matter yields for ethanol production, it is appropriate to choose forage sorghum varieties/types, which are primarily selected to produce higher volumes of dry matter for silage. Among different forage sorghums, three hybrids are used in the study: (1) NK300, (2) Sucrosorgo506 (SS506) and (3) 1990.

NK300 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 to 7 feet), excellent standability, very good drought tolerance, average stalk sweetness (sugar content) and medium early maturity. NK300 is therefore important for both greenchop (harvesting without allowing the biomass to dry) and stalk grazing (Sorghum Partners, 2010).

In contrast, SS506 is described as a late maturing sorghum, with a high plant height of 3.5m, very good standability, high tonnage yield performance and high stalk sweetness (sugar content). Thus, SS506 has limited use to greenchop, but it can be used for bioethanol production if biomass is dry harvested (Sorghum Partners, 2008b).

Finally, 1990 is a photoperiod sensitive sorghum (headless), which needs less than 12 hours and 20 minutes of daylight to produce a grain head. It is described as having high plant height of 3.5 m, good standability, very high tonnage yield performance and average stalk sweetness (sugar content) (Sorghum Partners, 2008a).

4. Water availability and cellulosic biomass production

4.1. Corn

In order to increase cellulosic biomass yield from corn fields, water availability has an important role. Roygard et al. (2002) pointed out that the main factor affecting corn development was water availability when comparing corn yields in different soils and years. However, water availability was also important for corn dry mass production. Pilbeam et al. (1995) concluded that higher precipitation resulted in higher corn transpiration efficiency and higher dry mass production. with values of transpiration efficiency during periods of high precipitation (475mm) being 109.9 kg ha^{-1} mm^{-1} and resulting in dry mass production of 6.5 Mg ha^{-1} versus a transpiration efficiency of 67.8 kg ha^{-1} mm^{-1} during periods of low precipitation (158mm) resulting in dry mass production of 1.8 Mg ha^{-1}.

To increase water availability to plants, irrigation is considered an effective practice that increases not only corn yield, but also dry matter production, where each plant component (grain, cob, and stover) tends to increase when water is supplied from irrigation, but only up to a point where it becomes excessive (Payero et al., 2008)

Cakir (2004) did not consider corn as a drought resistant plant, because plant height and leaf area were reduced due to water stress during vegetative and tasseling stages, where short-duration water stress during the rapid growth period was enough to decrease the corn dry matter weight by 28-32%. Thus, the plant height for irrigated plots reached 220 cm against 152 cm in non-irrigated plots. Additionally, Traore et al. (2000) found equivalent results, where water deficit during the vegetative period not only delayed leaf appearance and tasseling for 3 days, but also reduced leaf area by 33% and crop height by 15%, which culminated in reduced yields for grain and biomass production.

The water deficit in different periods affected corn development differently, by reducing grain yield and dry matter accumulation. For dry matter accumulation, Eck (1986) noticed that water stress beginning 41 days after planting (4 weeks deficit) decreased dry matter accumulation in leaves, stalks and ears, but water deficit applied after 55 days after planting (2 weeks deficit) only negatively affected stalk growth.

4.2. Sorghum

Cellulosic biomass production under minimal water resources is possible if plants that are able to produce considerable cellulosic biomass under low water supplies are selected. Sorghum is considered a drought resistant plant, where large amounts of biomass were produced in water-limited conditions and larger amounts of biomass produced when sorghum was irrigated (Habyarimana et al., 2004a).

On the other hand, Amaducci et al. (2000) found that sorghum dry matter did not differ significantly between irrigated and non-irrigated plots. Similar results were found by Habyarimana et al. (2004b), where drought resistant sorghum varieties (sorghum landraces-hybrids) reached the same biomass production levels in both irrigated and non-irrigated environments. This statement can be explained by a high degree of heterogeneity for the sorghum types that were evaluated, because Haussmann et al. (2006) found hybrids to be superior when comparing grain yield and above-ground biomass under drought stress conditions.

Sorghum drought resistance has not been considered during the entire growing season. Sorghum's drought resistance tended to change according to development stages, in which sorghum was more sensitive to drought stress in early stages ('leaf' stages), where the biomass productivity decreased substantially if water deficiency was applied (Mastrorilli et al., 1999). Their results showed that sorghum plants begin to close stomata after reach the wilting point (-0.4 MPa). Therefore, irrigation should be used in early growth stages and is necessary any time in which soil water falls below wilting point.

Another factor that affects sorghum drought resistance is plant density. Sorghum plants have the ability to compensate, where lower plant density resulted in higher leaf weight per plant, higher grain weight per panicle and higher tillering ability (Habyarimana et al., 2004a). Additionally, it was recommended that sorghum population be between 150,000 and 200,000 plants/ha.

Several studies compared corn and sorghum in different water regimes, in order to verify the best option when water availability is limited. Sorghum was considered a better option than corn under uncertain and inadequate water sources, due to the fact that sorghum always had a higher dry matter production than corn under extensive periods of water deficit (Singh and Singh, 1994; Amaducci et al., 2000; Farre and Faci, 2006), where sorghum and corn biomass produced under rainfed plots was, respectively, 26.1 and 18.3 t ha^{-1} (Amaducci et al., 2000). This statement was explained based on the different ability of sorghum and corn to extract water from soils, whereas corn absorbed more water from top soil (0 – 0.45 m) while sorghum absorbed more water from sub-soil (0.45 – 1.35 m) (Farre and Faci, 2006; Habyarimana et al., 2004a).

However, studies that evaluated sorghum and corn under irrigated plots, where water availability was not limited, showed different results. Farre and Faci (2006) reported that corn had higher production when both crops were evaluated in little or minimal water deficit. Conversely, sorghum and corn showed the same dry matter production under continuous irrigation (Singh and Singh, 1995). Amaducci et al. (2000) concluded that sorghum produced more dry matter than corn, in irrigated areas, with 26.3 tons ha^{-1} for sorghum and 19.7 tons ha^{-1} for corn.

5. Tillage and cellulosic biomass production.

5.1. Corn

Different tillage systems (no-tillage, minimum tillage, and conventional tillage) affect soil characteristics and consequently plant development. Corn plants can be affected not only in grain production, but also in aboveground mass production, where the potential bioethanol production in corn fields can also be influenced.

Tilled soils (conventional tillage and deep tillage) showed improved soil condition (density and porosity) and corn plant growth (plant height, corn yield and harvest index) compared to no-tilled soils (Khan et al., 2007). Similar results were found by Diaz-Zorita (2000) where vegetative yield was higher in tillage plots with or without deep tillage compared with no-tillage plots. Allmaras et al. (2004) also reported that fields treated with both moldboard plow and chisel plow had higher corn stover yields than in fields with no-tillage.

The explanations for these results were that no-tillage resulted in higher bulk density which culminated in reduced porosity, reduced water availability to plants and reduced root development (Diaz-Zorita, 2000). On the other hand, Khan et al. (2007) argued that these results were a consequence of the “transitional state”, whereby initial production suppression in crops happened due to conversion from a conventional to conservation tillage system.

Conversely, other studies found different results regarding corn dry matter production. Angers et al. (1997) concluded no significant differences among 2-year averages of surface tillage, ridge tillage, and moldboard plowing of silage corn yields. Linden et al. (2000) reported that harvest index (grain dry matter divided by total harvestable dry matter) for corn was not significantly different when compared among no-till, chisel plow, and moldboard systems. Shirani et al. (2002) concluded that reduced tillage (disk harrowing) and conventional tillage (moldboard plowing) showed no significant differences for soil properties and corn biomass production. No statistical differences in soil properties under different tillage systems were found, because the measurements were taken 5 months after tillage system application, with enough time for the soil physical properties to return to pre-tillage conditions.

Similar corn dry matter production was related to the fact that surface layers could offer sufficient nutrients for corn development, resulting in the same biomass production for fields under different tillage treatments. Therefore, deeper root development in tillage plots did not improve corn plant growth (Shirani et al., 2002). But, corn dry matter and grain yield tended to decrease after 5 years with continued no-tillage system as reported by Linden et al. (2000).

Another relevant study was performed by Al-Kaisi et al. (2005), which tested 5 different soil associations under no till and chisel plow. They pointed out that a no-tillage system was more suitable for corn when applied in soil associations with good drainage because higher corn yields (6.7%) were found in these soils. However, crop residue biomass production was similar under different treatments, but biomass quality showed significant differences, with no-tillage plots producing 13% higher N concentrations than chisel plow plots.

Finally, corn emergence and development were also studied for different tillage systems. Results showed that corn emergence rate and plant height (three different days after emergence) were higher in moldboard plow, lower in no-till, and intermediate for both chisel plow and till plant. Dry matter accumulation followed the same tendency in the first year for plant height, but in the second year dry matter between treatments had no significant difference. Although, differences were found during corn development, the measured parameters were not significantly different at the end of the growing season (Al-Darby and Lowery, 1987).

5.2. Sorghum

In order to select tillage managements that match soil conservation and high yields of grain and biomass, several authors studied the behavior of sorghum crops under different tillage systems. However, different results were reported, mostly due to different water content in soils and sorghum root growth.

Some authors, such as Pritchard et al. (2006) reported that sorghum grain yield was greater (6%) in conventional plots than in conservation. Sharma et al. (2005) reported that both sorghum grain and biomass yields were greater in conventional tillage (1476 kg ha^{-1}) than in minimum tillage (1003 kg ha^{-1}) under the highest nitrogen rate., Sainju et al. (2006) found similar results, where sorghum fields had higher grain, biomass yield and nitrogen uptake under chisel till (3,900 kg ha^{-1} for grain and 15,100 kg ha^{-1} for biomass) and strip till (3,400 kg ha^{-1} for grain and 13,900 kg ha^{-1} for biomass) than no-till (2,200 kg ha^{-1} for grain and 8,300 kg ha^{-1} for biomass).

The lower yields found in no-tillage plots were related to a shallow rooting system through the soil profile in those fields (Pritchard et al., 2006), where sorghum plants had less soil volume for water uptake than in plots that received tillage. However, another study also showed that no-tillage had lower production for both grain and straw yields in the second crop year; but, controversially, the first year had no significant differences between tillage and no-tillage plots (Ouedraogo et al., 2007).

Other results also showed that no-tillage had similar performance as other tillage management systems. For example, Baumhardt and Jones (2002) concluded that no-tillage treatments had higher sorghum grain production than stubble mulch-tillage and was unaffected by subsoil tillage practices (paratill, no-paratill). Moreover, Cogle et al. (1997) observed no significantly statistical differences among three different tillage managements (zero-tillage, shallow tillage – 10 cm, and deep tillage – 20 cm) for both corn and sorghum grain yields. The aboveground mass production was not significantly different among those tillage managements, but sorghum aboveground mass was always superior than corn in any treatment applied.

Not only tillage, but also residue management was investigated by Sow et al. (1997), who conducted a study using four different management systems: furrow disking (FD), conventional tillage (CT), and conservational tillage with (NT+) or without (NT-) wheat residue maintained on soil surface. The results showed that FD (4840 kg ha^{-1}) had the highest sorghum yield followed by NT+ (4690 kg ha^{-1}), and both treatments NT- and CT had the lowest yields, respectively, 4070 kg ha^{-1} and 4020 kg ha^{-1}. The authors explained that these different yields were due to different soil water content within the 0-30 cm of soil layer, where more evaporation occurred under CT and NT- due to residue absence, which resulted in less water availability for sorghum plants. Moreover, Thomas et al. (1990) studied sorghum development under different tillage management systems: disc (D), blade (B) and no-till (Z) tillage and also had two different residue treatments from previous crops: retained (+) and removed (-) for seven subsequent years. It was observed that plant establishment was lower in Z (high residue retention on surface). The plant dry matter during crop growth was lower in 3 years for Z-, where the other treatments showed similar values. Additionally, the grain yield was not significantly different between D+ and B+, but it was lower in Z+. Finally, the different treatments affected rooting distribution, because deeper roots (1.0-1.4 m) were found in B+, Z+ and D-, and shallower roots found in Z- (0.1-0.2 m).

6. Relevant soil characteristics to cellulosic biomass production.

6.1. Soil organic carbon, soil nitrogen and cellulosic biomass

Biofuel production based on cellulosic biomass must diminish GHGs emissions in atmosphere by 60% (RFA, 2010). GHGs such as CO_2 and NO_2 can be reduced from atmosphere in two different ways: decreasing their emissions and/or trapping them in soils. Therefore, cellulosic biofuels should capture high amount of GHGs in soils when produced and release less amount of them when combusted. Quantifying soil organic carbon (SOC) and nitrogen (N) balance in soils must be considered a fundamental tool in order to monitor the exchange of CO_2 and NO_2 between soil and atmosphere. Thus, SOC was considered the most powerful factor to monitor soil quality (Shukla et al., 2006; Brejda et al, 2000a, 2000b). SOC affected soil water content, movement and production (Shukla et al, 2006).

Several studies suggested that tillage was the major factor responsible for releasing and trapping C and N in soils. Reicosky et al. (1995) suggested that keeping organic matter at surface by reducing tillage diminished erosion and carbon dioxide release to atmosphere. Conservation tillage increased CO_2 retention up to 1.3 Mg ha^{-1} in top soil layers. Kern and Johnson (1993) also cited that no-tillage systems had a positive impact on soil, because it increased SOC.

Several authors found similar results. Potter et al. (1998) concluded that SOC changes were related to climatic conditions and soil management. Intense tillage management resulted in lower SOC than no-tillage in surface soil layers. Motta et al. (2002) concluded that SOC and N accumulation at 0.25 m surface layer was inversely proportional to tillage intensity. Zibilske et al. (2002) found higher SOC and N in no-tillage and conservation tillage treatments than conventional tillage in 0.08 m surface soil layer. Edwards et al. (1992) cited that SOC was increased to 56% at 0.10 to 0.15 m deep. Metay et al. (2007) found conservation tillage and no-tillage as the management system that accumulated more C in agriculture fields.

On the other hand, SOC and N were considered not significantly different under different tillage management, such as no-tillage, conservation tillage and conventional tillage by Angers et al. (1997) and Needelman et al. (1999). Other studies suggested that no-tillage and conservation tillage just redistributed SOC and N in soil, where their contents increased at surface layers, but the reverse tendency was found in deep layers (Dick et al., 1991; Torbert et al., 1999). Kay and VandenBygaart (2002) concluded similar SOC trend under no-tillage and conservation tillage, but they argued that those surface gains may persist longer than losses in deeper layers over time. Conservation tillage accumulates C and N via soil and biomass while conventional tillage just tends to accumulate these nutrients on soil, due to biomass incorporation followed by decomposition (oxidative environment) (Jabro, 2008).

Some studies have compared SOC and N under different irrigation regimes. In semi-arid agricultural lands, irrigation increased SOC accumulation in soils due to higher C sequestration inside microaggregates (Gillabel et al., 2007). Follet (2001) cited supplemental irrigation may have been beneficial, because increased water availability might result in soil C sequestration due to more biomass production. Similar studies reported no significant differences in SOC or N among different irrigation regimes (Churchman and Tate, 1986; Sommerfeldt et. al, 1988). However, Jabro et al. (2008) reported that soil CO_2 flux was higher in irrigated plots, where these plots released more than 7 Mg CO_2 ha^{-1} yr^{-1} than non-irrigated plots. Additionally, they found that no-tillage had lower CO_2 emissions than conventional tillage due to slower plant residue decomposition than when incorporated. Therefore, rational irrigation and adoption of less intensive tillage managements were recommended to reduce soil CO_2 flux.

6.2 Soil compaction and cellulosic biomass.

Several authors cited prejudicial effect of soil compaction on plant production. Hamza and Anderson (2005) cited that soil compaction negatively affected root growth in soils, which directly reduced biomass production. Similar conclusions were reported by Batey and McKenzie (2006) which additionally cited that soilborne diseases may have a higher incidence in plants under soil compaction stress. Therefore, soil compaction is a crucial factor to be considered when producing cellulosic biomass which must be monitored to avoid yield losses. Furthermore, bulk density (Bd) and cone index (CI) were considered two important soil measurements that are for the express purpose of measuring and assessing excessive soil compaction (Raper, 2005).

Soil water content was cited as the most important factor influencing soil compaction because wet soils were considered easy to compact due to reduced load support and increased deformation capacity (Hamza and Anderson, 2005). Raper (2005) also cited wet soils as an erosion factor because wet soil showed reduced soil strength and could be easily removed by running water.

6.2.1 Bulk density and tillage

Bulk density was defined as soil mass per unit volume which is a useful tool to quantify soil compaction (Raper, 2005). High bulk density values coincided with reduced soil porosity which was undesirable to plant production (Batey and McKenzie, 2006). Tillage has been used to reduce compacted soil profiles thus improving crop performance. However, in many cases this practice showed temporary benefits because the soil condition after tillage combined with natural soil wetting and drying cycles resulted in soil densification (Mapa et al., 1986).

Numerous authors have concluded that reduced tillage resulted in higher bulk density values. Yoo and Wander (2006) found high bulk densities in no-tillage fields which indicated soil consolidation. Potter and Chichester (1993) reported that controlled-traffic and no-till showed higher bulk density than conventional tillage. Lopez-Fando et al. (2007) suggested that no-tillage fields needed to be zone-till subsoiled to improve soil physical characteristics, such as bulk density. Conversely, other studies concluded that no-tillage systems showed lower bulk density values than conventional tillage (Edwards et al., 1992; Lal et al., 1994). Blanco-Canqui et al. (2004) also found that bulk density was not affected by different tillage systems (no-tillage vs. conventional).

A plausible explanation for these contrasting results was proposed by Raper and Kirby (2006). They argued that high values of bulk density in conservation tillage fields were found during the first few years of conversion from conventional tillage, which may not affect production negatively. Long-term conservation tillage systems may ultimately result in reduced bulk density values. Edwards et al. (1992) reported that the low bulk density values found in long term conservation tillage systems were related to accumulation of organic matter in soil.

6.2.2. Cone Index and tillage

Cone index was defined by ASAE standard S313.3 and EP 542 as the insertion force divided by the cross-sectional area of the base of the cone (ASAE Standards, 1999a; ASAE standards, 1999b), which was considered an easy approach to quantify compaction in the entire soil profile. However, cone index was greatly affected by soil moisture which could limit comparisons between soil conditions. Additionally, soil profiles with cone index values exceeding 2 MPa restricted root growth (Raper, 2005).

Varsa et al. (1997) concluded that deep tillage (0.6 and 0.9 m) increased corn root proliferation and grain yields due to reduction in penetrometer resistance (cone index values). Those beneficial results were considered temporary, because soil resistance increased with soil consolidation eventually taking place (Raper et al., 2005; Mapa et al., 1986).

Moreover, conservation tillage increased cone index values after conversion from conventional tillage (Raper et al., 2005). Other studies showed similar results. Potter and Chichester (2003) reported that no tilled fields showed higher cone index than tilled fields. Thus, cone index values were lower at a soil depth of 0.10 m than at 0.20 m. However, no-tillage systems were considered suitable for cropping, because penetrometer resistance never reached levels which restricted root growth (2 MPa). Conversely, Lopez-Fando et al. (2007) cited no-tillage fields with cone index values close to 3 MPa at a soil depth of 0.15 m which restricted root growth and reduced production. In-row subsoiling was applied to decrease soil resistance from 3 to less than 1 MPa. Other studies also reported non-inversion deep tillage as a means to alleviate compaction when high soil resistance was observed in conservation fields (Schwab et al., 2002; Wells et al., 2005; Sojka et al., 1997).

Wilkins et al. (2002) also affirmed that cone index values increased with reduced tillage. However, cone index values tended to decrease in a long term period (17 years) after conversion, reaching similar conditions to soils heavily tilled.

6.3. Soil water content and biomass production

Water is an essential factor for plant production because it influences all physical, chemical and biological activities in soil. Adequate soil water availability for plants is crucial to produce great amounts of cellulosic biomass. Some authors affirmed that reduced tillage was beneficial to soil water. Fabrizzi et al. (2005) cited that a no-tillage system showed higher soil water content than minimum tillage. No- tillage accumulated more water in soils during critical corn growth stage (from V11 to R1). The differences in soil water content were attributed to low evaporation in no-tillage system. Triplett, Jr. et al. (1968) reported that not only water storage, but also infiltration was higher in no preplant tillage plots than in conventional plots. They suggested that beneficial results in no- tillage plots were associated with higher surface residue cover. Jones et al. (1968) found similar results and concluded that high soil water storage under conservation tillage systems resulted in higher biomass and grains yield.

Conversely, other studies reported higher soil water content under conventional than in conservation fields. Furthermore, they suggested that deep tillage was the best approach to improve soil water contents (Busscher and Sojka, 1987; Sojka et al., 1997; Lopez-Fando et al., 2007). However, Xu and Memoud (2001) reported less total available water content in deep tilled fields (subsoiling). They explained that it occurred due to reduced volume of small pores (<10µm diameter) in subsoiled zone combined with an increase in the number of big pores (>50µm diameter) which increased infiltration.

Those contrasting conclusions may be explained by Buczko et al. (2006). They concluded that conservation tillage systems were beneficial in fine textured soils, such as silt loam, but was not significantly different than conventional tillage in coarse texture soils, such as sandy loam. Therefore, they argued that soil texture was an important factor when comparing water content in soils. They further stated that the tillage effect on soil water behavior varied according to soil texture, and pore size.

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I. SORGHUM BIOMASS PRODUCTION FOR CELLULOSIC BIOENERGY UNDER DIFFERENT IRRIGATION/TILLAGE SYSTEMS IN SOUTHEASTERN U.S.

ABSTRACT

Seeking renewable energy sources is necessary due to oil price fluctuations and environmental concerns. Sorghum *(Sorghum bicolor L.)* may be a reasonable alternative as an energy crop in the Southeastern U.S. because it is drought and nematode resistant. An experiment was developed to evaluate several types of sorghum for their potential as a bioenergy crop in Southern Alabama. The types of sorghum evaluated were: grain sorghum – NK300 (GS), high biomass forage sorghum – SS 506 (FS), and photoperiod sensitive forage sorghum - 1990 (PS). These 3 different varieties and a forage corn *(Zea mays L.)* – Pioneer 31G65 were grown for two consecutive years (2008 and 2009) under irrigated and non-irrigated treatments, and under two different tillage systems: conventional (total disked area to a depth of 0.15 m) and conservation tillage (in-row subsoiling to a depth of 0.30 m) which resulted in a strip-split-plot design. Additionally, a rye cover crop *(Secale cereale L.)* and sunn hemp *(Crotalaria juncea L.)* was integrated as a treatment to maximize the amount of biomass produced and provide ground cover during winter months. The parameters evaluated were: rye (RDM) and sunn hemp (SDM) dry matter production, plant population (PP), stomatal conductance (SC), plant

height (PH), sorghum/corn aboveground dry matter (ADM), and biomass quality (holocellulose, lignin, and ash). Results showed that RDM were 0.26 Mg ha^{-1} and 2.57 Mg ha^{-1} in 2008 and 2009, respectively with the higher RDM production in 2009 a result of favorable weather conditions (elevated temperatures in early spring). Sunn hemp, which was introduced on conservation plots in 2009, could have only had a minor effect on rye production due to low yields (0.62 Mg ha^{-1}).All sorghum varieties had higher dry aboveground dry matter production than corn. ADM production was higher in 2008 than 2009 for all crops due to high incidence of Anthracnose *(Colletotrichum graminicola)* and Southern corn leaf blight *(Bipolaris maydis)* diseases in 2009. Lodging was observed in PS and FS plots probably due to high plant populations (> 370,000 plants ha^{-1}). Irrigation affected ADM positively in both years, but conservation system improved ADM production only in 2009. SC data indicated that high ADM yields in irrigated and conservation tillage were related to good soil water content which might increase plant metabolism and growth. Holocellulose, lignin, and ash content differences among crops were lower than 8.3%, 2.0% and 1.9 %, respectively, for both years and considered minor. Therefore, PS was considered the best variety for cellulosic biomass (ADM) production which produced 26.04 and 30.13 Mg ha^{-1} at 18 and 24 weeks after planting (WAP). SS 506 – FS could be an alternative if harvest occurred at 14 WAP (21.27 Mg ha^{-1}). Plant height readings clarified that PS had slower development than other crops. However, its prolonged vegetative stage due to the southeastern U.S. photoperiod condition resulted in high cellulosic biomass production in late harvests. Thus, reduced plant population and crop rotation were recommended to maximize cellulosic biomass for bioenergy production.

Key words: photoperiod-sensitive, soil properties, cover crop, conservation

1. INTRODUCTION

Seeking renewable energy sources is necessary due to oil price fluctuations and environmental concerns. U.S. oil demand is projected to increase 1.7 % per year from 2000 to 2030, where the consumption will be about 15.3 million tons of oil equivalent; therefore, an oil shortage is predicted in the next decades (IEA, 2002). Finding alternative energy sources is necessary. Cellulosic material must be considered as an alternative source for bioenergy production, because it can result in U.S. energy independence (renewable) and diminish green house gas emissions. Much emphasis has been placed on perennial crops for cellulosic material production, such as switchgrass (*Panicum virgatum* L.*)* , which is cited as a reference for comparisons and the most probable feedstock for bioenergy (DOE, 2005). However, negative impacts on food production are expected when replacing conventional crops with perennial energy crops, because the agricultural land previously cultivated to produce food will be converted only to produce bioenergy feedstock (Peters and Thielman, 2008). Conversely, annual crops can be cultivated in a rotation system, where conventional crops and annual energy crops can be cultivated on the same agricultural land producing 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. Additionally, central and south Alabama agriculture has been negatively affected by drought conditions over the last several years which has dramatically reduced production. For these reasons, sorghum (*Sorghum bicolor* L.) may be a reasonable alternative as an energy crop in this region, because it is considered drought resistant and has high cellulosic biomass potential (Habyarimana et al., 2004a). Sorghum could be integrated in a conservation system as part of a crop rotation with typical 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 amount of biomass would be harvested for potential biofuel production.

Many sorghum varieties have been tested in the southwest U.S. with great success under irrigated conditions; however, they have not been evaluated in the Southeast under our dryland conditions. 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 our conditions (Hunt et al., 2004).

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

Additionally, a rye (*Secale cereale* L.) cover crop is integrated as a part of conservation system to maximize the amount of biomass produced and provide ground cover for conservation treatments during the winter months. Also, a new variety of sunn hemp (*Crotalaria juncea* L.) was included in conservation system to evaluate the benefits of this legume to provide additional nitrogen for the rye winter cover.

2. MATERIAL AND METHODS

2.1 Site description

A study was initiated in November of 2007 and conducted for 2 years at the E. V. Smith Alabama Agricultural Station – Field Crop Unit, Shorter, AL (85º:53’50” W, 32º:25’22” N). The location had been cropped previously with cotton for 8 years in a conservation tillage system following Alabama Extension System recommendations. The soil type was Marvyn Loamy sand (fine-loamy, kaolinitic, thermic, typic Kanhapludults). 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 cover crop before planting corn and sorghum. Preceding the rye was a new variety of sunn hemp to provide nitrogen.

2.2. Cultural practices and Treatments

Rye Elbon was planted at 100 kg ha^{-1}, in early November each year using a no-till drill (Great Plains Mfg. Inc., Salina, KS)[1]. Rye cultural practices were based on Alabama Cooperative Extension System recommendations. In early April each year, the rye cover crop was terminated with glyphosate (N-phosphonomethyl glycine).

In late April of each year, starter fertilizer was applied at a rate of 14, 4, 14 and 5 kg ha^{-1} of N, phosphorus (P), potassium (K) and sulfur (S), respectively according to the Alabama Cooperative Extension System soil test recommendations (Adams and Mitchell, 2000).

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[1] The use of company names or trade names does not indicate endorsement by Auburn University or USDA – ARS.

Two different tillage systems were implemented shortly after fertilization: conventional and conservation systems. 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/leveled using a 950 John Deere Disk (Deere & Company, Moline, IL) to a depth 0.15 m. Then, all four bioenergy crops, including grain sorghum - NK300 (GS), forage sorghum - SS506 (FS), photoperiod-sensitive sorghum - 1990 (PS), and hybrid corn Pioneer 31G65 were seeded in rows spaced at 0.92 m using a John Deere 1700 XP planter (Deere & Company, Moline, IL). Seeding rate was established by the company's recommendations which were 407,700 seeds ha^{-1} for FS, GS and PS (Sorghum Partners 2008a, 2008b, 2010c). Corn seeding rate was 78,300 seeds ha^{-1} (Pioneer Hi-bred International Inc., 2010). Tillage and planting were performed with a tractor equipped with a Trimble AgGPS Autopilot automatic steering system (Trimble, Sunnyvale, CA), with centimeter level precision. An additional 110 kg N ha^{-1} of ammonium nitrate (34%) was side dressed with a liquid applicator in row middles during growing season each year.

The irrigation plots were managed with two different regimes: non-irrigated (rainfed) and irrigated. In the irrigated plots, water was applied in appropriate timing and amounts to provide plants with good water availability during the growing season. Irrigation was terminated at 16 weeks after planting in both years. Alabama Cooperative Extension System recommendations were used to apply all insecticides (ACES, 1988).

Grain from grain sorghum variety and corn were harvested in late August using a Gleaner G combine (AGCO Company, Duluth, GA)**.** The remaining biomass was cut and baled. Sunn hemp was planted at a rate of 50 kg/ha immediately after harvest using a no-till drill (Great Plains Mfg. Inc., Salina, KS) in all conservation tillage plots. Photoperiod sensitive sorghum and forage sorghum were harvested in late October.

2.3. Experimental Design and Statistical Analysis

Bioenergy crops (crops), irrigation and tillage practices were evaluated in a strip-split plot design (factorial 4x2x2). The four crop varieties studied were GS, FS, PS, and corn and served as the horizontal treatments. Two irrigation regimes (irrigated and non-irrigated) served as the vertical plots, and two tillage systems (conservation and conventional) served as 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 plots), 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 systems) which resulted in 64 experimental units 9.1-m long by 3.7-m wide. Experimental units were composed of 4 rows with row spacings of 0.92 m. All measurements were collected from the two middle rows of each experimental unit.

Measurements were evaluated in a strip-split plot design with four replications, where crops, irrigation regimes and tillage systems were considered respectively horizontal, vertical and sub-treatments. Bioenergy crops were randomly assigned into each replication, irrigation regimes were assigned into each bioenergy crop, and tillage systems were randomly assigned into each irrigation regime.

All data were analyzed using the appropriate strip-split-plot design with PROC MIXED of the Statistical Analysis System (SAS) (Littel et al., 1996). Replication and its interactions with bioenergy crops (crops) and irrigation regimes were considered random effects and treatments and other interactions considered fixed. Data were analyzed and discussed considering both years, except when significant year x treatment interaction occurred. In this case, data were analyzed by year. Treatment means were separated by the LSMEANS procedure (SAS Inst. Inc., Cary, NC) when protected by F-tests significant at α of 0.10, and are reported as least squares means ± SE.

2.4. Data Collection

2.4.1. Cover crops

2.4.1.1. Rye dry matter samples

Rye dry matter samples were collected 1 week prior to planting for both years. Two 0.25 m^2 frames were used to sample rye aboveground biomass from each experimental unit. Those samples were oven-dried at 55 °C until constant weight in order to determine 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.

2.4.1.2. Sunn hemp dry matter samples

Sunn hemp biomass samples were collected prior to planting rye in 2009. Two 0.25 m^2 frames were used to sample sunn hemp aboveground biomass from the conservation plots. Those samples were oven-dried at 55 °C until constant weight in order to determine biomass yield.

2.4.2. Precipitation

Natural rainfall and irrigation were monitored during the growing season. Eight ECH2O Rain gauges - Model ECRN (Decagon Devices, Pullman, WA) were installed in the field. Rain gauges were combined in four sets. Each set was composed of 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 a irrigated plot and the other one installed in non-irrigated plot. All rain gauges were located 0.6 m from two middle rows.

2.4.3. 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 (harvest time).

2.4.4. Stomatal conductance

A SC-1 Leaf Porometer (Decagon Devices, Pullman, WA) was used to measure leaf stomatal conductance on the abaxial side of unshaded apical totally expanded leaves of corn and sorghum. Measurements were randomly taken from 5 different plants in the two middle rows of each plot. Stomatal conductance data were collected at three different times during the growing season of each year: 6, 12 and 16 weeks after planting. Measurements were collected in non-cloudy days when solar radiation was maximized.

2.4.5. Plant height

Plant height measurements were taken at five different times. Two sampling periods were done early during the growing season at 6 and 9 weeks after planting in both years. In 2008, the three remaining measurements occurred at 14, 18 and 24 weeks after planting. However, the fourth time period in 2009 was performed 20 weeks after planting instead of 18 weeks due to wet conditions in early September, 2009.

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

2.4.6. Aboveground dry matter

Aboveground biomass was harvested at 3 different times each year. In 2008, aboveground biomass was sampled 14, 18 and 24 weeks after planting. However, aboveground biomass was sampled 14, 20 and 24 weeks after planting in 2009. The delay in second sampling period in 2009 was caused by high precipitation during this period. 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.

In each of the two middle rows of all experimental units, aboveground biomass samples were collected in a 1.5 m long section. Grains, cobs and husks were separated from leaves and stems.

The wet biomass weights of leaves and stems were recorded. Sub-samples were collected, ground, weighed, and dried at 55º C until constant weight was achieved. Those sub-samples were reweighed to estimate aboveground dry matter production.

2.4.7. Grain production

All grain, cobs, and husks were dried at 55º C until constant weight. Corn and sorghum grain were shelled to remove all trash. Then, the grains were weighed and grain moisture recorded to estimated dry grain weight.

2.4.8. Aboveground biomass and grain nutrient removal

Dry aboveground and grain subsamples (corn and GS) were ground using a Wiley (Thomas Scientific, Swedesboro, NJ) and a cyclone (UDY Corp., Fort Collins, CO) mills to pass a 0.02 m screen. A 0.5 g plant tissue sample (dry aboveground dry matter subsample) was reduced to ash in a muffle furnace at 450 °C for 12 hours. Remaining ash was sequentially dissolved in 0.01 L of 1 N HNO_3, and in 0.10 L 1 N HCl (Hue and Evans, 1986). However, a 1.0 g grain sample was pre-digested over night in 0.025 L of 70:30 nitric : perchloric acid. Remaining solution was sequentially digested on a heated block under a perchloric hood at 200 ^{0}C until the volume was reduced to 0.003 L or less, then 0.01 L of 1 N HCl was added (John, 1972). The total Ca, Cu, Fe, K, Mg, P, and Zn content in the grain samples was analyzed by argon plasma (ICAP) spectroscopy (Spectro CIROS, CCD side on Plasma, Germany).

2.4.9. Aboveground biomass quality

Dry aboveground samples were ground using a Wiley (Thomas Scientific, Swedesboro, NJ) sample mill to pass a 0.01 m screen. Neutral Detergent fibers (NDF) which represents the insoluble matrix of plant cell wall (holocellulose and lignin) (Robbins et al., 1975) were analyzed using Robertson and Van Soest (1977) procedures.

A 0.5 g sub-sample was treated in 0.1 L of neutral-detergent solution, and in 0.001 to 0.002 L of amylase enzyme solution. The sample was then filtered, washed, filtered under vacuum, and completely dried in a forced air oven at 105°C for 8 hours. 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 official method (AOAC, 1975). A 1.0 g of ground sample was dissolved in 0.1 L of acid-detergent solution, and boiled to keep particles in suspension and refluxed for 1 hour. 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 hours, filtered, rinsed well and oven dried over night at 105 ^{0}C. Acid Detergent Lignin (ADL) residues were weighed and ashed at 450 ^{0}C over night. 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 over night at 105 ^{0}C. The residues were weighed to estimate 100% dry biomass content and ashed overnight at 450 ^{0}C. Afterward, the ash residues were re-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.

3. RESULTS AND DISCUSSION

3.1. Cover crops

3.1.1. Rye dry matter

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 = 0.3427). . No significant rye dry matter yields were found in plots for different tillage system (P = 0.3585) nor irrigation (P = 0.2984) treatments.

In 2009, rye dry matter samples collected in conservation fields before planting the four tested crops showed no significant differences in yields (P = 0.7167). The total rye dry matter production for all conservation plots was 2.58 Mg ha^{-1} resulting in good soil cover (> 1.4 Mg ha^{-1}). Irrigation was not applied during rye development, therefore no rye dry matter differences between irrigation treatments were found (P = 0.4790) (table1-1).

3.1.2. Sunn hemp dry matter

Sunn hemp was cultivated only in conservation plots for GS and corn because those two crops were terminated early enough (late August) in 2008 to establish the sunn hemp. The other two sorghum varieties, PS and FS were terminated later (late October) and was followed with rye being planted in all conservation plots.

Because no irrigation was applied during sunn hemp development, no significant differences in dry matter were found from previous irrigation treatments (P = 0.4777). However, fields previously cropped with corn showed higher sunn hemp yields 8 weeks after planting (WAP) than fields previously cropped with GS (0.87 and 0.37 Mg ha^{-1}, respectively; P = 0.0198; table 1-2). Mansoer et al. (1997) reported 5.9 Mg ha^{-1} of sunn hemp dry matter after 9 WAP when working with a different sunn hemp cultivar, which resulted in good soil cover, and accumulated 120 kg ha^{-1} of N in two different locations for Alabama. Similar results were found by Schomberg et al. (2007) in Piedmont and Coastal Pain regions of the southeastern US. Therefore, low sunn hemp biomass production in our fields in 2009 probably had no significant effect on rye development.

3.2. Precipitation

Weather data collected at E. V. Smith Alabama Agricultural Station indicated total rainfall in 2008 and 2009 were respectively 1,160 and 1,881 mm, therefore, 2009 had additional 721 mm of rainfall during whole year. Figure 1-1 showed rainfall mean monthly for 2008 and 2009 (AWIS Weather Service Inc., 2010). Rain gauges installed in field from planting to 14 weeks after planting showed also higher precipitation in 2009 during growing season. The average precipitation measured during this time in 2008 and 2009 were, respectively 337.5 and 570.0 mm (table 1-3).

In 2008, irrigated plots received a water increment of 132 mm distributed in 6 different days, such as 17 (12 mm), 31 (8 mm), 50 (24 mm), 63 (32 mm), 77 (31 mm), and 91 (25 mm) days after planting. However, the irrigated plots were watered on only 3 days during 2009 season, such as 1 day before planting (14 mm), 21 (19 mm) and 30 (24 mm) days after planting.

3.3. Plant Population

During growing season, all tested crops had no significant plant population differences for both years (P = 0.9081). FS, GS, PS and corn showed an average of 380,325; 375,840; 359,470 and 78,694 plants ha^{-1} , respectively, at 6 weeks after planting (WAP) for both years. Those plant population results were similar to the company's seed planting density recommendations which were between 271,800 to 407,700 plants ha^{-1} for FS, GS and PS (Sorghum Partners 2008a, 2008b, 2010c). Corn recommendations cited that the optimum plant population for this hybrid was 78, 300 plants ha^{-1} (Pioneer Hi-bred international Inc., 2010).

Conventional tillage had similar populations as conservation tillage (P = 0.542), and irrigation had similar populations as non-irrigated fields (P = 0.8471) for both years. Tillage and irrigation treatments were analyzed considering all evaluated crops in both years.

Significant plant population differences at 6 WAP were found within each crop when comparing measurements collected in growing season (6 WAP) and aboveground biomass sampling time (14 WAP) for both years. FS and GS had significant population decreases 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 ($P \leq 0.0001$). 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 ($P \leq 0.0001$). However, PS showed significant aboveground dry matter production differences only in 2009 when PS plant population decreased from 362,834 to 258,558 plants ha^{-1} (28.7 % reduction), $P \leq 0.0001$. Conversely, corn did not show significant differences in plant population (table 1-4).

The plant population reduction in sorghum could be partially related to plant lodging after 12 weeks of planting for both years. . Marsalis et al. (2010) reported no plant lodging and similar dry matter yield when working with 3 plant populations 249,383 (high), 214,815 (medium) and 185,185 plants ha^{-1} (low) for 2 forage sorghums. Habyarimana et al. (2004b) concluded that sorghum plants have the compensation ability, where lower plant density resulted in higher leaf weight per plant, higher grain weight per panicle and higher tillering ability. They recommended a sorghum population be between 150,000 and 200,000 plants ha^{-1}.

3.4. Stomatal Conductance

Stomatal conductance results were analyzed separately by weeks and year because weather variation such as temperature and solar radiation among days may affect stomatal conductance readings. Data collected at 8 weeks after planting (WAP) in 2008 (table 1-5) showed significant differences for crop and irrigation treatments, but tillage treatments and interactions were not significantly different from each other. In this sampling period, PS (342.08 mmol m^{-2} s^{-1}) and FS (330.93 mmol m^{-2} s^{-1}) was significantly higher than corn (295.99 mmol m^{-2} s^{-1}) and GS (291.39 mmol m^{-2} s^{-1}), $P = 0.0557$. Irrigated plots (397.81 mmol m^{-2} s^{-1}) showed higher stomatal conductance than non-irrigated plots (232.38 mmol m^{-2} s^{-1}), $P = 0.0005$. According to soil moisture content readings collected at the same time, volumetric soil water content in irrigated plots was

25.3 %, and 19.2 % in non-irrigated plots (P = 0.0138), due to 25 mm of water applied in irrigated plots. This additional water application in irrigated plots might increase plant respiration resulting in higher stomatal conductance values, because plant stomata activity indicated by stomatal conductance responds to soil water availability in stable weather conditions (Li et al., 2004). Conversely, stomatal conductance readings performed during the same period (8 WAP) in 2009 (table 1-6) showed no significant differences for any treatment and interaction. Irrigation treatments showed also no significant stomatal conductance differences due to 27 mm of rainfall at 8 WAP in 2009. This rainfall caused similar soil water content in irrigated fields (28.02 %) than in non-irrigated fields (27.19 %; P = 0.7116) which might result in similar plant respiration and stomatal activity.

After 12 WAP, crops showed no significant stomatal conductance differences, but PS and FS were numerically higher than GS and corn for both years. However, irrigation treatments were significantly different during this period for both years. In 2008, irrigated plots (235.51 mmol m^{-2} s^{-1}) showed significantly higher stomatal conductance than non-irrigated plots (210.04 mmol m^{-2} s^{-1}). Soil moisture data in irrigated and non-irrigated plots were 30.63% and 21.91% (P = 0.0006), respectively, during this period. Conversely, soil water content was not significantly different between irrigated (26.21 %) and non-irrigated plots (24.81 %) in 2009 (P = 0.2488), but stomatal conductance was significantly different in irrigated versus non-irrigated plots, respectively, 271.44 and 232.05 mmol m^{-2} s^{-1} (P = 0.0409). . Additionally, stomatal conductance readings in tillage treatments at 12 WAP were only significantly different in 2008, with conventional tillage (250.92 mmol m^{-2} s^{-1}) having higher stomatal conductance values than conservation tillage (194.63 mmol m^{-2} s^{-1}; $P = 0.0116$). This result might be related to higher soil water content found in conventional tillage plots (27.22 %) than in conservation tillage plots (24.77 %; $P < 0.0001$).

Stomatal conductance readings collected near the end of growing season (16 WAP) showed differences for crop treatments in 2008. GS (181.54 mmol m^{-2} s^{-1}) and FS (151.75 mmol m^{-2} s^{-1}) showed significantly higher stomatal conductance than corn (74.79 mmol m^{-2} s^{-1}). PS (126.63 mmol m^{-2} s^{-1}) was also found to be significantly higher than corn, equal to FS and lower than GS. The low values related to corn in 2008 are due to the fact that the crop was R6 to R7 growth stage development (senescent) during the period. No corn measurements were collected in 2009 because the crop was already terminated (R7 stage) at 16 WAP. Moreover, earlier stomatal conductance readings (at 14 or 15 WAP) for corn were not possible due to cloudy and raining days during this period which could have resulted in inaccurate readings. In 2009, the crops were not significantly different from each other.

Results showed that GS had the same or higher stomatal conductance than FS and PS at 16 WAP. It was expected that GS would have lower physiological activity than PS and FS, because GS was ending soft dough stage (growth stage development 7), and PS an FS were still in vegetative stage. However, Xin et al. (2009) concluded that different sorghum materials showed different enhanced transpiration efficiency (TE) which is defined as biomass accumulation per unit water transpired (g kg^{-1}). Sorghum plants with high values of enhanced TE could produce more biomass with the same water availability. Thus, TE showed a low relationship with instantaneous transpiration efficiency (nTE) which was measured at leaf level (stomatal conductance). Therefore, high stomatal conductance among different sorghum varieties did not explain higher biomass production in most cases.

The interaction “crop x irrigation” was significant at 16 WAP for both years. In 2008, stomatal conductance for irrigated GS (199.25 mmol m^{-2} s^{-1}) was considered higher than irrigated FS (142.80 mmol m^{-2} s^{-1}), PS (118.16 mmol m^{-2} s^{-1}) and corn (77.53 mmol m^{-2} s^{-1}). Non-irrigated GS (163.83 mmol m^{-2} s^{-1}) and FS (160.70 mmol m^{-2} s^{-1}) were considered higher than non-irrigated PS (134.60 mmol m^{-2} s^{-1}) and corn (72.05 mmol m^{-2} s^{-1}). Irrigated and non-irrigated corn was not significantly different from each other and showed the lowest values. In 2009, stomatal conductance in non-irrigated FS (372.85 mmol m^{-2} s^{-1}) was considered significantly higher than irrigated PS (249.45 mmol m^{-2} s^{-1}) and non- irrigated GS (161.61 mmol m^{-2} s^{-1}). The interaction “crop x irrigation” occurred due to rainfall of 43 mm and 66 mm in 2008 and 2009, respectively, which diminished the irrigation effect in field.

3.5. Plant Height

Corn showed the highest plant height value at 6 weeks WAP for 2008 and 2009, 1.50 and 1.66 m, respectively. In 2008, corn was followed by FS (1.37 m), GS (1.16 m), and PS (1.07 m). FS was significantly different from corn, GS, and PS. PS was not significantly different from GS ($P = 0.0002$). In 2009, the same trend was observed. Corn (1.66 m) showed the highest values followed by FS (1.25 m), GS (1.20 m) and PS (1.15 m). However, sorghum varieties were not significantly different from each other, but they were significantly different from corn ($P = 0.0016$; table 1-8). High precipitation at 6 WAP might have affected positively 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 indispensible any time in which soil water is below wilting point.

At 9 WAP, PS overcame GS in both years. In 2008, corn (2.73 m) was higher than FS (2.13 m), PS (1.61 m), and GS (1.32 m; $P \leq 0.0001$). The same trend was observed in 2009, where corn, FS, PS and GS were respectively 2.82, 2.01, 1.85 and 1.55 m ($P \leq 0.0001$; table 1-8). Additionally, PS and FS showed no significant plant height differences at 14 WAP for both years. PS and FS were 3.23 m in 2008, and 3.19 and 3.01 m in 2009. 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, $P \leq 0.0001$) because FS reached anthesis at 18 WAP which decreased vertical plant growth. The same results were found at 20 WAP in 2009, where PS was 3.83 m high. 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. Figures 1-2 and 1-3 illustrate plant height variation over time for the different crops.

Irrigation treatments were considered significantly different from each other in both years for all periods. Irrigated plots were significantly higher in plant height values than non-irrigated plots in all evaluated periods, except at 6 WAP in 2009. Carmi et al. (2006) found similar results for forage sorghum varieties, and Sakellariou-Makrantonaki et al. (2007) concluded that irrigation resulted in taller sorghum plants. However, no significant differences between irrigation (1800 mm vs. 2500 mm) were found between two different silage sorghums (Yosef et al., 2009). Additionally, non-irrigated plots (1.36 m) were slighter higher in plant height values than 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 crops x 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 had lower plant height than FS and PS (data not shown). Irrigation could not improve GS and corn plant height after 14 WAP, since both varieties were mature while PS and FS were continuously growing (vegetative stage).

Conservation tillage (in-row subsoiling with a cover crop) showed significantly taller plants than conventional tillage (total disked area) for both years during all periods, except 24 WAP. Omer and Elamin (1997) suggested that in-row subsoiling (vertical soil disruption) showed improvement in soil aeration and infiltration resulting in taller sorghum plants.

Significant crops x tillage interactions were found at 6 and 9 WAP in 2008. Corn was the only crop that showed higher plant height values 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 x tillage interactions were found at 20 WAP in 2009 (data not shown). Results suggested that tillage treatments were not significantly different for both PS and FS. Similar results were found at 24 WAP for both years.

3.6. Aboveground dry matter

Due to higher precipitation in 2009 (570 mm) than 2008 (337.5 mm), significant aboveground dry matter (ADM) differences among crops were found when comparing years ($P \leq 0.0001$). Therefore the results of ADM were analyzed by year (table1-9). Conservation plots (18.47 Mg ha^{-1}) and conventional plots (18.39 Mg ha^{-1}) showed no significant differences in ADM values in 2008 ($P = 0.8721$; figure 1-5). 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 is similar to results reported by Cogle et al. (1997) who reported no differences among different tillage systems, but also reported sorghum biomass yield was always higher than corn. In 2009, conservation plots (12.26 Mg ha^{-1}) showed higher ADM production than conventional plots (11.02 Mg ha^{-1}), $P = 0.0028$ (figure 1-5). Several factors might influence these ADM differences between tillage treatments in 2009. Increased amounts of rye cover crop produced in 2009 than in 2008 for conservation tillage might result in better 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 (Official Series Description, 2010). Furthermore, in row-subsoiling in conservation tillage enhanced plant growth due to increased root proliferation and water infiltration than conventional tillage systems (Reeves and Toucthon, 1986).

In 2008, aboveground dry matter differences among crops were found when comparing LS means calculated from all tillage and irrigation treatments. FS (21.27 Mg ha^{-1}) showed the highest ADM production at 14 WAP, followed by PS (18.08 Mg ha^{-1}), GS (12.38 Mg ha^{-1}) and corn (7.25 Mg ha^{-1}). However, PS (26.04 Mg ha^{-1}) overcame FS (22.83 Mg ha^{-1}) at 18 WAP followed by GS (13.41 Mg ha^{-1}) and corn (8.92 Mg ha^{-1}). 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 cellulosic 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, $P \leq 0.0001$ (figure 1-6).

Additionally, irrigated plots (20.50 Mg ha^{-1}) had higher ADM yields than non-irrigated plots (16.37 Mg ha^{-1}) in 2008, $P = 0.0090$ (figure 1-4). Because irrigation was terminated at 16 WAP, crops x irrigation interaction showed that PS had no ADM differences between irrigation treatments at 18 and 24 WAP, 30.61 Mg ha^{-1} and 32.90, respectively. Thus, irrigated FS was not significantly different for any period in 2008, but non-irrigated FS had higher ADM yields at 24 (22.98 Mg ha^{-1}) than 14 WAP (18.70 Mg ha^{-1}), $P = 0.0227$ (figure 1-8).

In 2009, the overall ADM yield (11.64 Mg ha^{-1}) were drastically lower than 2008 (18.43 Mg ha^{-1}), $P \leq 0.0001$. Excessive water, Anthracnose disease in sorghum plants, and Southern Corn Leaf Blight – SCLB (*Bipolaris maydis*) disease in corn plants decreased yields in 2009. At 14 WAP, PS (16.03 Mg ha^{-1}), GS (13.71 Mg ha^{-1}) and FS (12.26 Mg ha^{-1}) showed no significant differences in yields, but corn (8.77 Mg ha^{-1}) had lower ADM yields than sorghum varieties. However, PS (19.19 Mg ha^{-1}) showed the highest yield at 20 WAP followed by GS (11.51 Mg ha^{-1}), FS (9.62 Mg ha^{-1}) and corn

(5.81 Mg ha^{-1}). At 24 WAP, PS showed higher yields than FS, respectively, 13.21 Mg ha^{-1} and 6.29 Mg ha^{-1}. FS, GS and corn showed highest ADM values at 14 WAP. PS and FS showed lower yields at 24 WAP than 20 WAP. And FS, GS, and corn showed lower yields at 20 WAP than 14 WAP, $P \leq 0.0001$ (figure 1-7).

Anthracnose (*Colletotrichum graminicola*) was reported as the major sorghum disease (Metha et al., 2005) and it reduces sorghum yields in hot and humid conditions (Ali and Warren, 1992). High severity of anthracnose disease in sorghum varieties, such as 60 to 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 anthracnose incidence. And rice, soybeans, and corn planted before sorghum improved sorghum yields. Furthermore, corn plants were affected by SCLB. Ear leaf damage reached 21 to 30 % at 15 WAP (data not shown) which could be related to decrease in ADM at 20 WAP.

Irrigated plots (12.18 Mg ha^{-1}) had higher ADM yields than non-irrigated plots (11.11 Mg ha^{-1}) in 2009, $P = 0.0637$ (figure 1-4). But, crops x irrigation interaction ($P = 0.0396$) showed that irrigated PS just showed higher ADM production than non-irrigated PS at 14 WAP, 17.7 Mg ha^{-1} and 14.36 Mg ha^{-1} respectively. FS showed similar yields for all periods in 2009. GS had higher yield in irrigated treatments at 14 and 20 WAP. And, corn showed higher ADM production in non-irrigated fields at 14 WAP, $P = 0.0396$. The differences found in 2009 due to crops x irrigation interaction were difficult to explain because high precipitation diminished irrigation effect, and diseases may affect the crops differently (figure 1-9).

3.7. Corn grain dry matter

Corn grain dry matter (CGDM) yields were significantly different when comparing different years. The average CGDM production was higher in 2008 (8.47 Mg ha^{-1}) than in 2009 (7.62 Mg ha^{-1}), $P \leq 0.0001$, therefore CGDM data were analyzed separated by year. These different yields might be related to higher precipitations in 2009 which favored SCLB disease development and reduced corn grain yields. According to field evaluations performed at 20 weeks after planting (WAP), ear leaf damage reached 21 to 30 % at 15 WAP (data not shown) which might have decreased CGDM yields in 2009.

In 2008, CGDM yields were significantly different between sampling periods, $P = 0.0233$ (table 1-14). CGDM samples collected at 18 WAP showed higher yields than samples collected at 14 WAP, respectively, 8.76 Mg ha^{-1} and 8.17 Mg ha^{-1}. Irrigated plots (9.67 Mg ha^{-1}) showed higher yields than non-irrigated (7.26 Mg ha^{-1}), $P = 0.0072$. Several authors showed similar conclusions about corn development and dry matter production by concluding that irrigated corn plants had higher grain yields than non-irrigated plants (Roygard et al., 2002; Pilbeam et al.,1995; Payero et al., 2008). No significant differences were found between conservation and conventional systems in 2008, $P = 0.5576$. Several studies that worked with different tillage systems (conservation vs. conventional) also found no significant difference in CGDM yields among tillage systems. They concluded that both tillage systems resulted in similar soil conditions for corn plant development and grain production (Angers et al., 1997; Linden et. al., 2000; Shirani et al., 2002).

In 2009, CGDM produced at 20 WAP (8.18 Mg ha^{-1}) were higher than in 14 WAP (7.05 Mg ha^{-1}), P = 0.0691. Irrigated plots were not significantly different from non-irrigated plots (P = 0.7247), because irrigation effects in 2009 were diminished due to high precipitation during growing season. Tillage systems were also not significantly different from each other (P = 0.6013).

3.8. Sorghum grain dry matter

In 2008, GS showed no significant SGCM differences between 14 WAP (4.40 Mg ha^{-1}) and 18 WAP (4.62 Mg ha^{-1}), P = 0.5163. Irrigated plots (5.06 Mg ha^{-1}) showed higher SGDM yields than non-irrigated plots (3.957 Mg ha^{-1}), P = 0.0861 (table 1-17). Similar studies showed different results. They found that irrigated sorghum showed similar grain yields than rainfed sorghum (Amaducci et al., 2000; Habyarimana et al., 2004a). But, Habyarimana et al. (2004b) concluded that sorghum planted at a high plant density showed more susceptibility to water availability, and they recommended a sorghum population be between 150,000 and 200,000 plants ha^{-1}. GS were planted at a high plant density (407,700 seeds ha^{-1}); which might result in more drought susceptibility and lower yields in non-irrigated plots. However, no significant SGDM differences were found between conservation tillage (4.53 Mg ha^{-1}) and conventional system (4.49 Mg ha^{-1}) in 2008, P = 0.8212.

SGDM showed drastically lower yields at 20 WAP (1.54 Mg ha^{-1}) in 2009 than any period in 2008. High precipitation during growing season diminished irrigation effect, and similar yields were found for irrigated (1.81 Mg ha^{-1}) and non-irrigated (1.27 Mg ha^{-1}) fields. Conservation system (1.86 Mg ha^{-1}) produced same SGDM yields (1.52

Mg ha^{-1}) as conventional system. Low yields and no differences between any treatments might be related to Anthracnose disease observed in field during 2009. Field evaluations showed that GS was 49% - 59% leaf area diseased at 18 WAP in 2009 (data not shown).

3.9. Biomass quality

3.9.1. Holocellulose content

Holocellulose is the desirable portion of cellulosic biomass, because it can be converted to carbohydrates (xylose, mannose, galactose and glucose). Consequently, those carbohydrates can be used by ethanol production.

Holocellulose content (HC) was significantly higher in 2009 (689.8 g kg^{-1}) than in 2008 (682.3 g kg^{-1}), P = 0.0009. High precipitation and high incidence of Anthracnose disease in 2009 might decrease holocellulose content. Data were analyzed separated by years.

Significant differences were found at 14 weeks after planting (WAP) in 2008. During this period, PS (715.4 g kg^{-1}) had significantly higher HC than corn (687.4 g kg^{-1}), GS (686.5 g kg^{-1}), and FS (686.3 g kg^{-1}) at 14 WAP (P = 0.0216). However, crops x irrigation effect (P = 0.0197) at same period indicated that PS had significantly higher HC than the other crops in irrigated condition, but there was no significant differences among crops under non-irrigated conditions. At 18 WAP (P = 0.0022), PS (700.6 g kg^{-1}) showed significantly higher HC values than corn (675.9 g kg^{-1}), FS (653.7 g kg^{-1}) and GS (650.9 g kg^{-1}), but FS were not significantly different from GS. At 24 WAP, FS (692.6 g kg^{-1}) and PS (673.5 g kg^{-1}) showed no significant HC differences (table 1-20).

In 2009, corn (702.1 g kg^{-1}) and PS (696.5 g kg^{-1}) showed higher HC than FS (674.5 g kg^{-1}) and GS (656.0 g kg^{-1}) at 14 WAP (P = 0.0147). However, corn (765.9 g kg^{-1}) had significantly higher HC than PS (690.1 g kg^{-1}), FS (684.0 g kg^{-1}) and GS (683.5 g kg^{-1}) at 20 WAP ($P \leq 0.0001$). Furthermore, FS (682.0 g kg^{-1}) had no HC significant differences from PS (663.47 g kg^{-1}) 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 fields only had higher HC than non-irrigated fields at 18 WAP in 2008 (P = 0.0772). At this sampling period, irrigated treatments (676.7 g kg^{-1}) showed higher HC than non-irrigated treatments (664.9 g kg^{-1}). Tillage treatments showed no significant HC differences in 2008. Conversely, conservation treatments (713.1 g kg^{-1}) had higher HC than conventional treatments (698.6 g k^{-1}) at 18 WAP (P = 0.0049) in 2009 (table 1-21). 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 (DOE, 2005). Therefore, switchgrass was used as reference for bioenergy production. McLaughin et al. (1999) cited switchgrass holocellulose content ranging from 540 to 670 g kg^{-1}. However, all tested crops showed higher or equal holocellulose content 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.

3.9.2. Lignin content

Lignin is the undesirable portion of biomass when considering bioethanol production, because it cannot be converted into carbohydrates, and it has recalcitrant effect. In other words, lignin masks holocellulose (cellulose and hemicellulose) which forbids carbohydrate conversion. Therefore, low lignin content (LC) is desired in cellulosic materials in order to enhance bioethanol production (Weng et. al, 2008).

LC was significantly different between years ($P \leq 0.0001$). Higher LC were found in 2009 (77.9 g kg^{-1}) than in 2008 (69.2 g kg^{-1}). 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 low lignin content than stems (Carmi et. al, 2006), high lignin content could be expected in 2009 season for all crops.

Irrigated fields showed higher LC than non-irrigated fields at 14 ($P = 0.005$), 18 ($P = 0.0101$) and 24 ($P = 0.0014$) in 2008. In this year, irrigated treatments showed LC values of 70.1, 70.8 and 91.5 g kg^{-1} at 14, 18 and 24 WAP respectively; and, non-irrigated treatments showed LC values of 56.4, 61.3 and 83.2 g kg^{-1} respectively. In 2009, irrigated treatments (68.5 g kg^{-1}) had higher LC than non-irrigated treatments (62.4 g kg^{-1}, $P = 0.0129$). Carmi et al. (2006) found similar results. They cited 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. Conservation and conventional tillage showed, respectively, 65.0 and

61.5 g kg^{-1} in 2008 ($P = 0.0078$); and 68.0 and 62.9 g kg^{-1} in 2009 ($P = 0.0304$), tillage treatments had no significant LC differences at other sampling periods for both years.

Crops were significantly different in LC for both years. In 2008, FS (71.4 g kg^{-1}) had the highest LC which was significantly different from PS (65.7 g kg^{-1}), GS (58.2 g kg^{-1}) and corn (57.8 g kg^{-1}) at 14 WAP ($P \leq 0.0001$). However, at 18 WAP ($P \leq 0.0001$), PS (67.0 g kg^{-1}) showed significantly higher LC than FS (61.7 g kg^{-1}), GS (58.9 g kg^{-1}) and corn (57.7 g kg^{-1}). Thus, PS and FS were significantly different in LC for all sampling periods, where FS (91.3 g kg^{-1}) were significantly higher in LC than PS (83.5 g kg^{-1}) at 24 WAP ($P = 0.0629$). However, GS and corn always showed no significant differences in LC at 18 WAP (table 1-20).

In 2009, FS (74.5 g kg^{-1}) and PS (69.8 g kg^{-1}) had significantly higher LC than GS (60.0 g kg^{-1}) and corn (57.6 g kg^{-1}) at 14 WAP ($P \leq 0.0001$). However, at 20 WAP, all sorghum varieties: PS (94.1 g kg^{-1}), GS (92.1 g kg^{-1}) and FS (90.2 g kg^{-1}) showed significantly higher LC than corn (74.3 g kg^{-1}). Thus, FS (85.5 g kg^{-1}) showed higher LC than PS (81.2 g kg^{-1}) at 24 WAP, $P = 0.0164$ (table 1-12).

Switchgrass lignin content was cited as 190 g kg^{-1} (Lee et al., 2007). However, all tested crops showed lower lignin content 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.

3.9.3. Ash content

Ash content (AC) in cellulosic materials is relevant information for thermal and biochemical technologies which produce electricity and fuel. Low ash content 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., 2008). Therefore, low ash content is desirable to produce bioenergy.

Significant differences between years were found when comparing ash content (AC). AC was slightly higher in 2009 (53.90 g kg^{-1}) than in 2008 (49.74 g kg^{-1}), $P \leq 0.0001$.

Irrigation treatments were not significantly different in AC for both years, except to14 WAP at 2008 ($P = 0.0041$) where non-irrigated treatment (55.7 g kg^{-1}) had higher AC than irrigated treatment (51.1 g kg^{-1}).

Tillage treatments were significantly different in AC for both years at 14 WAP. Conservation tillage (54.7 g kg^{-1}) was significantly higher in AC than conventional tillage (52.1 g kg^{-1}) in 2008 ($P = 0.0063$). Conversely, conventional tillage (65.6 g kg^{-1}) showed higher AC than conservation tillage (58.1 g kg^{-1}) in 2009 ($P = 0.0002$). Furthermore, irrigation x tillage interaction ($P = 0.0081$) in 2008 indicated that conventional tillage had higher AC just in non-irrigated conditions in 2008, where tillage treatments were not significantly different in AC under irrigated conditions.

Crops were significantly different in AC for both years. In 2008, GS (58.0 g kg^{-1}) and corn (55.8 g kg^{-1}) were higher in AC than PS (52.0 g kg^{-1}) and FS (47.8 g kg^{-1}) at 14 WAP, but only GS were significantly different from FS at 14 WAP ($P = 0.0136$). The same trend was observed at 18 WAP ($P = 0.0296$), where GS, corn, PS and FS had AC values of 56.0, 50.2, 43.20 and 43.9 g kg^{-1}, respectively. But, GS was the only crop that showed significant LC differences from FS and PS. Thus, FS (51.7 g kg^{-1}) showed significantly higher AC than PS (38.9 g kg^{-1}) at 24 WAP (table 1-20), but those differences were valid just under irrigated treatments (crops x irrigation interaction; $P = 0.0967$).

In 2009, no significant AC differences were found among crops at 14 WAP. FS, GS, PS and corn had AC values of 65.2, 61.8, 60.5 and 59.8 g kg^{-1} respectively. GS (57.6 g kg^{-1}) and FS (55.1 g kg^{-1}) showed significantly higher AC than PS (44.6 g kg^{-1}) and corn (39.0 g kg^{-1}) at 20 WAP (P = 0.0067). And, PS (56.3 g kg^{-1}) showed higher AC than PS (39.2 g kg^{-1}) at 24 WAP (P = 0.0094) (table 1-21).

McLaughlin et al. (1996) cited switchgrass AC ranging from 45 to 58 g kg^{-1}. However, all tested crops showed similar ash content. 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.

4. CONCLUSIONS

All sorghum varieties showed higher biomass production than corn during all sampling periods in both years. All sorghum varieties were able to produce more yield than corn under all irrigation and tillage treatments which proved sorghum’s superiority in producing cellulosic biomass for a potential bioenergy industry. Higher cellulosic biomass production reported in 2008 than 2009 season was related to anthracnose and southern corn leaf blight diseases in sorghum and corn crops, respectively. Thus, crop rotation were recommended. Lodging which affected PS, FS and GS sorghum varieties could be related to high plant population. Therefore, sorghum plant population must be better evaluated for use in the southeastern U.S.

Irrigated treatments affected cellulosic biomass production positively in both years. Conservation system showed higher cellulosic biomass production than conventional tillage in 2009. Stomatal conductance readings showed that high yields under irrigated and conservation fields were related to plentiful amounts of water in soil which might increase plant metabolism. A better rye soil cover was found in 2009 (2.57 Mg ha^{-1}) than 2008 (0.26 Mg ha^{-1}) due to increased rye dry matter production in 2009 caused by better weather conditions (elevated temperatures in early spring 2009).

Cellulosic biomass quality parameters were only slightly significantly different among crops for all sampling periods. Holocellulose, lignin, and ash content variation among crops were less than 8.3, 2.0, and 1.9 % respectively. Therefore, cellulosic biomass quality was considered a minor factor and total cellulosic biomass production considered the major factor to select the best crop for bioenergy production.

Therefore, PS was considered the best tested crop in order to produce cellulosic biomass (ADM) which produced 26.04 and 30.13 Mg ha^{-1} at 18 and 24 WAP. However, FS can be an alternative if 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 due to southeastern U.S. photoperiod condition resulted in high cellulosic biomass production in late harvests.

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Table1-1: Results of the type 3 test of treatments and effects from PROC MIXED for rye dry matter (Mg ha^{-1}) yield for 2008 and rye dry matter yield (Mg ha^{-1}) and spontaneous vegetation (Mg ha^{-1}) in 2009.

Rye dry matter	**Years**	
	2008*	**2009****
	Rye (total field)	**Rye (conservation plots)**
Treatments	----*Dry matter (Mg ha^{-1})*----	------*Dry matter (Mg ha^{-1})*------
Crops		
PS***	0.26	2.66
FS ***	0.28	3.04
GS ***	0.28	2.04
Corn***	0.23	2.59
Irrigation		
Irrigated	0.27	2.51
non-irrigated	0.26	2.66
Tillage		
conventional	0.27	---
conservation	0.25	---
Source of Error	-------*p-value*------	------------*p-value*-----------
Crops (C)	0.3427	0.7167
Irrigation (I)	0.2984	0.4790
Tillage (T)	0.3583	---
CxI	0.8647	0.1297
CxT	0.2788	---
IxT	0.1773	---
CxIxT	0.5802	---

* Rye cover crop planted in total field.

** Rye cover crop planted just in conservation plots.

***PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

Table 1-2: Results of the type 3 test of treatments and effects from PROC MIXED for sunn hemp dry matter (Mg ha^{-1}) yield for fall 2008.

Sunn hemp dry matter	**Year**
	2008
Treatments	---*Dry matter(Mg ha^{-1})*---
Crops	
GS**	0.37b
Corn**	0.87a
Irrigation	
Irrigated	0.57a
Non-irrigated	0.67a
Source of error	----------*p-value*----------
Crops	0.0198*
Irrigation	0.4777
Crops x Irrigation	0.1022

*

Significant at 0.10 level of probability.

**GS: grain sorghum (NK300), Corn: Pioneer31G65.

Table1-3: Precipitation (mm) in irrigated and non-irrigated plots monitored by rain gauges installed in field from planting to 14 weeks after planting for both years.

Rain gauges set	**Precipitation (mm)**			
	2008		**2009**	
	Irrigated	**Non-irrigated**	**Irrigated**	**Non-irrigated**
1	462	343	630	577
2	473	329	616	554
3	477	342	637	568
4	467	336	641	581
Mean	469.7	337.5	631.0	570.0
C.V. (%)*	1.4%	1.9%	1.7%	2.1%

*Coefficient of variation.

Table 1-4: Results of the type 3 test of treatments and effects from PROC MIXED for Plant population within each crop during growing season and harvest time in 2008 and 2009.

Weeks after planting	**Crops**			
	PS**	**FS****	**GS****	**Corn****
6 weeks	**--------------------------------- Plants ha^{-1}--------------------------**			
2008	356,106a	383,913a	376,064a	79,608a
2009	362,834a	376,737a	375,616a	77,781a
14 weeks				
2008	327,012a	337,942b	355,882b	77,141a
2009	258,558b	208,326c	289,729c	73,553a
p-value	≤0.0001*	≤0.0001*	≤0.0001*	0.3739

* Significant at 0.10 level of probability.

**PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

Table 1-5: Results of the type 3 test of treatments and effects from PROC MIXED for Stomatal conductance (mmol m^{-2} s^{-1}) yield for 2008.

Year 2008	**Weeks after planting**		
	8	**12**	**16**
Treatments	-----*Stomatal Conductance (mmol m^{-2} s^{-1})*-----		
Crops			
PS**	342.08a	257.45a	126.63b
FS**	330.93a	241.48a	151.75ab
GS**	291.39b	227.64a	181.54a
Corn**	295.99b	164.53a	74.79c
Irrigation			
Irrigated	397.81a	235.51a	134.56a
Non-irrigated	232.38b	210.04b	132.79a
Tillage			
Conventional	320.62a	250.92a	133.39a
Conservation	309.58a	194.63b	133.96a
Effect	-----------------------*ρ-value*---------------------		
Crops	0.0557*	0.2394	0.0011*
Irrigation	0.0050*	0.0218*	0.9306
Tillage	0.2603	0.0116*	0.9413
Crops x Irrigation	0.3919	0.7319	0.0170*
Crops x Tillage	0.3061	0.3677	0.7484
Irrigation x Tillage	0.2894	0.4578	0.3459
Crops x Irrigation x Tillage	0.8706	0.6214	0.4449

* Significant at the 0.10 level of probability.

**PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

Table 1-6: Results of the type 3 test of treatments and effects from PROC MIXED for Stomata conductance (mmol m^{-2} s^{-1}) yield for 2009.

Year 2009	**Weeks after planting**		
	8	**12**	**16**
Treatments	*-----Stomata Conductance (mmol m^{-2} s^{-1})-----*		
Crops			
PS**	323.70a	256.73a	277.81a
FS**	307.54a	262.68a	377.99a
GS**	323.16a	245.38a	233.84a
Corn**	340.91a	242.18a	---
Irrigation			
Irrigated	327.56a	271.44a	286.12a
Non-irrigated	320.09a	232.05b	280.31a
Tillage			
Conventional	309.46a	230.60a	297.39a
Conservation	338.20a	272.80a	269.04a
Effect	----------------------*ρ-value*---------------------		
Crops	0.9576	0.9891	0.2050
Irrigation	0.8991	0.0409*	0.8271
Tillage	0.4957	0.0132*	0.1933
Crops x Irrigation	0.3152	0.5122	0.0200*
Crops x Tillage	0.7179	0.5529	0.5293
Irrigation x Tillage	0.2454	0.6855	0.4199
Crops x Irrigation x Tillage	0.5396	0.0900*	0.4495

* Significant at the 0.10 level of probability.

**PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

Table 1-7: Results of the type 3 test of treatments and effects from PROC MIXED for Plant height (m) in 2008.

Year 2008	**Weeks after planting**				
	6	**9**	**14**	**18**	**24**
Treatments	-----------------*Plant height (m)*-----------------				
Crops					
PS**	1.07c	1.61c	3.23a	3.67a	3.84a
FS**	1.37b	2.13b	3.23a	3.25b	3.43b
GS**	1.16c	1.32d	1.70c	1.72c	-
Corn**	1.50a	2.73a	2.80b	2.74c	-
Irrigation					
Irrigated	1.34a	2.14a	3.00a	3.12a	3.90a
Non-irrigated	1.21b	1.76b	2.44b	2.57b	3.37b
Tillage					
Conservation	1.31a	2.01a	2.78a	2.89a	3.67a
Conventional	1.24b	1.89b	2.67b	2.80b	3.61a
Effect	------------------------*ρ-value*----------------------				
Crops	0.0002*	0.0001*	0.0001*	0.0001*	0.0276*
Irrigation	0.0517*	0.0046*	0.0068*	0.0012*	0.0178*
Tillage	0.0024*	0.0001*	0.0177*	0.0535*	0.4223
Crops x Irrigation	0.5508	0.4943	0.0153*	0.0717*	0.1632
Crops x Tillage	0.0192*	0.0023*	0.3870	0.7846	0.4617
Irrigation x Tillage	0.6238	0.1187	0.1740	0.7466	0.2549
Crops x Irrigation x Tillage	0.9850	0.6852	0.7798	0.9218	0.4848

* Significant at the 0.10 level of probability.

**PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

Table 1-8: Results of the type 3 test of treatments and effects from PROC MIXED for Plant height (m) in 2009.

Year 2009	**Weeks after planting**				
	6	**9**	**14**	**20**	**24**
Treatments	-----------------*Plant height (m)*-----------------				
Crops					
PS**	1.15b	1.85c	3.19a	3.83a	4.09a
FS**	1.25b	2.01b	3.01a	3.05b	3.08b
GS**	1.20b	1.55d	1.70c	1.76d	-
Corn**	1.66a	2.82a	2.58b	2.56c	-
Irrigation					
Irrigated	1.28b	2.14a	2.75a	2.95a	3.72a
Non -irrigated	1.36a	1.97b	2.45b	2.65b	3.45b
Tillage					
Conservation	1.48a	2.21a	2.71a	2.86a	3.62a
Conventional	1.16b	1.90b	2.53b	2.75b	3.56a
Effect	------------------------*ρ-value*----------------------				
Crops	0.0016*	0.0001*	0.0001*	0.0001*	0.0018*
Irrigation	0.0391*	0.0028*	0.0031*	0.0057*	0.0493*
Tillage	0.0001*	0.0001*	0.0002*	0.0193*	0.4591
Crops x Irrigation	0.4540	0.4943	0.0892*	0.4627	0.5319
Crops x Tillage	0.2654	0.1055*	0.1712	0.0795*	0.3132
Irrigation x Tillage	0.6791	0.0006*	0.0461*	0.0644*	0.5319
Crops x Irrigation x Tillage	0.6709	0.2620	0.0903*	0.1957	0.4848

* Significant at the 0.10 level of probability.

**PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

Table 1-9: Results of the type 3 test of treatments and effects from PROC MIXED for Aboveground dry matter (Mg ha^{-1}) for 2008 and 2009.

Aboveground dry matter (Mg ha^{-1})	**Years**	
	2008	**2009**
Source of Error	----------------------*ρ-value*	---------------------
Crops	0.0001*	0.0001*
Irrigation	0.0090*	0.0637*
Tillage	0.8721	0.0028*
Crops x Irrigation	0.0227*	0.0396*
Crops x Tillage	0.7618	0.2716
Irrigation x Tillage	0.6863	0.1431
Crops x Irrigation x Tillage	0.1737	0.5302

* Significant at the 0.10 level of probability.

Table 1-10: Results of the type 3 test of treatments and effects from PROC MIXED for P, K, Ca, and Mg aboveground dry matter uptake (mg kg^{-1}) for all sampling periods in 2008.

2008	**Primary nutrients uptake**						**Secondary nutrients uptake**					
	Phosphorus (P)			**Potassium (K)**			**Calcium (Ca)**			**Magnesium (Mg)**		
	14WAP**	**18WAP****	**24WAP****	**14WAP****	**18WAP****	**24WAP****	**14WAP****	**18WAP****	**24WAP****	**14WAP****	**18WAP****	**24WAP****
Effects	-------------*mg kg^{-1}*-------------			-------------*mg kg^{-1}*-------------			-------------*mg kg^{-1}*-------------			-------------*mg kg^{-1}*-------------		
Crops												
PS***	1133a	1623	822	14490ab	11401b	8037b	2322b	2991	1718	2536a	2321a	1879
FS***	1087a	1172	1116	12887c	10301b	10974a	2145b	1929	1984	2128b	1958b	1588
GS***	893b	829	---	15429a	13245a	---	2628a	2351	---	2700a	2310a	---
Corn***	807b	1007	---	14270b	10492b	---	2541a	2233	---	1930b	1819b	---
Irrigation												
irrigated	973	1030	1002	13474b	10943	9236	2351	2094	1798	2176	2057	1682
non-irrigated	987	1284	937	15064a	11776	9775	2467	2658	1904	2371	2147	1785
Tillage												
conservation	1029a	1348	962	14630a	11916a	9318	2344b	2630	1810	2312	2164	1725
conventional	931b	967	976	13908b	10803b	9692	2474a	2122	1892	2335	2040	1742
	-------------*p-value*-------------			-------------*p-value*-------------			-------------*p-value*-------------			-------------*p-value*-------------		
Source of Error												
crops (C)	0.0034*	0.3307	0.1725	0.0100*	0.0100*	0.0329*	0.0077*	0.5653	0.2246	0.0011*	0.0010*	0.1725
irrigation (I)	0.8333	0.4694	0.4935	0.0033*	0.3332	0.5855	0.1665	0.3136	0.4114	0.4303	0.4093	0.4400
tillage (T)	0.0036*	0.1640	0.7569	0.0851*	0.0036*	0.2755	0.0575*	0.2916	0.3665	0.7471	0.1176	0.8710
CxI	0.0016*	0.4663	0.4842	0.1532	0.3831	0.3966	0.0813*	0.4981	0.3163	0.0313*	0.6700	0.2584
CxT	0.9872	0.3173	0.9806	0.3178	0.4481	0.6476	0.5356	0.3037	0.5798	0.2393	0.2697	0.4626
IxT	0.2842	0.3819	0.1364	0.8528	0.6893	0.4137	0.9882	0.4782	0.0601*	0.9375	0.1680	0.0855*
CxIxT	0.4402	0.4435	0.5953	0.4374	0.7668	0.6307	0.3209	0.4548	0.2986	0.3425	0.3882	0.7199

* Significant at 0.10 level of probability.
**Weeks after planting.
***PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

Table 1-11: Results of the type 3 test of treatments and effects from PROC MIXED for P, K, Ca, and Mg aboveground dry matter uptake (mg kg^{-1}) for all sampling periods in 2009.

2009	**Primary nutrients uptake**						**Secondary nutrients uptake**					
	Phosphorus (P)			**Potassium (K)**			**Calcium (Ca)**			**Magnesium (Mg)**		
	14WAP**	**20WAP****	**24WAP****	**14WAP****	**20WAP****	**24WAP****	**14WAP****	**20WAP****	**24WAP****	**14WAP****	**20WAP****	**24WAP****
Effects	-------------*mg kg^{-1}*-------------			-------------*mg kg^{-1}*-------------			-------------*mg kg^{-1}*-------------			-------------*mg kg^{-1}*-------------		
Crops												
PS***	1460	1283a	1206	16263ab	10791b	10169b	2343c	1417c	1281	2601b	1835b	1520
FS***	1727	1331a	1211	17718a	15416a	15934a	2551bc	1317c	1500	2749b	1608c	1444
GS***	1672	1379a	---	14933b	13383a	---	2964ab	2032a	---	3453a	2574a	---
Corn***	1416	850b	---	14518b	7305c	---	3380a	1672b	---	2602b	1713bc	---
Irrigation												
irrigated	1628	1257	1169	15309	11635	13153	2672	1613	1343	2765	1937	1423
non-irrigated	1509	1164	1248	16406	11812	12915	2947	1606	1438	2938	1928	1540
Tillage												
conservation	1451b	1170b	1221	14860b	12104a	13522a	2595b	1588	1332	2592b	1850b	1464
conventional	1686a	1251a	1196	16856a	11344b	12581b	3024a	1631	1349	3111a	2015a	1499
	-------------*p-value*-------------			-------------*p-value*-------------			-------------*p-value*-------------			-------------*p-value*-------------		
Source of Error												
crops (C)	0.1057	0.0037*	0.9343	0.0844*	0.0008*	0.0100*	0.0193*	0.0003*	0.2020	0.0546*	0.0001*	0.6699
irrigation (I)	0.4874	0.3363	0.3286	0.2465	0.7311	0.7855	0.1120	0.9131	0.1788	0.2638	0.8007	0.2097
tillage (T)	0.0087*	0.0693*	0.7183	0.0061*	0.0549*	0.0595*	0.0004*	0.4905	0.1746	0.0001*	0.0035*	0.6067
CxI	0.5858	0.4975	0.5671	0.3647	0.2625	0.7032	0.4704	0.3828	0.6793	0.6718	0.1385	0.8268
CxT	0.0295*	0.0444*	0.1867	0.0036*	0.0249*	0.6779	0.0016*	0.0927*	0.5017	0.0015*	0.0584*	0.1822
IxT	0.5996	0.6797	0.6381	0.6628	0.3004	0.9406	0.2833	0.7723	0.8385	0.7816	0.4084	0.7379
CxIxT	0.8507	0.0430*	0.9348	0.8027	0.2343	0.8198	0.6605	0.8242*	0.5388	0.8896	0.7802	0.7134

* Significant at 0.10 level of probability.
**Weeks after planting.
***PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

Table 1-12: Results of the type 3 test of treatments and effects from PROC MIXED for Cu, Fe, and Zn aboveground dry matter uptake (mg kg^{-1}) for all sampling periods in 2009.

2008	**Micronutrients**								
	Copper (Cu)			**Iron (Fe)**			**Zinc (Zn)**		
	14WAP**	**18WAP****	**24WAP**-**	**14WAP****	**18WAP**-**	**24WAP****	**14WAP****	**18WAP****	**24WAP****
Effects	-------------*mg kg^{-1}*-------------			-------------*mg kg^{-1}*-------------			-------------*mg kg^{-1}*-------------		
Crops									
PS***	5.13	3.82	2.35b	157.05	186.84	138.18	23.92a	12.63	17.69
FS***	7.27	3.48	4.51a	105.33	174.20	170.53	19.98ab	18.27	20.54
GS***	5.83	3.54	---	107.61	210.58	---	19.86b	10.63	---
Corn***	6.30	4.26	---	114.50	174.40	---	16.64b	15.54	---
Irrigation									
irrigated	5.75	3.95	3.91	130.57	197.63	161.99	18.85b	11.92	20.02
non-irrigated	6.52	3.60	2.94	111.67	175.37	146.71	21.36a	16.66	18.21
Tillage									
conservation	6.28	3.95	3.31	120.08	191.01	159.38	20.83a	15.21	19.58
conventional	5.98	3.60	3.55	122.16	181.99	149.32	19.37b	13.38	18.65
	-------------*p-value*-------------			-------------*p-value*-------------			-------------*p-value*-------------		
Source of Error									
crops (C)	0.8093	0.7785	0.0058*	0.3070	0.7872	0.5483	0.0559*	0.4884	0.4818
irrigation (I)	0.5841	0.2522	0.5082	0.4314	0.4223	0.6459	0.0021*	0.1308	0.3094
tillage (T)	0.7875	0.4451	0.7796	0.8959	0.3635	0.6010	0.0804*	0.3542	0.5905
CxI	0.2875	0.8002	0.4972	0.3934	0.7305	0.4979	0.0631*	0.6424	0.8306
CxT	0.0110*	0.1361	0.4443	0.7892	0.1118	0.3799	0.2551	0.0409	0.8204
IxT	0.0898*	0.2642	0.4097	0.4081	0.1424	0.3839	0.7329	0.0294	0.8835
CxIxT	0.4673	0.8062	0.1796	0.7994	0.1811	0.3558	0.1728	0.4842	0.9551

* Significant at 0.10 level of probability.
** Weeks after planting
***PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

Table 1-13: Results of the type 3 test of treatments and effects from PROC MIXED for Cu, Fe, and Zn aboveground dry matter uptake (mg kg^{-1}) for all sampling periods in 2009.

2009	**Micronutrients**								
	Copper (Cu)			**Iron (Fe)**			**Zinc (Zn)**		
	14WAP**	**20WAP****	**24WAP****	**14WAP****	**20WAP****	**24WAP****	**14WAP****	**20WAP****	**24WAP****
Effects	-------------*mg* kg^{-1}-------------			-------------*mg* kg^{-1}-------------			-------------*mg* kg^{-1}-------------		
Crops									
PS***	6.43	4.25	2.35b	107.05	169.86	152.48	15.75	20.80	18.94
FS***	9.87	5.42	4.30a	193.36	201.35	163.48	26.98	20.12	17.97
GS***	8.57	4.08	---	131.04	173.04	---	19.98	29.60	---
Corn***	10.13	4.66	---	128.47	147.56	---	18.41	21.80	---
Irrigation									
irrigated	8.87	5.45a	3.40	157.09	192.50	185.67	20.24	22.63	19.52
non-irrigated	8.63	3.76b	3.26	122.88	153.41	130.29	20.32	23.52	17.39
Tillage									
conservation	7.29b	4.73	3.16	116.87b	172.09	167.03	19.22	24.79a	19.28
conventional	10.21a	4.48	3.48	163.09a	173.82	148.93	21.34	21.36b	17.62
Source of Error	-------------*p-value*-------------			-------------*p-value*-------------			-------------*p-value*-------------		
crops (C)	0.1389	0.5764	0.0201*	0.6268	0.8252	0.7683	0.2796	0.5974	0.6812
irrigation (I)	0.8261	0.0397*	0.7476	0.3448	0.4210	0.2174	0.9781	0.7017	0.5631
tillage (T)	0.0007*	0.5339	0.5292	0.0020*	0.9220	0.5142	0.1789	0.0618*	0.4573
CxI	0.2650	0.9655	0.9804	0.5321	0.2747	0.4875	0.0626	0.2217	0.5203
CxT	0.0146*	0.1624	0.9438	0.3349	0.0070	0.7609	0.0033*	0.4627	0.3184
CxT	0.1360	0.5860	0.4688	0.6424	0.7874	0.7429	0.0602*	0.5874	0.6454
CxIxT	0.4068	0.2438	0.5736	0.0734	0.1189	0.7844	0.3996	0.1172	0.3119

* Significant at 0.10 level of probability
** Weeks after planting
***PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

Table 1-14: Results of the type 3 test of treatments and effects from PROC MIXED for corn grain dry matter (Mg ha^{-1}) yield for 2008 and 2009.

Corn grain yield	**Years**	
	2008	**2009**
Treatments	--------*Grain dry matter (Mg ha^{-1})*-------	
Sampling period		
14 WAP**	8.17b	7.05b
18 / 20 WAP***	8.76a	8.18a
Irrigation		
Irrigated	9.67a	7.76
Non-irrigated	7.26b	7.48
Tillage		
Conservation	8.54	7.77
Conventional	8.40	7.46
Source of Error	-----------------*ρ-value*------------------	
Sampling period (SP)	0.0233*	0.0691*
Irrigation (I)	0.0072*	0.7247
Tillage (T)	0.5576	0.6013
SP x I	0.1785	0.4364
SP x T	0.6689	0.4121
I x T	0.6679	0.3760
SP x I x T	0.6633	0.8692

* Significant at the 0.10 level of probability.

** Weeks after planting.

*** Samples collected at 18 WAP** in 2008, and at 20 WAP** in 2009.

Table 1-15: Results of the type 3 test of treatments and effects from PROC MIXED for P, K, Ca and Mg corn grain uptake (mg kg^{-1}) for all sampling periods in 2008 and 2009.

Corn Grain	**Primary nutrients uptake**				**Secondary nutrients uptake**			
	Phosphorus (P)		**Potassium (K)**		**Calcium (Ca)**		**Magnesium (Mg)**	
	2008	**2009**	**2008**	**2009**	**2008**	**2009**	**2008**	**2009**
Treatments	-------------*g kg^{-1}*-------------		-------------*g kg^{-1}*-------------		-------------*g kg^{-1}*-------------		-------------*g kg^{-1}*-------------	
Sampling period								
14WAP***	3423.67a	3414.56a	4128.33a	4194.46a	62.75a	66.78	1378.88a	1363.01a
18 / 20 WAP**	2701.00b	2603.81b	3444.75b	2965.29b	47.38b	77.39	1057.10b	1083.16b
Irrigation								
irrigated	2760.48b	2723.13b	3570.49b	3336.88b	46.95b	66.26	1103.11b	1094.73b
non-irrigated	3364.19a	3295.24a	4002.58a	3822.87a	63.18a	77.91	1332.87a	1351.43a
Tillage								
conservation	3161.31a	3065.43	3795.78	3571.66	54.40	66.85	1247.03a	1240.53
conventional	2664.36b	2952.94	3777.30	3588.09	55.76	77.32	1188.95b	1205.64
Source of Error	-------------*p-value*-------------		-------------*p-value*-------------		-------------*p-value*-------------		-------------*p-value*-------------	
Sampling period (SP)	0.0023*	0.0055*	0.0132*	0.0009*	0.0588*	0.6631	0.0017*	0.0052*
irrigation (I)	0.0119*	0.0326*	0.0175*	0.0374*	0.0742*	0.4460	0.0063*	0.0395*
tillage (T)	0.0375*	0.2464	0.8243	0.8455	0.6095	0.2706	0.0986*	0.4154
SPxI	0.5312	0.0831*	0.0569*	0.4583	0.5604	0.3431	0.4366	0.0772*
SPxT	0.8998	0.4226	0.6637	0.8788	0.3570	0.2660	0.7526	0.2830
SPxT	0.3586	0.7666	0.1112	0.6933	0.7007	0.2844	0.7946	0.8945
SPxIxT	0.3477	0.2649	0.9170	0.3276	0.3905	0.9230	0.5091	0.6993

* Significant at the 0.10 level of probability.
** Weeks after planting.
*** Samples collected at 18 WAP** in 2008, and at 20 WAP** in 2009.

Table 1-16: Results of the type 3 test of treatments and effects from PROC MIXED for Cu, Fe, and Zn corn grain uptake (mg kg^{-1}) for all sampling periods in 2008 and 2009.

Corn** Grain**	**Micronutrients**					
	Copper (Cu)		**Iron (Fe)**		**Zinc (Zn)**	
	2008	**2009**	**2008**	**2009**	**2008**	**2009**
Treatments	-------------*g kg^{-1}*-------------		-------------*g kg^{-1}*-------------		-------------*g kg^{-1}*-------------	
Sampling period						
14WAP**	4.50	2.26	12.33	15.01a	26.22a	25.62a
18 / 20 WAP***	1.60	1.58	21.76	6.39b	21.40b	19.69b
Irrigation						
irrigated	4.07	1.82	13.36b	7.46	20.72b	19.91b
non-irrigated	2.03	2.02	20.73a	13.94	26.91a	2541a
Tillage						
conservation	4.05	1.89	15.83	9.49	24.82a	22.77
conventional	2.05	1.95	18.25	11.91	22.80b	22.55
Source of Error	-------------*p-value*-------------		-------------*p-value*-------------		-------------*p-value*-------------	
Sampling period (SP)	0.2794	0.3614	0.3747	0.0508*	0.0145*	0.0037*
irrigation (I)	0.4292	0.6727	0.0669*	0.3305	0.0064*	0.0663*
tillage (T)	0.3558	0.7421	0.6909	0.4516	0.0661*	0.8377
SPxI	0.4624	0.7965	0.8344	0.5384	0.2818	0.0112*
SPxT	0.4323	0.1606	0.9546	0.3036	0.2229	0.5494
SPxT	0.3351	0.1730	0.3132	0.6252	0.2150	0.8105
SPxIxT	0.2722	0.3469	0.7416	0.4913	0.6712	0.1285

* Significant at the 0.10 level of probability.
** Weeks after planting.
*** Samples collected at 18 WAP** in 2008, and at 20 WAP** in 2009.
****Corn: Pioneer31G65.

Table 1-17: Results of the type 3 test of treatments and effects from PROC MIXED for GS grain dry matter (Mg ha^{-1}) yield for 2008 and 2009.

GS** – grain yield**	**Years**	
	2008	**2009**
Treatments	--------*Grain dry matter (Mg ha^{-1})*-------	
Sampling Period		
14 WAP**	4.40	---
18 / 20 WAP***	4.62	1.54
Irrigation		
Irrigated	5.06a	1.81
Non-irrigated	3.96b	1.27
Tillage		
Conservation	4.49	1.86
Conventional	4.53	1.52
Source of Error	-----------------*ρ-value*------------------	
Sampling Period (SP)	0.5163	---
Irrigation (I)	0.0861*	0.2659
Tillage (T)	0.8212	0.3799
SP x I	0.8787	---
SP x T	0.8553	---
I x T	0.8232	0.2842
SP x I x T	0.0707*	---

* Significant at the 0.10 level of probability.

** Weeks after planting.

*** Samples collected at 18 WAP** in 2008, and at 20 WAP** in 2009.

*** GS: grain sorghum (NK300)

Table 1-18: Results of the type 3 test of treatments and effects from PROC MIXED for P, K, Ca, and Mg GS grain uptake (mg kg^{-1}) for all sampling periods in 2008 and 2009.

GS** Grain**	**Primary nutrients uptake**				**Secondary nutrients uptake**			
	Phosphorus (P)		**Potassium (K)**		**Calcium (Ca)**		**Magnesium (Mg)**	
	2008	**2009**	**2008**	**2009**	**2008**	**2009**	**2008**	**2009**
Treatments	-------------*g kg*$^{-1}$-------------		-------------*g kg*$^{-1}$-------------		-------------*g kg*$^{-1}$-------------		-------------*g kg*$^{-1}$-------------	
Sampling period								
14WAP**	3154.26b	---	3628.78b	---	135.20	---	1666.36b	---
18 / 20 WAP***	4325.52a	3904.99	4355.52a	3463.38	131.16	221.04	2176.27a	2041.05
Irrigation								
irrigated	3734.01	3707.02	3946.13	3365.56	105.90	218.57	1858.23	1956.66
non- irrigated	3745.78	4102.95	4038.17	3561.19	160.46	223.51	1984.41	21.2544
Tillage								
conservation	3818.45	3697.31	4054.85	3436.31	117.82b	190.60b	1916.88	1924.57b
conventional	3661.33	4112.66	3929.45	3490.44	148.54a	251.48a	1925.76	2157.53a
Source of Error	-------------*p-value*-------------		-------------*p-value*-------------		-------------*p-value*-------------		-------------*p-value*-------------	
Sampling period (SP)	0.0196*	---	0.0536*	---	0.8050	---	0.0074*	---
irrigation (I)	0.9393	0.1494	0.5076	0.5073	0.1363	0.8852	0.1370	0.3222
tillage (T)	0.4815	0.1470	0.5294	0.8568	0.0576*	0.0610*	0.9361	0.0498*
SPxI	0.9775	---	0.3996	---	0.4332	---	0.9062	---
SPxT	0.9427	---	0.9668	---	0.9541	---	0.9892	---
IxT	0.0772*	0.0847*	0.4731	0.2142	0.0670	0.1224	0.0914*	0.0912*
SPxIxT	0.1229	---	0.1314	---	0.7033	---	0.2172	---

* Significant at the 0.10 level of probability.
** Weeks after planting.
*** Samples collected at 18 WAP** in 2008, and at 20 WAP** in 2009.
**** GS: grain sorghum (NK300)

Table 1-19: Results of the type 3 test of treatments and effects from PROC MIXED for Cu, Fe, and Zn GS grain uptake (mg kg^{-1}) for all sampling periods in 2008 and 2009.

GS** Grain**	**Micronutrients**					
	Copper (Cu)		**Iron (Fe)**		**Zinc (Zn)**	
	2008	**2009**	**2008**	**2009**	**2008**	**2009**
Treatments	-------------*g kg^{-1}*-------------		-------------*g kg^{-1}*-------------		-------------*g kg^{-1}*-------------	
Sampling period						
14WAP**	3.78	---	28.02	---	19.32b	---
18 / 20 WAP***	1.82	3.03	47.52	23.4	29.64a	22.39
Irrigation						
Irrigated	1.31	3.44a	32.70	19.15	21.66b	19.83b
non-irrigated	4.28	2.61b	42.84	27.85	27.29a	24.95a
Tillage						
Conservation	1.86	3.04	34.05	20.39	24.87	20.08b
Conventional	3.74	3.01	41.48	26.61	24.09	24.71a
Source of Error	-------------*p-value*-------------		-------------*p-value*-------------		-------------*p-value*-------------	
Sampling period (SP)	0.2477	---	0.1580	---	0.0610*	---
irrigation (I)	0.1911	0.0225*	0.3801	0.4604	0.0489*	0.0199*
tillage (T)	0.1201	0.9600	0.4488	0.2756	0.6759	0.0125*
SPxI	0.2313	---	0.2350	---	0.8760	---
SPxT	0.1688	---	0.3045	---	0.3266	---
IxT	0.1850	0.3698	0.7637	0.2522	0.2093	0.2000
SPxIxT	0.1292	---	0.1250	---	0.2629	---

* Significant at the 0.10 level of probability.
** Weeks after planting.
*** Samples collected at 18 WAP** in 2008, and at 20 WAP** in 2009.
**** GS: grain sorghum (NK300)

Table 1-20: Results of the type 3 test of treatments and effects from PROC MIXED for aboveground dry matter holocellulose, lignin, and ash content (g kg^{-1}) for all sampling periods in 2008.

2008	**Biomass fiber and ash content**								
	Hollocellulose			**Lignin**			**Ash**		
	14WAP**	**18WAP****	**24WAP****	**14WAP****	**18WAP****	**24WAP****	**14WAP****	**18WAP****	**24WAP****
Effects	-------------*g kg*$^{-1}$-------------			-------------*g kg*$^{-1}$-------------			-------------*g kg*$^{-1}$-------------		
Crops									
PS***	715.4a	700.6a	673.5	65.7b	67.0a	83.5b	52.0bc	43.2b	38.9b
FS***	686.83b	653.7c	692.6	71.4a	61.7b	91.3a	47.8c	43.9b	51.7a
GS***	686.5b	650.9c	---	58.2c	58.9c	---	58.0a	56.0a	---
Corn***	687.4b	675.9b	---	57.8c	57.7c	---	55.8ab	50.2ab	---
Irrigation									
Irrigated	699.6	676.7a	682.5	70.1a	70.8a	91.5a	51.1b	46.6	44.8
non-irrigated	688.2	664.9b	683.6	56.4b	61.3b	83.2b	55.7a	50.0	45.8
Tillage									
Conservation	692.7	670.1	678.0b	65.0a	65.4	87.5	54.7a	49.4	45.5
Conventional	695.1	670.5	688.1a	61.5b	66.7	87.3	52.1b	47.2	45.0
	-------------*p-value*-------------			-------------*p-value*-------------			-------------*p-value*-------------		
Source of Error									
crops (C)	0.0216*	0.0022*	0.3817	0.0001*	0.0001*	0.0629*	0.0136*	0.0296*	0.0967*
irrigation (I)	0.1631	0.0772*	0.7512	0.0005*	0.0101*	0.0014*	0.0041*	0.3224	0.8430
tillage (T)	0.4781	0.9499	0.0030*	0.0078*	0.3382	0.9387	0.0063*	0.1619	0.8115
CxI	0.0197*	0.1146	0.5314	0.1431	0.6888	0.6452	0.1421	0.5428	0.0767*
CxT	0.2788	0.5611	0.4948	0.5754	0.1969	0.7504	0.7137	0.4186	0.3360
IxT	0.2180	0.4027	0.2796	0.5530	0.6693	0.1069	0.0081*	0.4197	0.1523
CxIxT	0.2341	0.8175	0.3533	0.0739*	0.2012	0.9542	0.0836*	0.7765	0.9701

* Significant at the 0.10 level of probability.
**Weeks after planting.
***PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

Table 1-21: Results of the type 3 test of treatments and effects from PROC MIXED for aboveground dry matter holocellulose, lignin, and ash content (g kg^{-1}) for all sampling periods in 2009.

2009	**Biomass fiber and ash content**								
	Holocellulose			**Lignin**			**Ash**		
	14WAP**	**20WAP****	**24WAP****	**14WAP****	**20WAP****	**24WAP****	**14WAP****	**20WAP****	**24WAP****
Effects	-------------*g kg^{-1}*-------------			-------------*g kg^{-1}*-------------			-------------*g kg^{-1}*-------------		
Crops									
PS***	696.5ab	690.1b	663.5	69.8b	94.1a	81.2a	60.5	44.6b	39.2b
FS***	674.5bc	684.0b	682.0	74.5a	90.2a	85.5b	65.2	55.1a	56.3a
GS***	656.0c	683.5b	---	60.0c	92.1a	---	61.8	57.6a	---
Corn***	702.1a	765.9a	---	57.5c	74.3b	---	59.8	39.0b	---
Irrigation									
Irrigated	686.04	707.3	675.4	68.5a	89.3	86.9	61.5	49.3	47.6
non-irrigated	678.2	704.5	669.0	62.4b	86.1	79.7	62.1	48.8	47.9
Tillage									
Conservation	683.6	713.1a	672.4	68.0a	89.0	83.9	58.1b	48.3	47.9
Conventional	681.0	698.6b	673.0	62.9b	86.4	82.7	65.6a	49.8	47.5
	-------------*p-value*-------------			-------------*p-value*-------------			-------------*p-value*-------------		
Source of Error									
crops (C)	0.0147*	0.0001*	0.1706	0.0001*	0.0010*	0.0164*	0.1885	0.0067*	0.0094*
irrigation (I)	0.2251	0.5584	0.4269	0.0129*	0.3689	0.1254	0.7946	0.8884	0.8558
tillage (T)	0.3839	0.0049*	0.9529	0.0304*	0.1809	0.6456	0.0002*	0.3252	0.8390
CxI	0.4571	0.5794	0.3862	0.6709	0.7545	0.8239	0.2820	0.8065	0.9897
CxT	0.3007	0.3728	0.5554	0.6107	0.7580	0.7427	0.0505*	0.0763*	0.1736
IxT	0.7015	0.9937	0.8711	0.8194	0.2593	0.5265	0.1931	0.1994	0.9359
CxIxT	0.3462	0.5613	0.6894	0.7474	0.9929	0.2016	0.9307	0.7705	0.9438

* Significant at the 0.10 level of probability.
**Weeks after planting.
***PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

Figure 1-1: Mean monthly 2008, 2009, and long-term (1999–2009) precipitation at experimental location near E. V. Smith Alabama Agricultural Station – Field Crop Units, Shorter, AL.

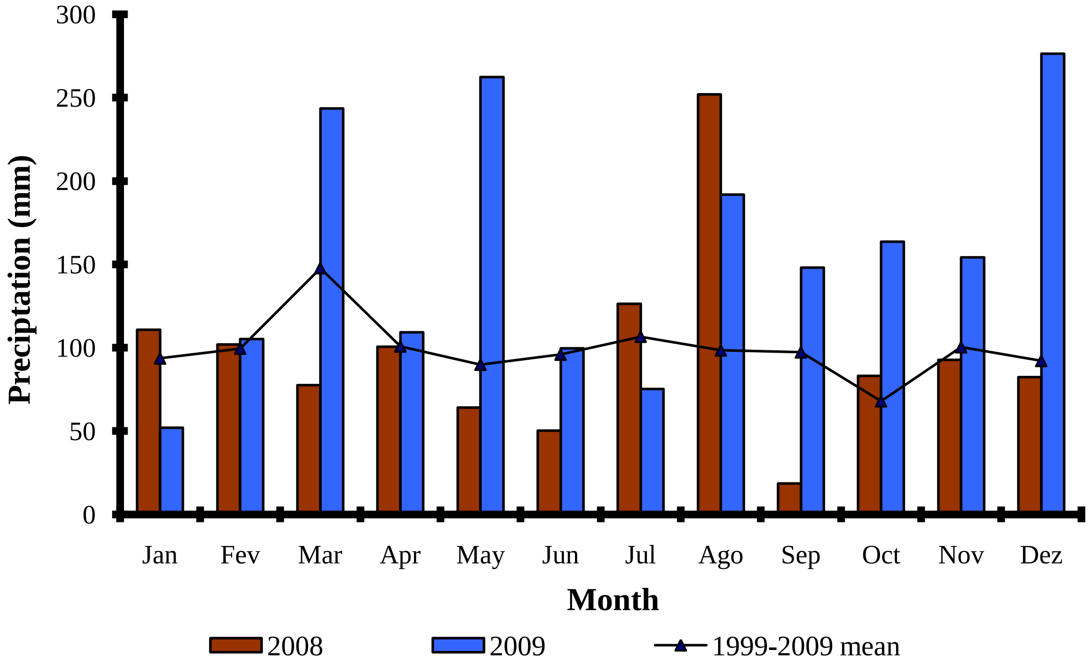


Figure 1-2: Crops effect on plant height at 6, 9, 14, 18 and 24 weeks after plant in 2008. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

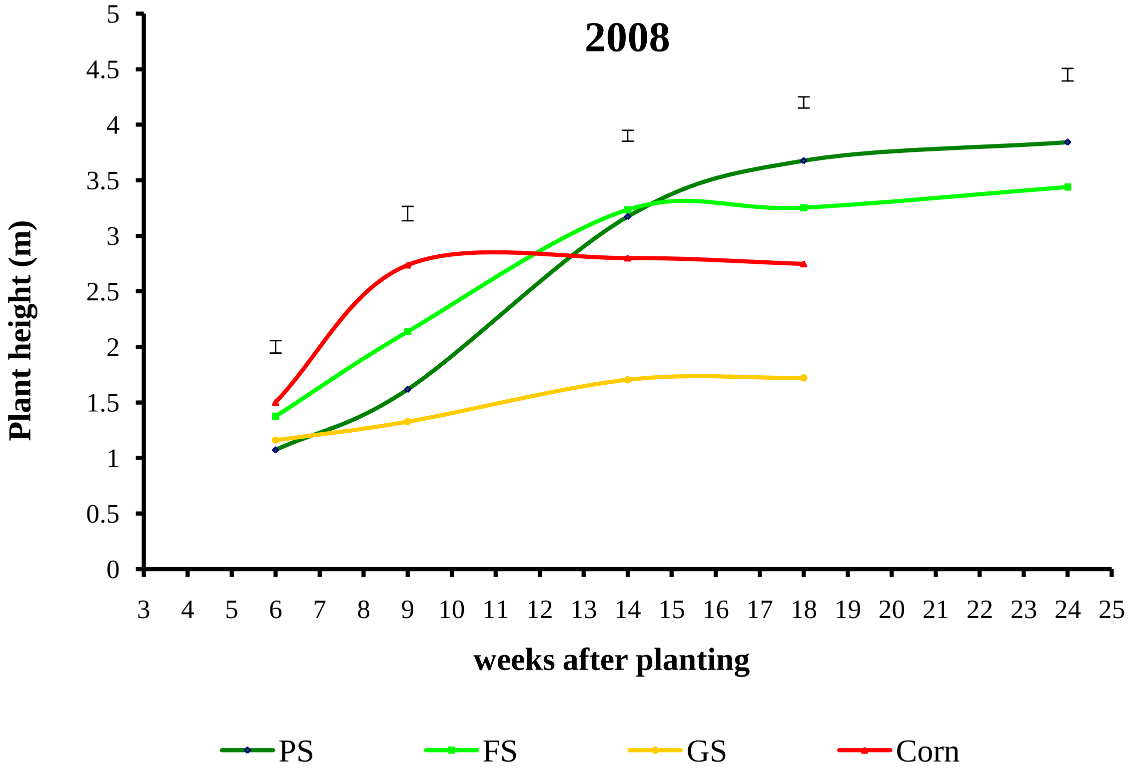


Figure 1-3: Crops effect on plant height at 6, 9, 14, 18, and 24 weeks after plant in 2009. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

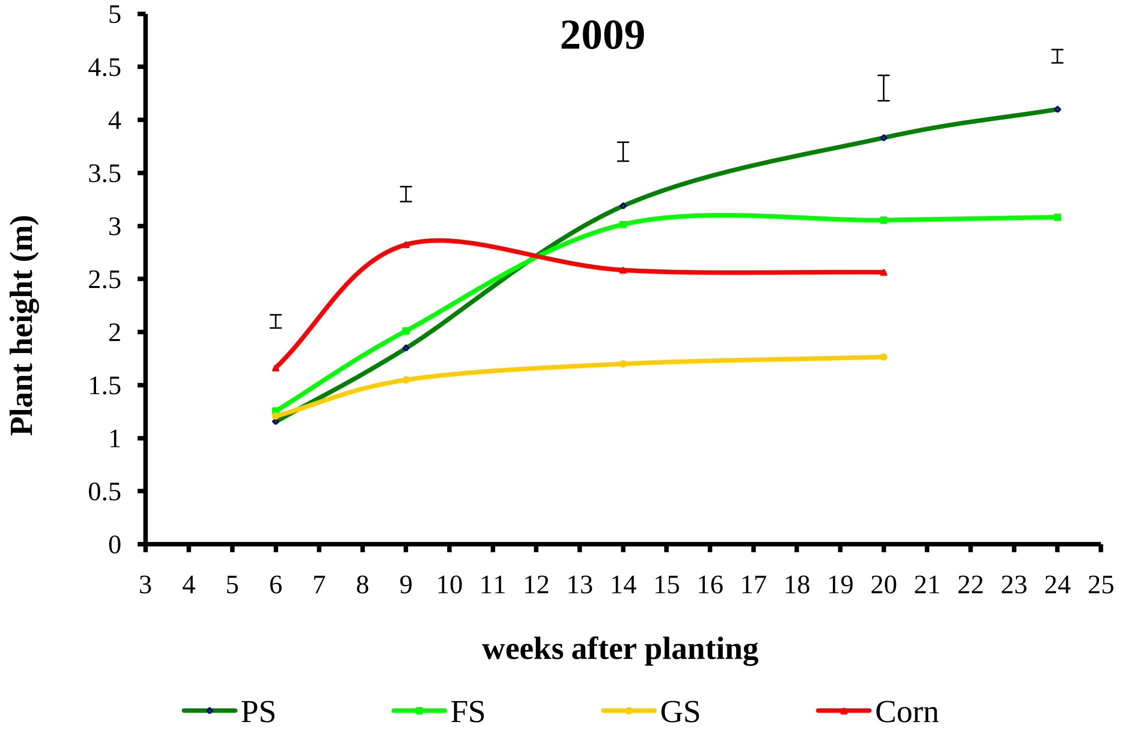


Figure 1-4: Irrigation effect on aboveground dry matter (Mg ha^{-1}) for both years. Letters denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$ means separation between treatments at the same year.

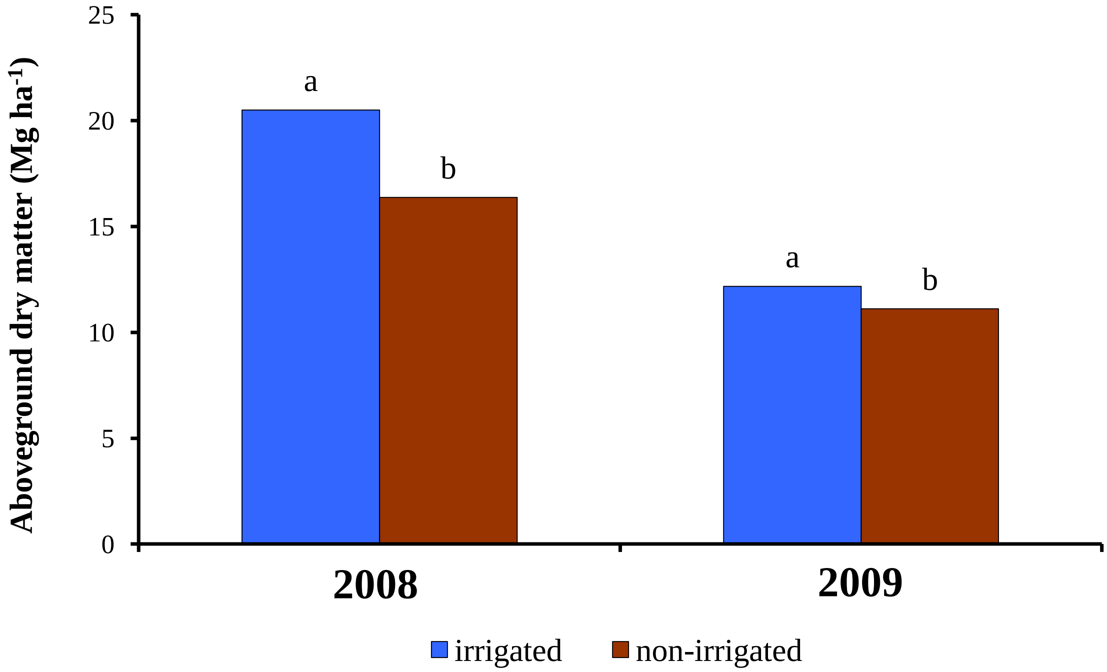


Figure 1-5: Tillage effect on aboveground dry matter (Mg ha^{-1}). Letters denote significant differences – Difference of L.S. means $S.E._{(0.10)}$ means separation between treatments at the same year.

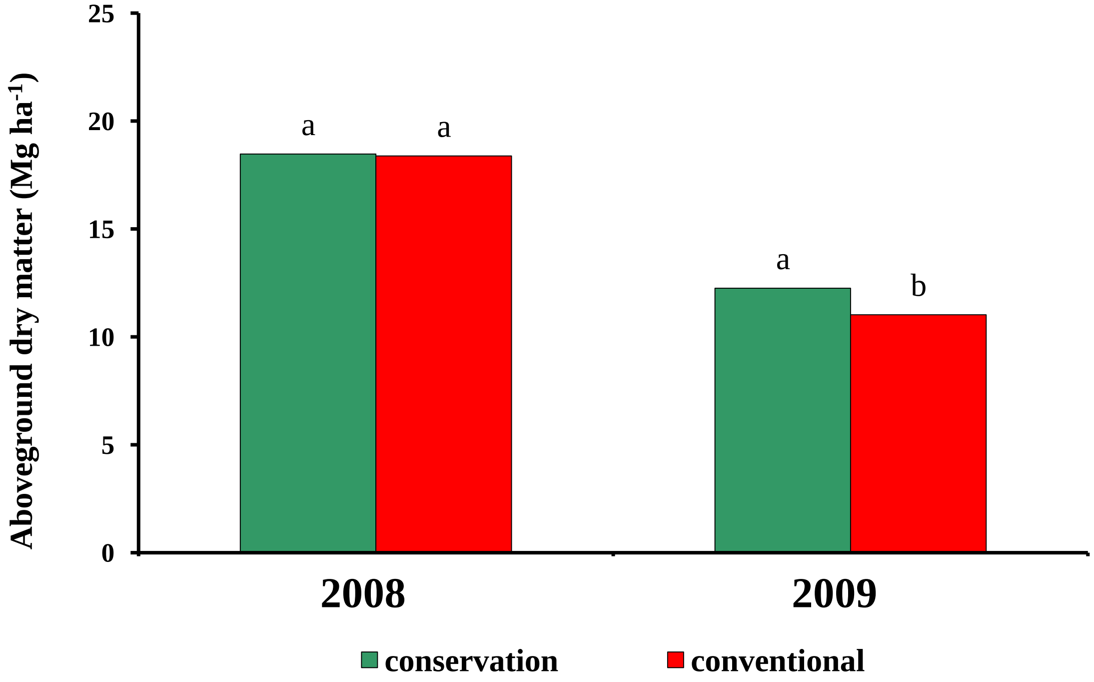


Figure 1-6: Crops effect on aboveground dry matter production (Mg ha^{-1}) during 3 different periods in 2008. Letters denote separation significant differences – Difference of L.S. means S.E.$_{(0.10)}$ among all treatments in any period. PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

Figure 1-7: Crops effect on aboveground dry matter production (Mg ha^{-1}) during 3 different periods in 2009. Letters denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$ separation among all treatments in any period. PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

Figure 1-8: Crops x irrigation interaction effect on aboveground dry matter (Mg ha^{-1}) during 3 different periods in 2008. Vertical error bars denote significant differences – Difference of L.S. means $S.E._{(0.10)}$. WAP: weeks after planting, PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

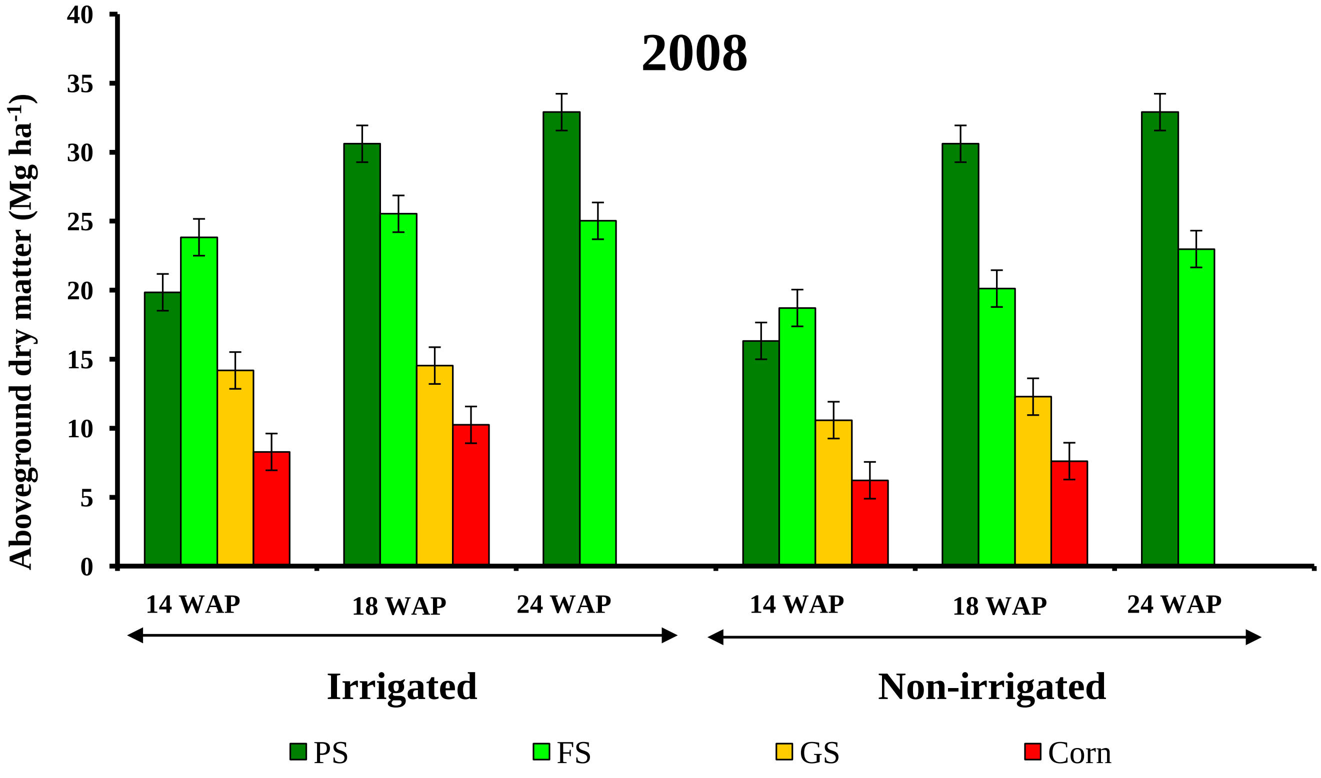
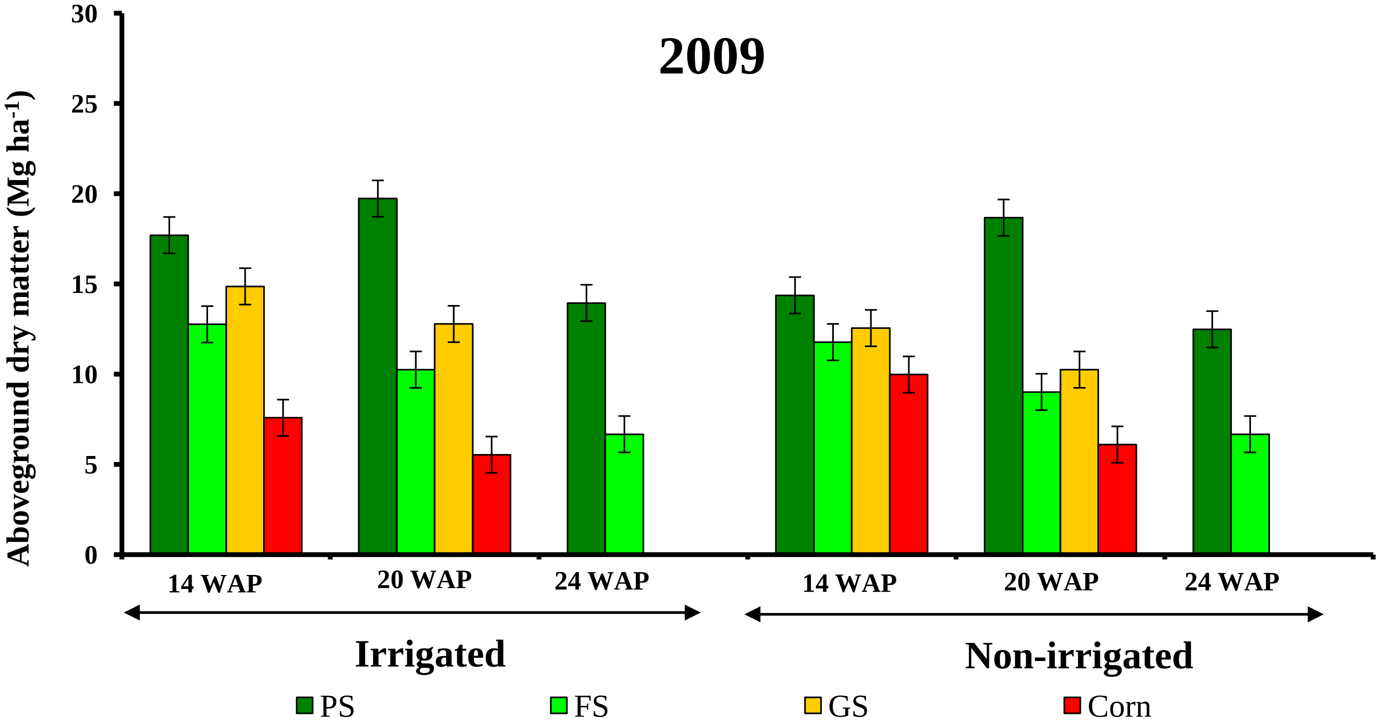


Figure 1-9: Crops x treatments interaction effect on aboveground dry matter (Mg ha^{-1}) during 3 different periods in 2009. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: weeks after planting, PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.



II. EFFECT OF SORGHUM BIOFUEL PRODUCTION SYSTEMS ON SOIL CHARACTERISTICS IN SOUTHEASTERN U.S.

ABSTRACT

According to Renewable Fuels Standard (RFS) – Energy Policy Act of 2005, the U.S. must reduce foreign oil dependence, where the target is to produce 36 billion gallons of oil equivalent in 2022 (RFA, 2010). Cellulosic material is considered an alternative source for bioenergy production, because it is renewable and environmental improved (Peters and Thielman, 2008). Annual crops, such as sorghum *(Sorghum bicolor L.)* can be cultivated in current row-crop production systems, which could provide food and cellulosic feedstock production. However, the impacts of removing cellulosic biomass on agricultural soils must not be ignored. The objective of this study was to evaluate the effect of tillage and irrigation on soil characteristics such as soil organic carbon (SOC), nitrogen (N), bulk density (Bd), cone index (CI), and volumetric water content (Wv) when producing cellulosic bioenergy feedstock from sorghum and corn in southeastern U.S. Three sorghum varieties and one forage corn were evaluated. The types of sorghum evaluated were: grain sorghum – NK300 (GS), high biomass forage sorghum – SS 506 (FS), and a variety of photoperiod sensitive forage sorghum - 1990 (PS). These 3 different varieties and a forage corn *(Zea mays L.)* – Pioneer 31G65 were grown for two consecutive years (2008 and 2009) under irrigated and non-irrigated treatments, and under two different tillage systems: conventional (total disked area to a depth of 0.15 m) and conservation tillage (in-row subsoiling to a depth of 0.30 m) which resulted in a strip-split-plot design. Results showed that SOC increased near soil surface (0.10 – 0.15 m), but it decreased from 0.40 – 0.45 after 2 years of cropping. SOC losses were higher in conventional than conservation tillage. Total nitrogen in soil (N) drastically increased at all evaluated soil depths (0 – 0.50 m). This N increment in soil might be related to high N application during both years. N was increased in deep layers due to percolation which could result in environmental degradation. Additionally, soil consolidation was observed after two years of cropping. Bulk density values increased at all evaluated depths after two year period, but those values were always lower than threshold for soil compaction (2 Mg ha^{-1}). PS showed significant lower Bd than corn in surface layers (0.05 – 0.20 m). Irrigated plots had higher Bd than non-irrigated plots at both 0.05 – 0.10 and 0.20 – 0.25 m soil layers. In addition, conventional plots showed higher Bd at (0.15 – 0.30 m). Higher Bd in conventional plots might restrict water drainage which could explain its higher Wv values at 0.10, 0.20 and 0.40 m soil depths in most days. Finally, CI values also showed improved soil conditions at in-row positions for conservation plots, with restrictive layers being found at depths of 0.15 m for conventional plots. Therefore, conservation tillage, PS and potentially reduced N applications were recommended in order to decrease farmer inputs, to improve soil condition, to maximize cellulosic biomass production and to prevent environmental degradation.

Key words: Biofuels, biomass, sorghum, cone index, SOC, nitrogen, bulk density

1. INTRODUCTION

The US government established the Energy Independence and Security Act of 2007 amending the Renewable Fuels Standard (RFS) – Energy Policy Act of 2005, in order to reduce foreign oil dependence, greenhouse gas emissions and provide meaningful economic opportunity in US. The RFS target for the US is to produce 36 billion gallons in 2022 (RFA, 2010). Cellulosic material must be considered as an alternative source for bioenergy production, because it can result in security of energy supply (renewable) and diminish green house gas emissions to the atmosphere (Peters and Thielman, 2008). In regards to food production, cellulosic biomass must be considered as a potential crop from agricultural lands. One potential bioenergy crop that could be produced in traditional row-crop systems is sorghum which could exist in a rotation system. However, one of the negative impacts of removing large amounts of cellulosic biomass from fields is the impact on agricultural soils which should not be ignored.

Southern Coastal Plain soils are highly weathered, erodible, carbon depleted and have low water holding capacity. Compounding the agricultural production problem in the southeastern U.S. is the prevalent droughts that have severely limited production over the last several years. Appropriate soil and water management systems must be developed for sorghum production in order to achieve high amounts of cellulosic biomass production without land degradation. Conservation systems, including cover crops combined with in-row subsoiling have shown improvement in soil conditions (water retention, organic matter, and soil structure) when applied in southeastern conditions

(Reeves, 1994; Ess et al., 1998; Raper et al., 2000), therefore they should be evaluated for producing bioenergy feedstock in the southeast U.S..

Different parameters are considered crucial to evaluate soil under different managements. Quantifying soil organic carbon (SOC) and nitrogen (N) balance in soils is considered a fundamental tool in order to monitor the exchange of CO_2 and NO_2 between soil and atmosphere. Thus, SOC is considered the most powerful factor to monitor soil quality (Shukla et al., 2006; Brejda et al, 2000a, 2000b). SOC has been shown to affect soil water content, soil movement and overall production (Shukla et al, 2006).

Soil compaction has negatively impacted plant production. Hamza and Anderson (2005) cited that soil compaction negatively affected root growth in soils, which directly resulted in reduced biomass production. Therefore, soil compaction is a crucial factor to be considered in our Southeastern soils when producing sorghum cellulosic biomass to avoid yield losses. Furthermore, bulk density (Bd) and cone index (CI) were considered two important tools to monitor soil compaction (Raper, 2005). Additionally, soil water content is an important parameter for plant production, because it influences all physical, chemical and biological activities in soil. Good soil water content (Wv) for plants is crucial to produce high amounts of cellulosic biomass.

The objective of our study was to evaluate the effect of two tillage systems: conservation (in-row subsoiling to a depth of 0.30 m) and conventional (total disked area to a depth of 0.15 m) under two irrigation systems (irrigated vs. rainfed) on soil characteristics such as SOC, N, Bd, CI, and Wv when producing cellulosic bioenergy feedstock from sorghum and corn.

Additionally, a rye (*Secale cereale L.*) cover crop was integrated as part of conservation system to maximize the amount of biomass produced and provide ground cover for conservation treatments during the winter months. Also, a new variety of sunn hemp (*Crotalaria juncea L.*) was included in conservation system to provide additional nitrogen for the rye winter cover.

2. MATERIAL AND METHODS

2.1 Site description

A study was initiated in November of 2007 and conducted for 2 years at the E. V. Smith Alabama Agricultural Station – Field Crop Units, Shorter, AL (85º:53’50” W, 32º:25’22” N). The location had been cropped previously with cotton (*Gossipyum hirsutum L.*) for 8 years in a conservation tillage system following Alabama Extension System recommendations. The soil type was a Marvyn Loamy sand (fine-loamy, kaolinitic, thermic, typic Kanhapludults). 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 cover crop before planting corn and sorghum. Preceding the rye was a new variety of sunn hemp to provide nitrogen.

2.2. Cultural practices and Treatments

Rye Elbon was planted at 100 kg ha^{-1}, in early November each year using a no-till drill (Great Plains Mfg. Inc., Salina, KS)[1]. Rye cultural practices were based on Alabama Cooperative Extension System recommendations. In early April each year, the rye cover crop was terminated with glyphosate (N-phosphonomethyl glycine).

In late April of each year, starter fertilizer was applied at a rate of 14, 4, 14, and 5 kg ha^{-1} of N, phosphorus (P), potassium (K) and sulfur (S), respectively according to the Alabama Cooperative Extension System soil test recommendations (Adams and Mitchell, 2000).

Two different tillage systems were implemented shortly after fertilization: conventional and conservation systems. 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/leveled using a 950 John Deere Disk (Deere & Company, Moline, IL) to a depth 0.15 m. Then, all four bioenergy crops, including grain sorghum - NK300 (GS), forage sorghum - SS506 (FS), photoperiod-sensitive sorghum - 1990 (PS), and hybrid corn Pioneer 31G65 were seeded in rows spaced at 0.92 m using a John Deere 1700 XP planter (Deere & Company, Moline, IL). Seeding rate was established by the company's recommendations which were 407,700 seeds ha^{-1} for FS, GS and PS (Sorghum Partners 2008a, 2008b, 2010c). Pioneer 31G65 seeding rate were 78,300 seeds ha^{-1} (Pioneer Hi-bred International Inc., 2010). Tillage and planting were performed with a tractor equipped with a Trimble AgGPS Autopilot automatic steering system (Trimble, Sunnyvale, CA), with centimeter level precision. An

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[1] The use of company names or trade names does not indicate endorsement by Auburn University or USDA – ARS.

additional 110 kg N ha^{-1} of ammonium nitrate (34%) was side dressed with a liquid applicator in row middles during growing season each year.

During the growing season each year, the irrigation plots were managed with two different regimes: non-irrigated (rainfed) and irrigated. In the irrigated plots, water was applied in appropriate timing and amounts to provide plants with good water availability during the growing season. Irrigation was terminated at 16 weeks after planting in both years. Alabama Cooperative Extension System recommendations were used to apply all insecticides (ACES, 1988).

Grain from GS and corn were harvested in late August using a Gleaner G combine (AGCO Company, Duluth, GA)**.** The remaining biomass was cut and baled. Sunn hemp was planted at a rate of 50 kg/ha immediately after harvest using a no-till drill (Great Plains Mfg. Inc., Salina, KS) in all conservation tillage plots. PS and FS were harvested in late October.

2.3. Experimental Design and Statistical Analysis

Bioenergy crops, irrigation and tillage practices were evaluated in a strip-split plot design (factorial 4x2x2). The four crops served as the horizontal treatments. Two irrigation regimes (irrigated and non-irrigated) served as the vertical plots, and two tillage systems (conservation and conventional) served as 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 plots), 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 systems) which resulted in 64 experimental units 9.1-m long by 3.7-m wide. Experimental units were composed of 4 rows with row spacings of 0.92 m. All measurements were collected from the two middle rows of each experimental unit.

Measurements were evaluated in a strip-split-plot design with four replications, where crops, irrigation regimes and tillage systems were considered respectively horizontal, vertical and sub-treatments. Bioenergy crops were randomly assigned into each replication, irrigation regimes were assigned into each bioenergy crop, and tillage systems were randomly assigned into each irrigation regime.

All data were analyzed using the appropriate strip-split plot design with PROC MIXED of the Statistical Analysis System (SAS) (Littel et al., 1996). Replication and its interactions with bioenergy crops (crops) and irrigation regimes were considered random effects and treatments and other interactions considered fixed. Data were analyzed and discussed considering both years, except when significant year x treatment interaction occurred. In this case, data were analyzed by year. Treatment means were separated by the LSMEANS procedure (SAS Inst. Inc., Cary, NC) when protected by F-tests significant at α of 0.10, and are reported as least squares means ± SE.

2.4. Data Collection

2.4.1. Soil organic carbon (SOC) and total nitrogen (N).

Soil organic carbon and total nitrogen nutrient were determined from soil samples collected before planting in 2008, and after harvesting in 2009. In each experimental unit, soil core samples (9 cm of diameter) were collected in ten different depth ranges: 0 –

0.05, 0.05 – 0.10, 0.10 – 0.15, 0.15 – 0.20, 0.20 – 0.25, 0.25 – 0.30, 0.30 – 0.35, 0.35 – 0.40, 0.40 – 0.45, 0.45 – 0.50 m for each of three different non-trafficked middle row positions. The soil samples were oven dried at 55 °C until constant weight, slightly crushed, sieved through 2 mm mesh, and then finely ground using a conveyor-belt roller mill. Soil subsamples were submitted to dry combustion (Yeomans and Bremner, 1991) using LECO TruSpec analyzer (Leco Corporation, St. Joseph, MI).

2.4.2. Soil bulk density (Bd).

Soil core samples were collected before planting in 2008, and after harvesting in 2009 using a tractor mounted, hydraulically-driven, soil core sampler (9 cm diameter) to determine soil bulk density (Raper et al., 1999). In each experimental unit, three insertions of soil core sampler were obtained in the non-trafficked middle row where soil core samples were collected at ten different depths: 0 – 0.05 , 0.05 – 0.10, 0.10 – 0.15, 0.15 – 0.20, 0.20 – 0.25, 0.25 – 0.30, 0.30 – 0.35, 0.35 – 0.40, 0.40 – 0.45, 0.45 – 0.50 m. The undisturbed soil core samples were oven dried at 55 °C until constant weight.

2.4.3. Cone Index (CI).

Cone Index measurements were taken 1 week after plating, and 1 week after harvesting for both years, using a tractor-mounted, hydraulic-driven, soil cone penetrometer (Raper et al., 1999). In each experimental unit, three insertions of multi-probe soil cone penetrometers were performed where five different positions were recorded per insertion: 1) in row; 2) untrafficked interrow – 0.225 m away from row; 3) untrafficked interrow – 0.45 m away from row; 4) wheel-trafficked row – 0.225 cm away from row; and 5) wheel-trafficked row – 0.45 cm away from row. Cone index was determined using a soil cone penetrometer with 130 mm^2 base area (ASAE Standards, 2004a; ASAE Standards, 2004b) which were continuously (25 points per second) inserted in the soil to a depth of 50cm. Data were averaged for every 0.10 m depth range in order to perform statistical analysis and develop contour graphs using Surfer 8 software (Golden Software Inc., Golden, CO). Furthermore, soil samples were taken at 0 – 0.15 m and 0.15 – 0.30 m positions and oven dried at 105°C until constant weight to determine soil moisture during cone index readings.

2.4.4. Soil water content (Wv).

A TRIME-T3 probe (Micromodultechnik GMBH, Germany) was used to measure soil water content based on Time Domain Reflectometry method. PVC access tubes having 0.06 m of diameter and 1 m long were installed in one of the two middle rows in each experimental unit. Soil water content was measured in row inserting the TRIME-T3 probe in the access tubes, and readings were collected three times at four different depths: 0.10, 0.20, 0.40, and 0.60 m. Measurements were stored in a TRIME Data Pilot (Micromodultechnik GMBH, Germany) which was connected to TRIME-T3 probe. Thus, readings were collected twice per week on mornings throughout the growing season.

3. RESULTS AND DISCUSSION

3.1. Soil Organic Carbon

In 2008 before planting, no significant differences were found among samples collected in different positions in field for any depth (data not shown). Results suggested that the entire field was in similar condition before starting the experiment. Therefore, all SOC changes in 2009 after harvesting were related to treatments applied over those two years.

Comparing soil organic carbon samples – SOC (Mg ha^{-1}) collected in 2008 before planting with samples collected in 2009 after harvesting, SOC significantly increased 11 and 17 % in the two top layers: 0 – 0.05 and 0.05 – 0.10 m, respectively, after two consecutive years of cropping. However, our measurements showed reduced SOC from 0.10 to 0.50, but those differences were only significant at 0.20 – 0.25 and 0.35 – 0.50 m deep (table 2-1) which showed SOC reductions of 23 and 27 %, respectively. Furthermore, soil organic carbon – SOC (Mg ha^{-1}) tended to decrease with depth for both years.

In 2009, SOC was not significantly different for each crop at all evaluated depths, except for top soil layer (0 – 0.05 m). At this depth, PS plots (6.9 Mg ha^{-1}) had lower SOC than FS (7.5 Mg ha^{-1}), corn (7.4 Mg ha^{-1}), but had similar SOC as GS (6.9 Mg ha^{-1}), P = 0.0551 (figure 2-1). SOC did not vary with irrigation treatment at any depth (figure 2-2). Other studies found similar results when studying different irrigation regimes (Churchman and Tate, 1986; Sommerfeldt et al., 1988). Tillage treatments were significant different at 0.1 – 0.15 m (P = 0.0351) and 0.4 – 0.45 m depths (P = 0.0896). In both layers, conservation tillage showed higher SOC than conventional tillage, 5.2 vs. 4.4 Mg ha^{-1} and 2.3 vs. 2.0 Mg ha^{-1}, respectively (figure 2-3). Several authors cited that conservation tillage resulted in higher SOC than conventional tillage particularly in layers shallower than 0.25 m (Potter et al., 1998; Motta et al., 2002; Zibilske et al, 2002). These SOC increases might be related to good amounts of rye biomass which was produced and not incorporated under the conservation tillage system in 2009. However, other authors pointed out that conservation tillage just redistributed SOC in soil, where their contents increased at top layers, but the reverse tendency was found in deep layers (Dick et al., 1991; Torbert et al., 1999).

3.2. Total Nitrogen (TN)

In 2008 before planting, no significant differences were found among total nitrogen in soils - TN (Mg ha^{-1}) samples collected at different positions for any depth (data not shown). Results suggested that the entire field was in the same condition before starting the experiment. Therefore, all TN changes in 2009 after harvesting were related to treatments during those two years.

Comparing TN (Mg ha^{-1}) samples collected in 2008 before planting with samples collected in 2009 after harvesting, TN content increased drastically in all depths after two consecutive years of cropping (table 2-2). This N increment in soil might be related to high N application during both years in order to express the highest potential of all tested crops. Furthermore, TN (Mg ha^{-1}) tended to decrease with depth before planting in 2008. A reverse trend was found in 2009 where TN showed higher values in deep layers after two years of experiment (2009 after harvest). Because, part of the N applied during both years might not be uptaken by plants, it could percolate deep in the soil because Marvyn loamy sand is a well drained and moderately permeable soil which allows easy translocation of nutrients (Official Series Description, 2010).

In 2009 after harvest, TN was not significantly different among crops at all evaluated depths (figure 2-4). Irrigation treatments also showed no significant differences in any depth (figure 2-5). Tillage treatments were significantly different at the 0.25 – 0.30 m depth, P = 0.0862 (figure 2-6). In this soil layer, conservation tillage showed higher TN than conventional tillage, 0.40 and 0.36 Mg ha^{-1}, respectively.

3.3. Bulk Density

Comparing soil bulk density samples collected in 2008 before planting with samples collected in 2009 after harvest, Bd significantly increased at all layers, except at 0.45 -0.50 m soil layer where Bd was not significantly different after two years of cropping. In both years, Bd tended to increase drastically from near the surface to 0.3 m in depth and it tended to increase slightly in layers deeper than 0.30 m (table 2-3).

In 2009, crop affected soil bulk density significantly at three different soil layers: 0.05 – 0.10 m (P = 0.0471), 0.10-0.15m (P = 0.0102), and 0.15 – 0.20 (P = 0.0295). In those 3 soil layers, PS always had the lowest Bd, respectively, 1.58, 1.63, and 1.68 Mg m^{-3}. Conversely corn always showed the greatest Bd values, 1.70, 1.72 and 1.78 Mg m^{-3} respectively. A reasonable explanation for differences in PS and corn could be that higher PS population could increase root density from 0.05 to 0.20 m. High root density in PS fields may alleviate soil consolidation due to soil disruption. The other two crops showed intermediate Bd values at these same soil depths. GS had Bd values of 1.61, 1.68 and

1.74 Mg m^{-3}, respectively and FS showed Bd values of 1.60, 1.71 and 1.76 Mg m^{-3}, respectively (figure 2-7). Bulk density values for all crops were in the range proposed for a sandy loam soil (1.20 -1.80 Mg m^{-3}), and Bd values from this study were below 2 Mg m^{-3} threshold value for soil compaction (Raper, 2005). Therefore, we found that the sorghum varieties evaluated in the experiment had good development under these reasonable soil conditions which resulted in high cellulosic biomass production.

Irrigated plots were significantly higher in Bd than non-irrigated fields at 0.10 – 0.15 m ($P = 0.0533$) and 0.20 – 0.25 m ($P = 0.0539$) depths in 2009 after harvest (figure 2-8). In both soil positions, irrigated plots (1.71 and 1.78 Mg m^{-3}, respectively) had higher Bd values than non-irrigated plots (1.66 and 1.74 Mg m^{-3}, respectively). According to soil moisture measurements obtained during the growing seasons for both years, irrigated plots always showed higher soil moisture at 0.10 and 0.20 m depths. And, soils with high soil moisture were considered easy to compact due to reduced load support and increased deformation capacity, which resulted in higher Bd values (Hamza and Anderson, 2005). However, the higher Bd values found in irrigated treatments were still lower than 2 Mg ha^{-1} (threshold for restrictive soil layer) (Raper, 2005).Therefore irrigated plots could offer good soil conditions for plant growth, and ADM and grain yields would not be negatively affected.

Tillage treatments were significantly different at 0.10 – 0.15 m ($P = 0.0131$), 0.15-0.20 m ($P = 0.0005$), and 0.20 - 0.25 m ($P = 0.0074$) depths (figure 2-9). Conventional tillage (total disked area) always showed significant higher Bd values than conservation fields (in-row subsoiled). At these depths (0.10 – 0.15, 0.15 – 0.20, and 0.20 – 0.25 m) Bd values in conventional tillage plots were 1.72, 1.78, and 1.79 Mg m^{-3}, respectively And, Bd values in conservation tillage plots were 1.65 , 1.71, and 1.73 Mg m^{-3}, respectively. Other researchers have found similar values with lower Bd values in conservation fields being caused by high biological soil activity due to large amounts of residue left on the soil (Lal et al. 1994), and high accumulation of organic matter (Edwards et al., 1992). In our fields, conservation plots also showed higher organic matter accumulation than conventional plots from 0.10 to 0.25 m depth in soil, but they were significantly higher only at depths of 0.10 to 0.15 m.

3.4. Cone Index

In all sampling periods, CI data were analyzed by separating in 3 different positions; non-traffic, in-row, and traffic. All positions were significantly different from each other when comparing between the four different periods of collection ($P \leq 0.0001$). Therefore, the statistical analysis was conducted separated by period, position and depth (tables 2-4 to 2-8). Tillage was considered the most explanatory factor for CI in all data sets, and crop and irrigation treatments had minor effect in CI.

Conservation tillage showed lower CI values (27 %) than conventional tillage at in-row and non-traffic positions from 0 to 0.30 m soil depth in most sampling periods. However, different results were found in traffic positions from 0 to 0.30 m, where CI values were 26 and 29 % higher in conventional tillage than conservation tillage in spring 2008 and 2009, respectively, but conventional tillage tended to have lower CI values than conservation tillage in fall 2008 (14 %) and 2009 (37 %). At deep soil layers (0.30 – 0.50 m), CI values were mostly not significantly different when comparing tillage treatments in all positions for spring 2009 and fall 2008 / 2009. Similar CI values between conventional and conservation fields were expected at traffic and non-traffic positions, because the soil was not disrupted at deep layers (0.30 – 0.50 m) for those positions. However, low CI values could be found for conservation tillage at in-row position, because narrow-shanked subsoiler disrupted the soil down to 0.45 m deep. Moreover, conservation tillage showed higher CI values than conventional treatment for all positions in spring 2008. Those unexpected results might be related to shallow in-row subsoiling (< 0.30m deep) in 2008 and/or different soil moisture between tillage plots at same period. Contour graphs generating penetration isolines were plotted using CI means (figures 2-10 and 2-11). Gravimetric soil water content (GWC) was evaluated at all sampling periods (table 2-9), which showed small variation in depth and sampling period. Those small variations were attributed to different weather conditions among sampling periods.

In spring of both years, conservation tillage reduced soil resistance to penetration at in-row position at subsoiled layer (0 - 0.30m) to values lower than 1.0 MPa which offered good conditions for root growth (CI < 2.0 MPa). However, conventional plots showed a restrictive layer (CI > 2.0 MPa) at 0.10 – 0.30 m soil layer in spring of 2009 which could explain the significantly lower dry aboveground dry matter (ADM) production observed in conventional fields (12.2 Mg ha^{-1}) than conservation plots (11.0 Mg ha^{-1}), P = 0.0028. Restrictive layers in Spring 2008 nor low ADM were found for conventional fields in 2008.

In both years, CI values were higher after harvest (fall) than after planting (spring). Note that CI values were particularly elevated (2 to 3 fold) in fall 2008 in both conventional and conservation treatments. However, better soil conditions for root growth were always found at in-row position in conservation plots than conventional plots, therefore, in-row subsoiling must be recommended.

3.5. Soil water content

Crops showed no significant volumetric water (Wv) differences at 0.10 m depth for both seasons, except for 82 and 89 days after planting (DAP) at a depth of 0.10 m in 2009, where FS showed higher Wv values than corn. Generally, corn and GS showed lower Wv values than FS and PS at 0.20 m, 0.40 m and 0.60 m depths in both years. Those differences were significant for most days in 2009 season at 0.20 and 0.40 depths. A plausible explanation for those differences was that GS and corn required more water from soils due to the fact that they produced grains while FS and PS just produced biomass. Moreover, both FS and PS were cited as drought tolerant (Sorghum Partners, 2008a; Sorghum Partners, 2008b), because forage sorghums were able to extract water in deeper soil layers: 0.45 – 1.35 m (Farre and Faci, 2006).

Irrigated plots always had higher Wv values than non-irrigated fields in both years, but those differences were higher in 2008 than in 2009. High precipitation in 2009 might have reduced the irrigation effect because the aboveground dry matter difference between irrigated and non-irrigated fields was greater in 2008 (4.13 Mg ha^{-1}) than 2009 (1.07 Mg ha^{-1}). Volumetric water content (Wv) differences between irrigation treatments tended to decrease in depth for both seasons, where significant differences between irrigation regimes were not found at 0.60 m depth.

Conventional tillage plots showed higher volumetric water than conservation plots during most days at 0.10, 0.20 and 0.40 m depths for both years. But, no significant differences were found at 0.60 m depth. In-row subsoiling 0.30 m deep applied on conservation tillage plots might have increased in-row water infiltration causing water to move to deep soil layers. Conversely, conventional plots (total disked area to a depth of 0.15 m) might not result in good soil water drainage, causing water to be retained at soil layers above 0.40 m. Additionally, bulk density data were also higher in conventional plots than conservation at 0.1 - 0.35 m soil layers, resulting in lower soil porosity. Therefore, anaerobic conditions for plants could have occurred during 2009 season which contributed to lower aboveground dry matter yields than 2008 season. Figures 2.12 to 2.35 illustrated Wv for all treatments and depths in both years.

4. CONCLUSIONS

After 2 years of cropping, SOC increased at surface layers (0 – 0.10 m), but it decreased from 0.10 to 0.50 m. Soil organic carbon losses in deep soil layers were numerically higher in conventional tillage than conservation tillage, but SOC significant differences between tillage system were only found at 0.10 – 0.15 and 0.4 – 0.45 m deep in soil. Irrigation and crops showed no effect in SOC.

Nitrogen drastically increased in all soil depths (0 – 0.50 m) after 2 years of cropping. This N increment in soil was probably related to high N application during both years in order to express the highest potential cellulosic biomass production of all tested crops. Furthermore, total N was higher in deep layers after two years of cropping, because part of applied N was not taken up by plants, and it percolated deep in soil which could result in environmental degradation.

Soil consolidation was observed after two years of cropping. Bulk density (Bd) values increased in all depths during this period. However, all plots showed Bd values ranging between 1.58 to 1.79 Mg ha^{-1} which were below the threshold for soil compaction (2 Mg ha^{-1}). Among all tested crops, PS had the lowest Bd values in superficial layers (0.05 – 0.20 m) which was significantly lower than corn. Irrigated plots showed higher Bd values than non-irrigated at the 0 to 0.25 m soil layer, but those differences were only significantly higher at 0.05 – 0.10 and 0.2 – 0.25 m depths.

Additionally, conservation tillage (in-row subsoiling to a depth of 0.30 m) resulted in better soil conditions than conventional tillage (total disked area to a depth of 0.15 m) in the depths disrupted by the practice of in-row subsoiling in conservation tillage (0.15 – 0.30 m) because significantly lower values of Bd were found in those plots. Higher Bd values in conventional tillage might restrict soil water drainage which could explain its higher volumetric water content (Wv) at 0.10, 0.20 and 0.40 m soil depths on most days. Cone index (CI) values also showed better soil conditions at in-row position for conservation plots. A restrictive layer at a depth of 0.15 m was found in conventional plots after one year of cropping (2008) which could restrict plant growth and cellulosic biomass production.

Therefore, conservation tillage should be used to grow PS which produced the highest biomass and is the recommended bioenergy crop. Reduced nitrogen application should be investigated to decrease inputs and potentially prevent environmental degradation.

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Table 2-1: Comparison of Marvyn loamy sand SOC (Mg ha $^{-1}$) within depth between 2008 and 2009. (Least Squares Means; LS means)

Depth (m)	**LS means**		**p-value**
	2008	**2009**	
	----Soil organic carbon (Mg ha^{-1})----		
0 – 0.05	6.47	7.25	0.0005*
0.05 – 0.10	6.08	7.27	0.0006*
0.10 – 0.15	5.06	4.78	0.2189
0.15 – 0.20	4.68	4.45	0.1454
0.20 – 0.25	4.26	3.29	0.0001*
0.25 – 0.30	3.59	3.29	0.2544
0.30 – 0.35	3.17	2.60	0.0005*
0.35 – 0.40	3.02	2.66	0.0550*
0.40 – 0.45	3.07	2.13	0.0001*
0.45 – 0.50	3.28	1.85	0.0002*

* Significant at the 0.10 level of probability.

Table 2-2: Comparison of Marvyn loamy sand TN (Mg ha $^{-1}$) within depth between 2008 and 2009. P-values denote significant differences between TN LS means.

Depth (m)	**Total Nitrogen**				**p-value**
	2008		**2009**		
	----LS means (Mg ha $^{-1}$)----	*--C/N--*	*----LS means (Mg ha $^{-1}$)----*	*--C/N--*	
0 – 0.05	0.28	23	0.40	18	0.0001*
0.05 – 0.10	0.25	24	0.41	18	0.0001*
0.10 – 0.15	0.14	35	0.37	20	0.0001*
0.15 – 0.20	0.10	48	0.38	12	0.0001*
0.20 – 0.25	0.08	50	0.37	9	0.0001*
0.25 – 0.30	0.05	66	0.38	9	0.0001*
0.30 – 0.35	0.06	52	0.46	6	0.0001*
0.35 – 0.40	0.08	40	0.49	5	0.0001*
0.40 – 0.45	0.08	37	0.49	4	0.0001*
0.45 – 0.50	ND**	--	0.47	4	--

* Significant at the 0.10 level of probability.
** not detected.

Table 2-3: Comparison of Marvyn loamy sand bulk density (Mg m^{-3}) within depth between 2008 and 2009.

Depth (m)	**LS means**		**p-value**
	2008	**2009**	
	---------Bulk density (Mg m^{-3})---------		
0 – 0.05	1.18	1.43	≤0.0001*
0.05 – 0.10	1.38	1.62	≤0.0001*
0.10 – 0.15	1.50	1.69	≤0.0001*
0.15 – 0.20	1.61	1.74	≤0.0001*
0.20 – 0.25	1.67	1.76	≤0.0001*
0.25 – 0.30	1.73	1.79	≤0.0020*
0.30 – 0.35	1.74	1.80	≤0.0011*
0.35 – 0.40	1.72	1.76	≤0.0240*
0.40 – 0.45	1.69	1.73	≤0.0182*
0.45 – 0.50	1.65	1.62	≤0.1448

* Significant at the 0.10 level of probability.

Table 2-4: Results of the type 3 test of treatments and effects from PROC MIXED for Cone index (MPa) for Marvyn loamy sandy at 0 – 0.1 m soil layer in all sampling periods of 2008 and 2009. Letters denote significant differences (L.S. means S.E.$_{(0.10)}$ within treatment and sampling period).

	Cone Index											
0 - 0.1 m	**Spring 2008**			**Fall 2008**			**Spring 2009**			**Fall 2009**		
	Non-traffic	**In row**	**Traffic**	**Non-traffic**	**In row**	**Traffic**	**Non-traffic**	**In row**	**Traffic**	**Non-traffic**	**In row**	**Traffic**
Effects	-------------*MPa*-------------			-------------*MPa*-------------			-------------*MPa*-------------			-------------*MPa*-------------		
Crops												
PS**	0.49	0.32c	0.30	1.04b	0.91b	1.73bc	0.70	0.39	1.23	0.74b	0.56	1.36a
FS**	0.55	0.35bc	0.35	0.98b	0.84b	1.57c	0.70	0.35	1.18	0.70b	0.58	1.13b
GS**	0.57	0.43a	0.40	1.14ab	0.88b	1.88b	0.71	0.33	1.29	0.83ab	0.56	1.37a
Corn**	0.54	0.39ab	0.35	1.37a	1.07a	2.85a	0.69	0.37	1.39	0.96a	0.59	1.44a
Irrigation												
irrigated	0.54	0.36	0.37	1.10	0.89	1.83	0.76	0.36	1.33	0.79	0.58	1.28b
non-irrigated	0.53	0.38	0.33	1.16	0.96	1.83	0.64	0.35	1.22	0.82	0.57	1.36a
Tillage												
conservation	0.35b	0.22b	0.18b	0.80b	0.83b	1.87	0.60b	0.20b	1.17b	0.68b	0.46b	1.38a
conventional	0.73a	0.52a	0.52a	1.46a	1.02a	1.79	0.80a	0.52a	1.37a	0.94a	0.68a	1.27b
	-------------*p-value*-------------			-------------*p-value*-------------			-------------*p-value*-------------			-------------*p-value*-------------		
Source of Error												
crops (C)	0.4513	0.0358*	0.2416	0.0688*	0.0518*	0.0138*	0.9896	0.6906	0.2470	0.0262*	0.9425	0.0271*
irrigation (I)	0.8090	0.2484	0.5179	0.6276	0.2758	0.9813	0.1448	0.8473	0.1626	0.7951	0.7270	0.0439*
tillage (T)	0.0001*	0.0001*	0.0001*	0.0001*	0.0087*	0.3050	0.0001*	0.0001*	0.0189*	0.0006*	0.0001*	0.0396*
CxI	0.1656	0.7335	0.1244	0.3091	0.2258	0.4533	0.1263	0.2725	0.4236	0.8950	0.4873	0.4496
CxT	0.8179	0.6468	0.5897	0.0949*	0.4186	0.7473	0.7522	0.8496	0.8700	0.2376	0.3984	0.6492
IxT	0.7743	0.3041	0.4629	0.7126	0.4891	0.5804	0.1752	0.6150	0.7828	0.5343	0.3809	0.6918
CxIxT	0.2625	0.1234	0.4277	0.2309	0.4741	0.4503	0.5368	0.0281*	0.4075	0.7916	0.0354*	0.0986

* Significant at the 0.10 level of probability.
**PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

Table 2-5: Results of the type 3 test of treatments and effects from PROC MIXED for Cone index (MPa) for Marvyn loamy sandy at 0.1– 0.2 m soil layer in all sampling periods of 2008 and 2009. Letters denote significant differences (L.S. means S.E.$_{(0.10)}$ within treatment and sampling period).

0.1 - 0.2 m	**Cone Index**											
	Spring 2008			**Fall 2008**			**Spring 2009**			**Fall 2009**		
	Non-traffic	**In row**	**Traffic**	**Non-traffic**	**In row**	**Traffic**	**Non-traffic**	**In row**	**Traffic**	**Non-traffic**	**In row**	**Traffic**
Effects	-------------*MPa*-------------			-------------*MPa*-------------			-------------*MPa*-------------			-------------*MPa*-------------		
Crops												
PS**	1.22b	0.68	1.63	2.17	1.70	3.19b	1.59	1.02	2.35	1.47c	0.85	2.33
FS**	1.16b	0.64	1.65	1.25	1.73	3.02b	1.75	0.99	2.34	1.55bc	0.91	2.24
GS**	1.55a	1.09	1.62	2.35	1.74	3.36b	1.84	0.85	2.41	1.56b	0.72	2.49
Corn**	1.15b	0.67	1.65	2.67	2.04	4.06a	1.72	1.05	2.43	1.72a	0.75	2.52
Irrigation												
irrigated	1.26	0.81	1.69	2.22	1.74	3.37	1.83	1.02	2.43	1.60	0.79	2.31
non-irrigated	1.29	0.73	1.63	2.50	1.86	3.44	1.62	0.93	2.34	1.56	0.82	2.49
Tillage												
conservation	0.98b	0.54b	1.53b	1.87b	1.09b	3.62a	1.29b	0.25b	2.21b	1.27b	0.65b	2.55a
conventional	1.56a	1.00a	1.79a	2.85a	2.51a	3.19b	2.16a	1.70a	2.56a	1.88a	0.96a	2.25b
	-------------*p-value*-------------			-------------*p-value*-------------			-------------*p-value*-------------			-------------*p-value*-------------		
Source of Error												
crops (C)	0.0861*	0.1982	0.8890	0.2322	0.1532	0.0035*	0.5647	0.5017	0.9521	0.0014*	0.1168	0.2546
irrigation (I)	0.9055	0.7190	0.6369	0.2796	0.5457	0.7039	0.2326	0.6066	0.5343	0.7920	0.6608	0.1117
tillage (T)	0.0023*	0.0175*	0.0152*	0.0001*	0.0001*	0.0040*	0.0021*	0.0001	0.0001*	0.0001*	0.0002*	0.0004*
CxI	0.9025	0.9415	0.6439	0.5984	0.6589	0.2514	0.9830	0.6373	0.4101	0.3255	0.2866	0.1660
CxT	0.0427*	0.0789*	0.0803*	0.9131	0.5766	0.9274	0.1782	0.9226	0.8308	0.1002	0.5064	0.1536
IxT	0.2422	0.2987	0.2382	0.8054	0.2234	0.9202	0.4142	0.9034	0.1991	0.2498	0.1122	0.7248
CxIxT	0.0556	0.1397	0.0615*	0.3154	0.1567	0.6483	0.4446	0.1293	0.6423	0.5121	0.1246	0.7486

* Significant at the 0.10 level of probability.
**PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65

Table 2-6: Results of the type 3 test of treatments and effects from PROC MIXED for Cone index (MPa) for Marvyn loamy sandy at 0 .2 – 0.3 m soil layer in all sampling periods of 2008 and 2009. Letters denote significant differences (L.S. means S.E.$_{(0.10)}$ within treatment and sampling period).

0.2 - 0.3 m	**Cone Index**											
	Spring 2008			**Fall 2008**			**Spring 2009**			**Fall 2009**		
	Non-traffic	**In row**	**Traffic**	**Non-traffic**	**In row**	**Traffic**	**Non-traffic**	**In row**	**Traffic**	**Non-traffic**	**In row**	**Traffic**
Effects	-------------*MPa*-------------			-------------*MPa*-------------			-------------*MPa*-------------			-------------*MPa*-------------		
Crops												
PS**	1.86	1.07	2.05	2.85	1.93	3.12b	1.76	1.10	2.46	1.48	0.96	2.32
FS**	1.48	0.64	1.90	2.62	2.13	3.19b	1.99	1.10	2.25	1.43	1.01	2.30
GS**	2.01	1.20	2.18	3.18	2.03	3.89a	2.33	1.04	2.69	1.54	0.96	2.49
Corn**	1.63	1.07	1.94	3.00	1.94	3.65a	1.92	1.06	2.51	1.47	0.99	2.29
Irrigation												
irrigated	1.76	0.94	2.00	2.74	1.96	3.41	2.17	1.21	2.60	1.37b	0.91	2.23
non-irrigated	1.73	1.02	2.03	3.08	2.05	3.51	1.83	0.94	2.36	1.58a	1.05	2.46
Tillage												
conservation	1.70	0.96	1.95	2.80	0.95b	3.70a	1.81	0.96	2.33b	1.20b	1.28a	2.51a
conventional	1.79	1.00	2.08	3.02	3.06a	3.23b	2.20	1.19	2.63a	1.75a	0.68b	2.19b
	-------------*p-value*-------------			-------------*p-value*-------------			-------------*p-value*-------------			-------------*p-value*-------------		
Source of Error												
crops (C)	0.3073	0.2128	0.4167	0.3865	0.8314	0.0076*	0.5308	0.9733	0.4493	0.9402	0.1280	0.3641
irrigation (I)	0.9453	0.8464	0.9213	0.3034	0.5984	0.6069	0.1098	0.1200	0.2785	0.0766*	0.1896	0.1176
tillage (T)	0.7013	0.8858	0.4301	0.4204	0.0001*	0.0171*	0.1139	0.5616	0.0859*	0.0001*	0.0001*	0.0305*
CxI	0.9135	0.9652	0.8133	0.2899	0.7139	0.1939	0.8307	0.7464	0.6614	0.5773	0.8979	0.4441
CxT	0.1556	0.1978	0.1767	0.9710	0.5575	0.7909	0.0886	0.3688	0.3022	0.2542	0.0969*	0.1985
IxT	0.1569	0.1724	0.0635*	0.4128	0.1546	0.5209	0.1307	0.5725	0.0685	0.0857*	0.1732	0.7518
CxIxT	0.0565*	0.2914	0.1050	0.3779	0.1683	0.6522	0.5704	0.8289	0.9417	0.8292	0.9857	0.1659

* Significant at the 0.10 level of probability.

**PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

Table 2-7: Results of the type 3 test of treatments and effects from PROC MIXED for Cone index (MPa) for Marvyn loamy sandy at 0.3 – 0.4 m soil layer in all sampling periods of 2008 and 2009. Letters denote significant differences (L.S. means S.E.$_{(0.10)}$ within treatment and sampling period).

0.3 - 0.4 m	**Cone Index**											
	Spring 2008			**Fall 2008**			**Spring 2009**			**Fall 2009**		
	Non-traffic	**In row**	**Traffic**	**Non-traffic**	**In row**	**Traffic**	**Non-traffic**	**In row**	**Traffic**	**Non-traffic**	**In row**	**Traffic**
Effects	-------------*MPa*-------------			-------------*MPa*-------------			-------------*MPa*-------------			-------------*MPa*-------------		
Crops												
PS**	1.66	1.22	1.58	2.48	2.00	2.19b	1.32	0.94	1.55	1.72	1.55	1.56
FS**	1.19	0.92	1.31	2.19	2.01	2.19b	1.37	0.95	1.36	1.12	1.94	1.41
GS**	1.65	1.20	1.65	3.05	2.16	3.00a	1.80	1.02	1.70	1.22	1.61	1.64
Corn**	1.48	0.97	1.36	2.38	1.92	2.17b	1.43	0.77	1.50	1.05	1.50	1.34
Irrigation												
Irrigated	1.49	1.00	1.46	2.44	1.95b	2.44	1.56	0.97a	1.65	1.11b	1.89	1.45
non-irrigated	1.50	1.15	1.49	2.61	2.09a	2.34	1.40	0.87b	1.41	1.22a	1.41	1.52
Tillage												
conservation	1.73a	1.21a	1.59a	2.76a	1.53b	2.41	1.63a	0.99	1.59	1.09b	1.59	1.53
conventional	1.26b	0.95b	1.36b	2.29b	2.51a	2.36	1.32b	0.85	1.46	1.25a	1.71	1.45
	-------------*p-value*-------------			-------------*p-value*-------------			-------------*p-value*-------------			-------------*p-value*-------------		
Source of Error												
crop (C)	0.2995	0.3335	0.3110	0.2694	0.8995	0.0007*	0.3368	0.1123	0.5786	0.4297	0.3002	0.2320
irrigation (I)	0.9628	0.2595	0.7985	0.4148	0.0245*	0.4216	0.2791	0.0926*	0.2129	0.0001*	0.2026	0.4450
tillage (T)	0.0047*	0.0171*	0.0091*	0.0364*	0.0001*	0.7348	0.0720*	0.2729	0.4276	0.0858*	0.1938	0.4774
CxI	0.9124	0.9953	0.8216	0.2090	0.4198	0.5447	0.7175	0.9491	0.8835	0.3020	0.5037	0.8586
CxT	0.4848	0.1309	0.1123	0.9563	0.2091	0.9721	0.2570	0.1310	0.6222	0.7138	0.4555	0.8329
IxT	0.8202	0.2559	0.7252	0.6039	0.6977	0.5622	0.2884	0.9020	0.4802	0.1209	0.5638	0.8071
CxIxT	0.1993	0.4434	0.3593	0.8219	0.1149	0.2783	0.4186	0.6310	0.1446	0.1734	0.5513	0.3214

* Significant at the 0.10 level of probability.

**PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65

Table 2-8: Results of the type 3 test of treatments and effects from PROC MIXED for Cone index (MPa) for Marvyn loamy sandy at 0 .4 – 0.5 m soil layer in all sampling periods of 2008 and 2009. Letters denote significant differences (L.S. means S.E.$_{(0.10)}$ within treatment and sampling period).

0.4 - 0.5 m	**Cone Index**											
	Spring 2008			**Fall 2008**			**Spring 2009**			**Fall 2009**		
	Non-traffic	**In row**	**Traffic**	**Non-traffic**	**In row**	**Traffic**	**Non-traffic**	**In row**	**Traffic**	**Non-traffic**	**In row**	**Traffic**
Effects	-------------*MPa*-------------			-------------*MPa*-------------			-------------*MPa*-------------			-------------*MPa*-------------		
Crops												
PS**	1.20	1.45	1.20	1.85	2.32	1.96	1.00	0.85	1.16	1.07	1.47a	1.40
FS**	1.06	1.27	1.07	1.82	2.06	1.79	1.02	0.86	1.24	1.10	1.36ab	1.41
GS**	1.18	1.38	1.15	2.01	2.16	2.16	1.03	0.85	1.27	0.90	1.30bc	1.47
Corn**	1.17	1.36	1.15	1.99	2.52	1.79	1.96	0.85	1.17	0.97	1.19c	1.40
Irrigation												
irrigated	1.15	1.37	1.14	1.94	2.12	2.00a	1.04	0.88	1.22	1.02	1.21	1.39
non-irrigated	1.15	1.35	1.15	1.89	2.41	1.86b	0.97	0.82	1.20	1.00	1.45	1.45
Tillage												
conservation	1.22a	1.42a	1.19a	2.00a	2.28	1.94	1.08a	0.86	1.23	1.03	1.27	1.41
conventional	1.08b	1.31b	1.09b	1.83b	2.25	1.92	1.93b	0.85	1.19	0.99	1.38	1.42
	-------------*p-value*-------------			-------------*p-value*-------------			-------------*p-value*-------------			-------------*p-value*-------------		
Source of Error												
crops (C)	0.3691	0.3285	0.2923	0.9164	0.6368	0.3910	0.8848	0.9984	0.6445	0.2119	0.0653*	0.9772
irrigation (I)	0.8729	0.7509	0.8665	0.1062	0.1147	0.0920*	0.2507	0.3346	0.7533	0.7556	0.1597	0.3534
tillage (T)	0.0126*	0.0604*	0.0330*	0.0619*	0.7141	0.7816	0.0040*	0.7802	0.1408	0.4347	0.2111	0.7817
CxI	0.3912	0.2262	0.6239	0.1880	0.1308	0.8786	0.7128	0.6428	0.9377	0.8138	0.6080	0.1646
CxT	0.5610	0.5734	0.1493	0.0328*	0.4997	0.0788*	0.2559	0.1213	0.0145*	0.0660*	0.8459	0.4812
IxT	0.4839	0.8063	0.4530	0.3263	0.7292	0.5558	0.5682	0.8086	0.0665*	0.3202	0.6734	0.8197
CxIxT	0.5817	0.5305	0.6954	0.6199	0.0312*	0.8937	0.3385	0.8005	0.7062	0.7649	0.4894	0.7060

* Significant at the 0.10 level of probability.
**PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

Table 2-9: LS means of gravimetric water content (GWC) of a Marvyn loamy sand at the time of Cone Index measurements.

	Gravimetric Water Content			
	Spring 2008	**Fall 2008**	**Spring 2009**	**Fall 2009**
	-------$m^3\ m^{-3}$-------	-------$m^3\ m^{-3}$-------	-------$m^3\ m^{-3}$-------	-------$m^3\ m^{-3}$-------
Depth				
0 – 0.15 m	0.17a	0.11a	0.15a	0.14a
0.15 – 0.30 m	0.13b	0.10b	0.13b	0.12b
	-----*p-value*----	-----*p-value*----	-----*p-value*----	-----*p-value*----
	0.0001*	0.0001*	0.0001*	0.0001*

* Significant at the 0.10 level of probability.

Figure 2-1: Soil organic carbon (Mg ha^{-1}) at non-trafficked middle row affected by crop treatments in 2009, and overall SOC before planting in 2008. Horizontal error bars indicate crop significant differences - Difference of L.S. Means S.E. $_{(0.10)}$. PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

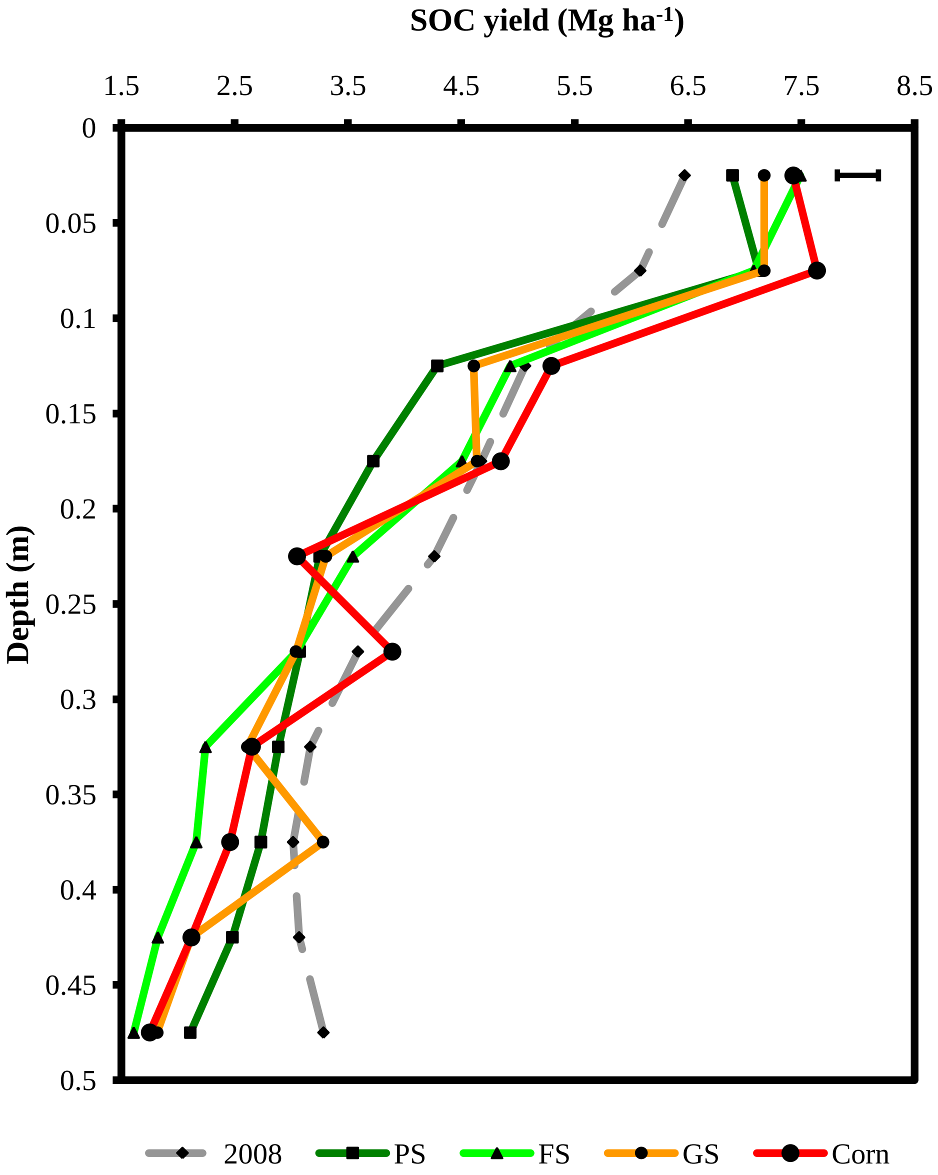


Figure 2-2: Soil organic carbon (Mg ha^{-1}) at non-trafficked middle row affected by irrigation treatments in 2009, and overall SOC before planting in 2008. Horizontal error bars indicate irrigation significant differences - Difference of L.S. Means S.E. $_{(0.10)}$.

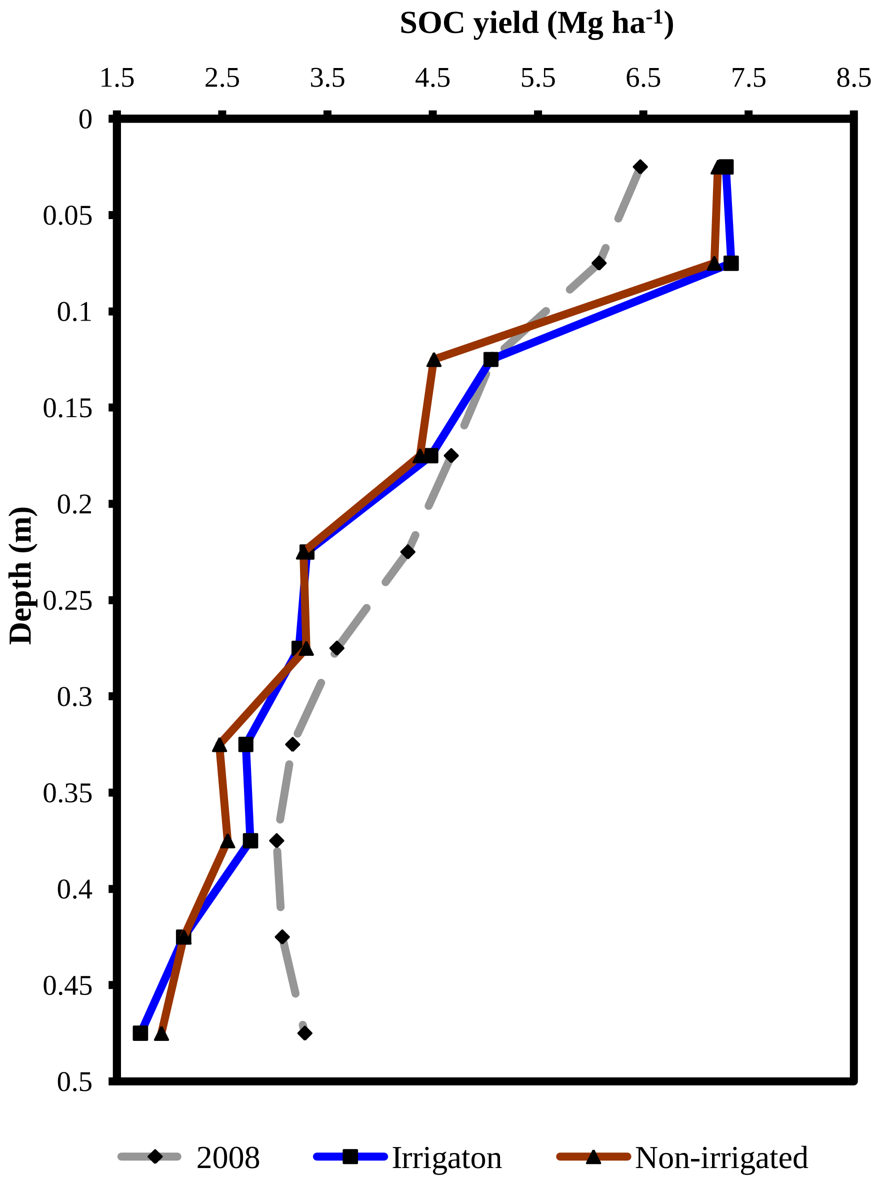


Figure 2-3: Soil organic carbon (Mg ha^{-1}) at non-trafficked middle row affected by tillage treatments in 2009, and overall SOC before planting in 2008. Horizontal error bars indicate tillage significant differences - Difference of L.S. Means S.E. $_{(0.10)}$.

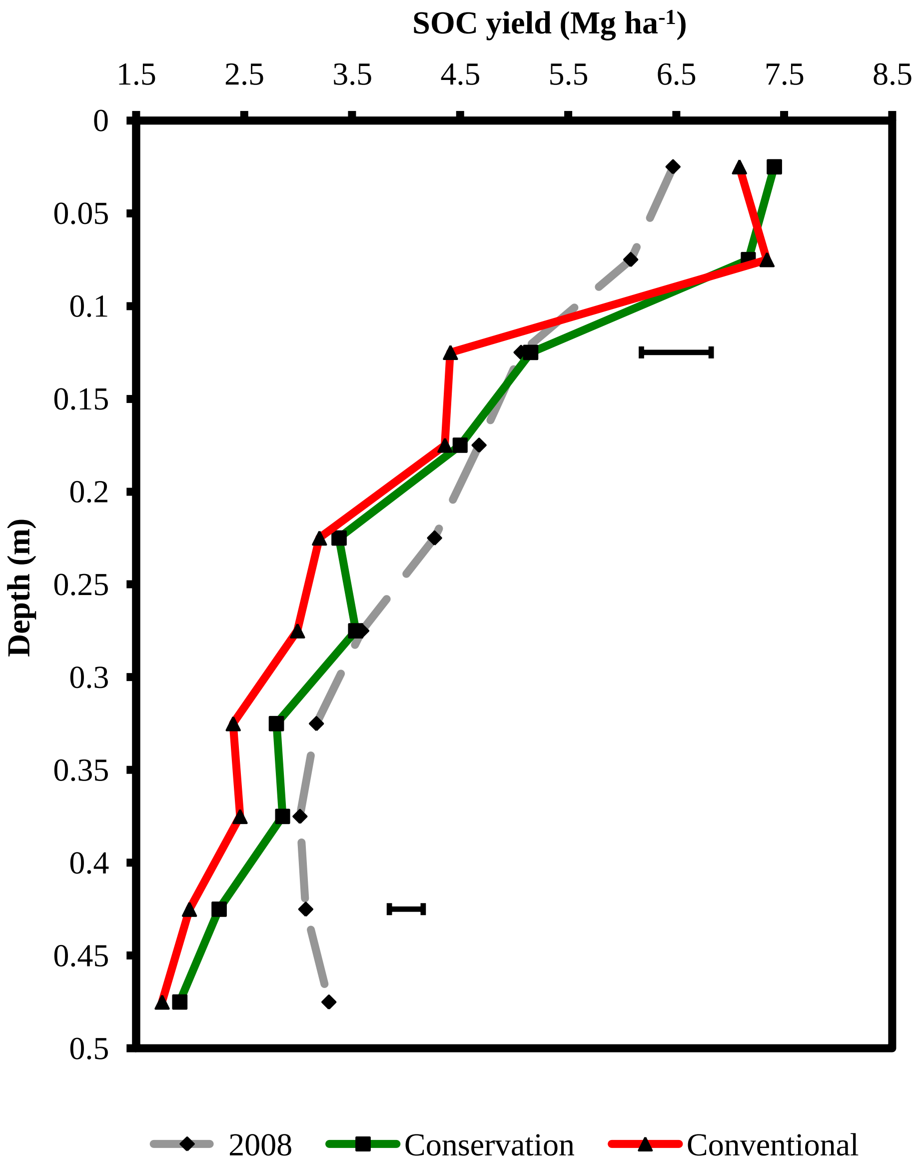


Figure 2-4: Total nitrogen (Mg ha^{-1}) at non-trafficked middle row affected by crop treatments in 2009 and overall TN before planting in 2008. Horizontal error bars indicate crop significant differences - Difference of L.S. Means S.E. $_{(0.10)}$. PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

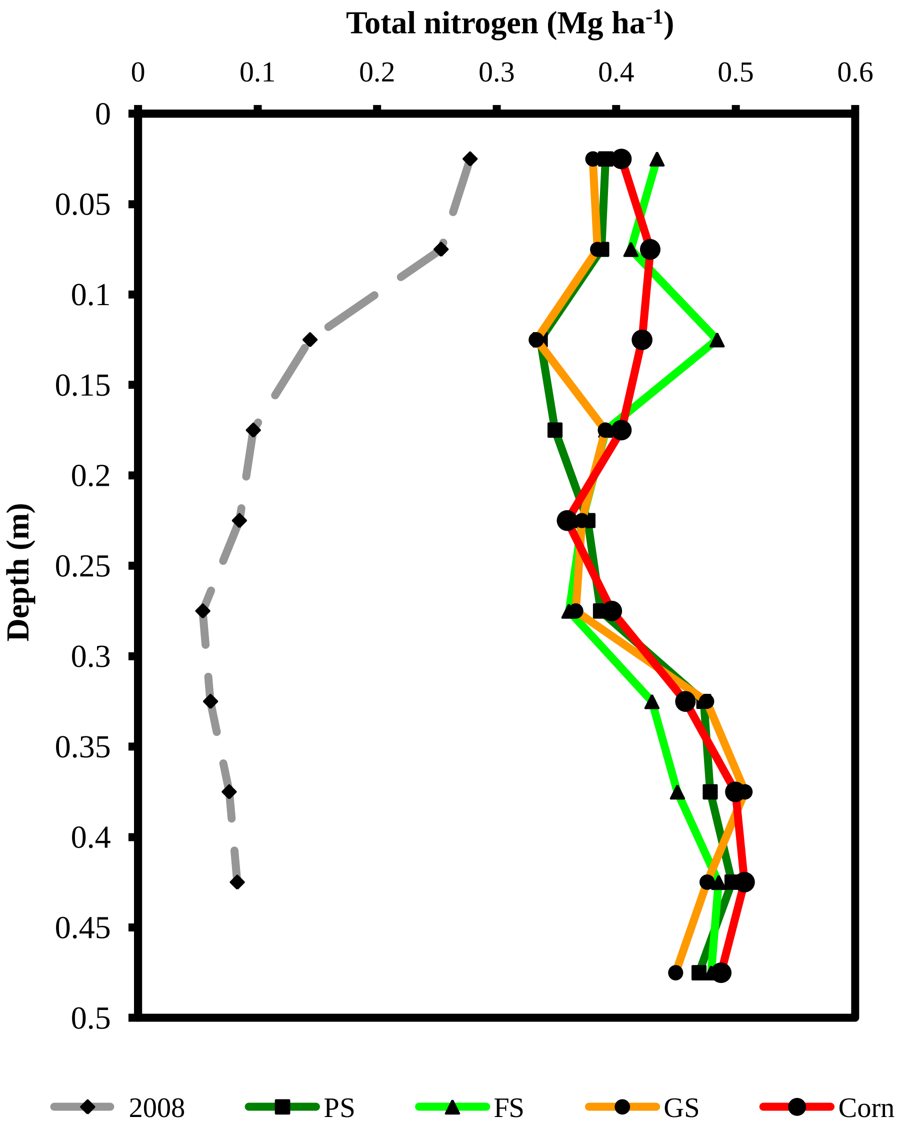


Figure 2-5: Total nitrogen (Mg ha^{-1}) at non-trafficked middle row affected by irrigation treatments in 2009 and overall TN before planting in 2008. Horizontal error bars indicate irrigation significant differences - Difference of L.S. Means S.E. $_{(0.10)}$.

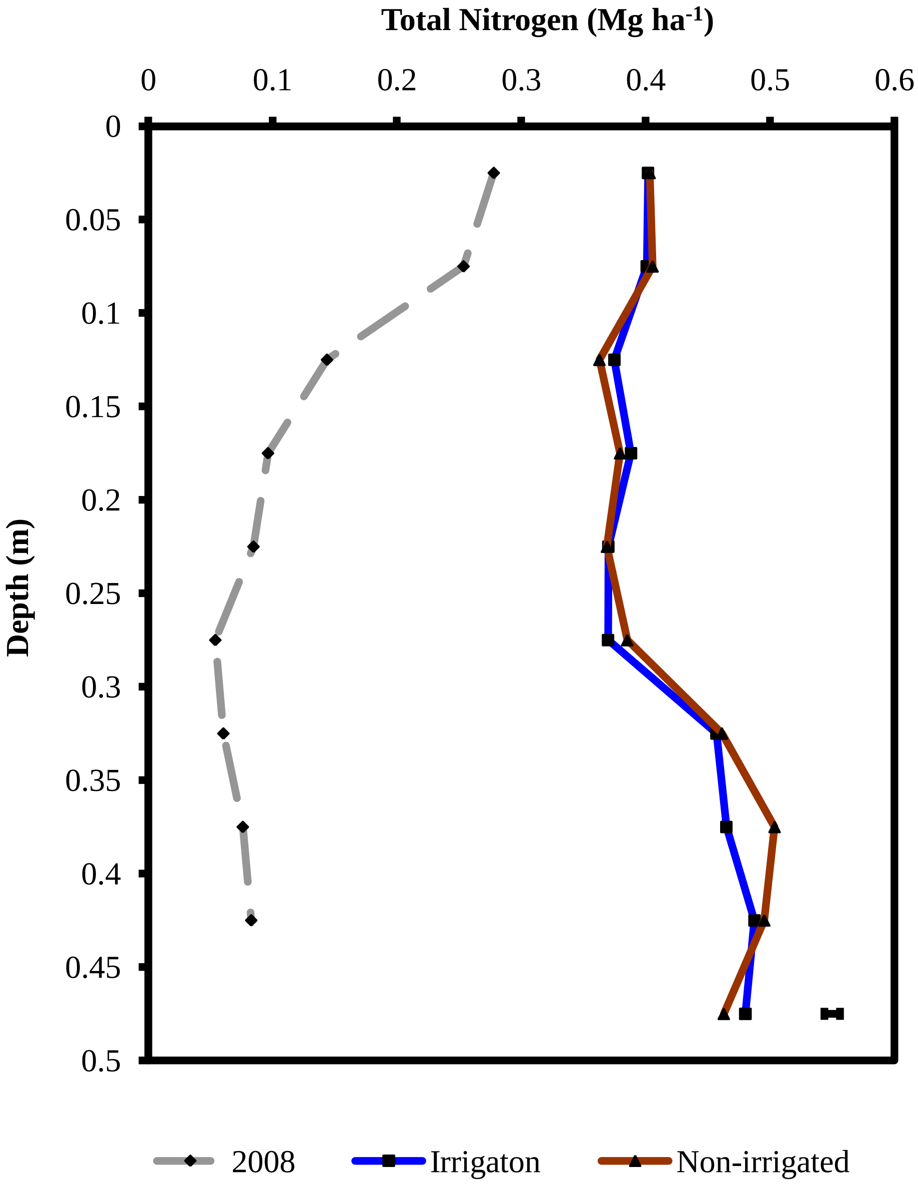


Figure 2-6: Total nitrogen (Mg ha^{-1}) at non-trafficked middle row affected by tillage treatments in 2009, and overall TN before planting in 2008. Horizontal error bars indicate tillage significant differences - Difference of L.S. Means S.E. $_{(0.10)}$.

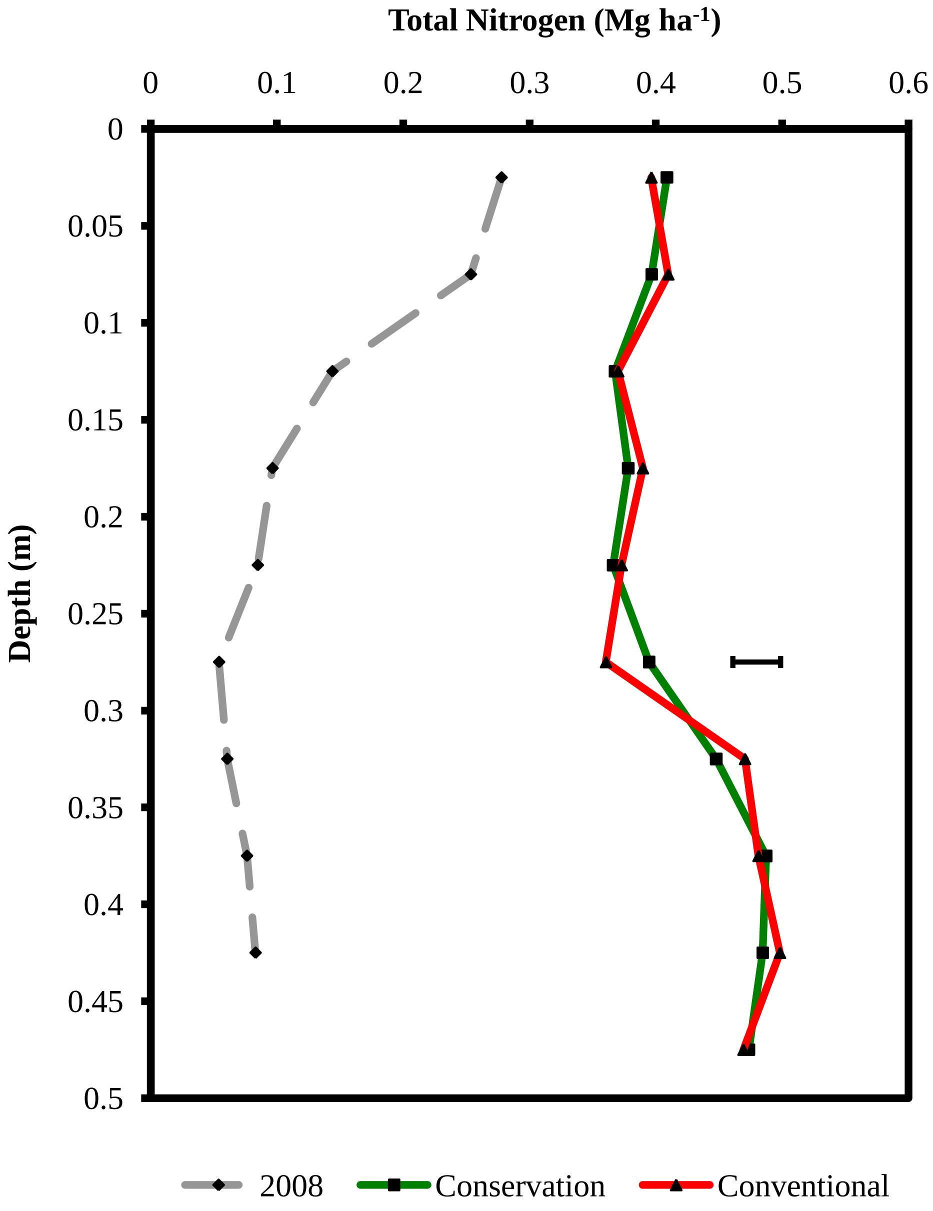


Figure 2-7: Bulk density (Mg m^{-3}) at non-trafficked middle row affected by crop treatments in 2009 and overall Bulk density before planting in 2008. Horizontal error bars indicate crop significant differences - Difference of L.S. Means S.E. $_{(0.10)}$. PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

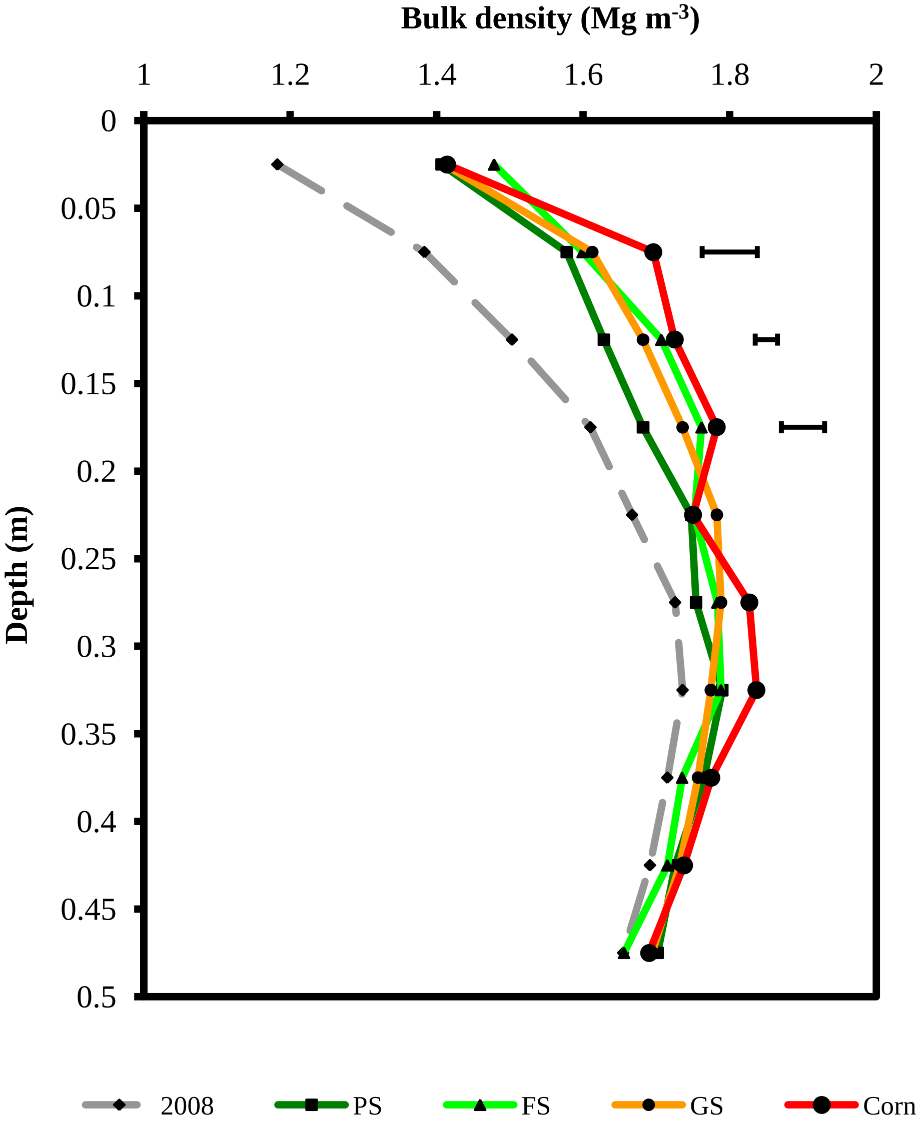


Figure 2-8: Bulk density (Mg m^{-3}) at non-trafficked middle row affected by irrigation treatments in 2009 and overall Bulk density before planting in 2008. Horizontal error bars indicate irrigation significant differences - Difference of L.S. Means S.E. $_{(0.10)}$.

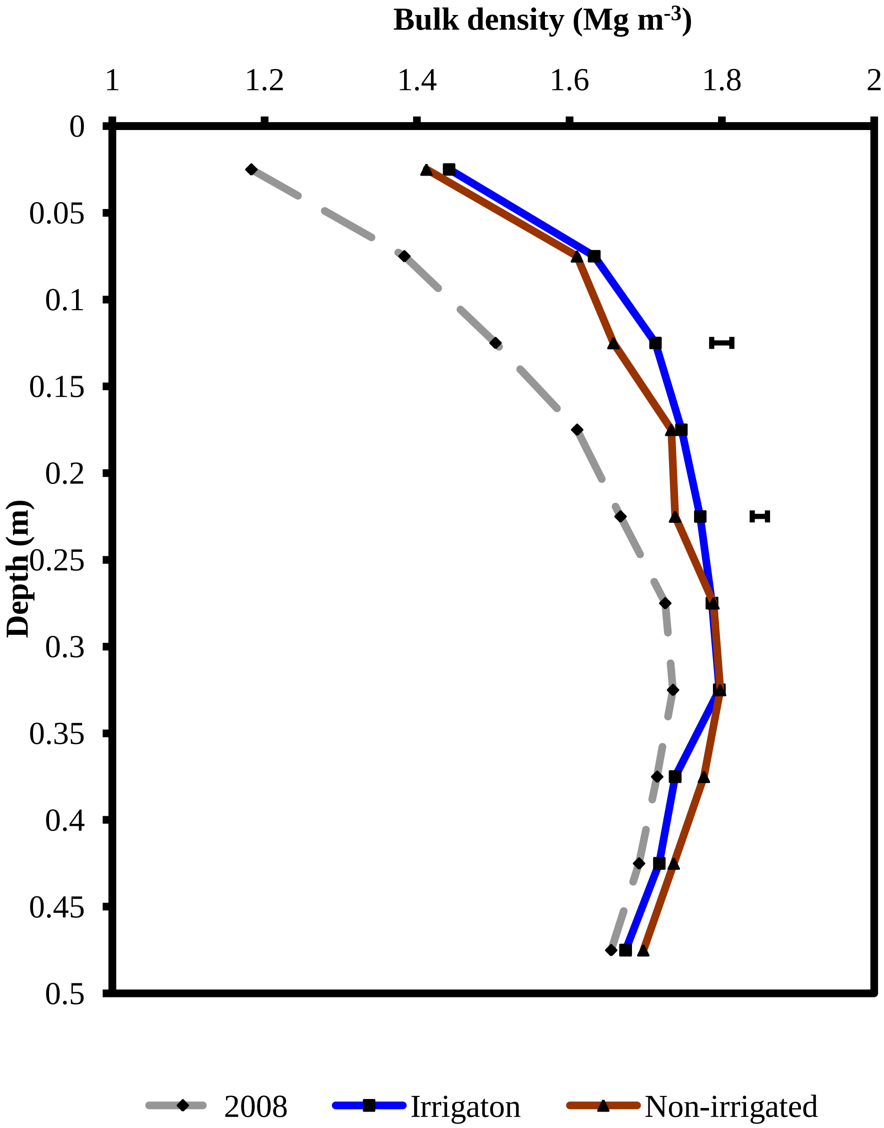


Figure 2-9: Bulk density (Mg m^{-3}) at non-trafficked middle row affected by tillage treatments in 2009, and overall Bulk density before planting in 2008. Horizontal error bars indicate tillage significant differences - Difference of L.S. Means S.E. $_{(0.10)}$.

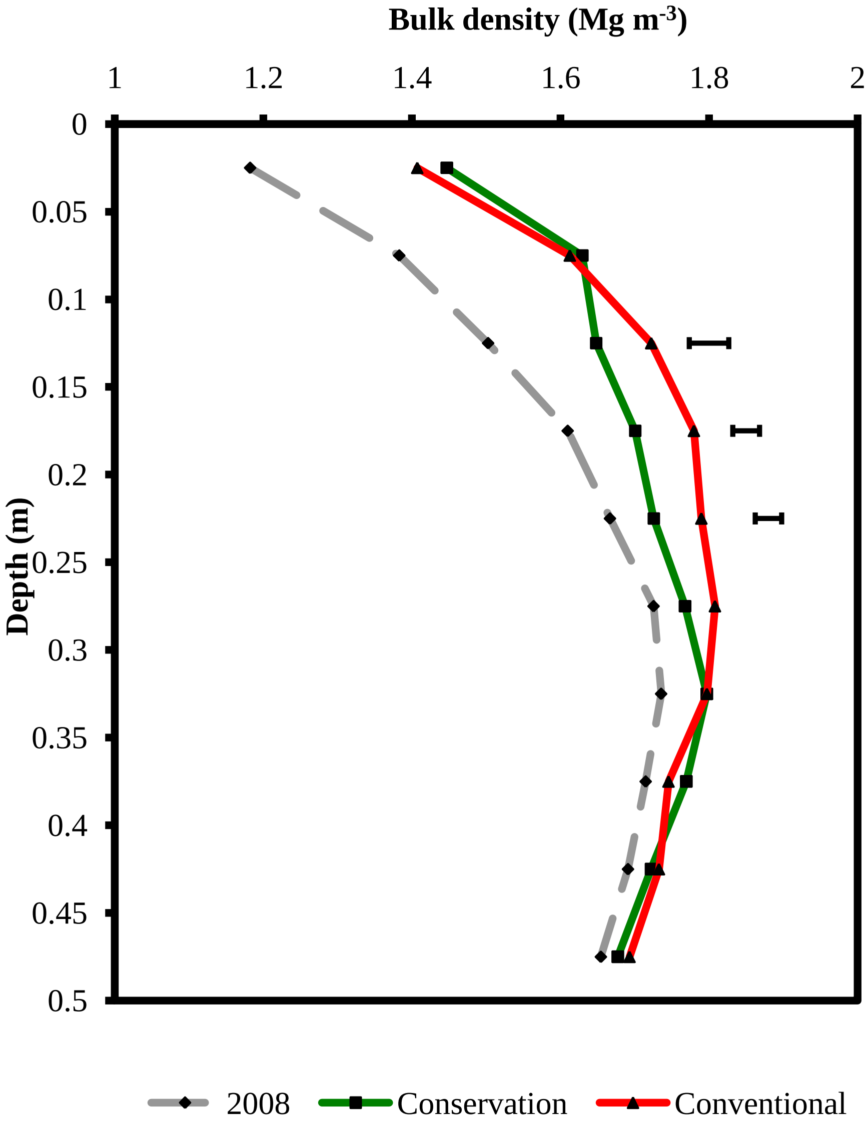


Figure 2-10:.Contour graphs of penetration isolines using Cone Index – CI (MPa) values for Marvyn loamy sand at tillage treatments in all sampling periods of 2008. Spring CI values were collected 1 week after planting. Fall CI values were collected 1 week after harvesting.

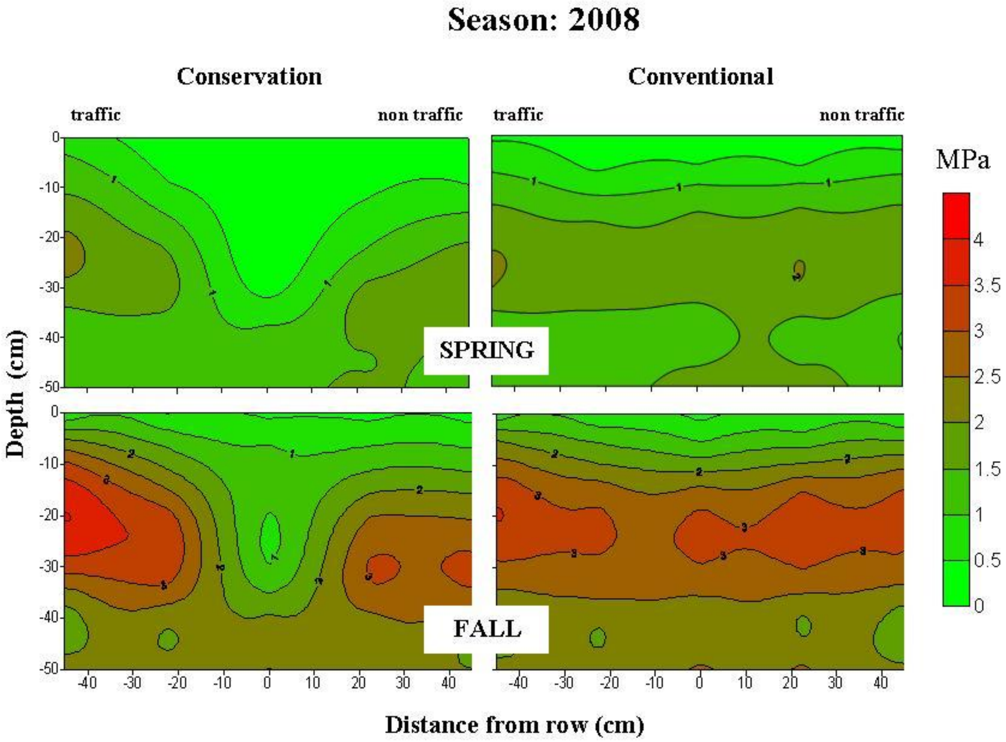


Figure 2-11: Contour graphs of penetration isolines using Cone Index – CI (MPa) values for Marvyn loamy sand at tillage treatments in all sampling periods of 2009. Spring CI values were collected 1 week after planting. Fall CI values were collected 1 week after harvesting.

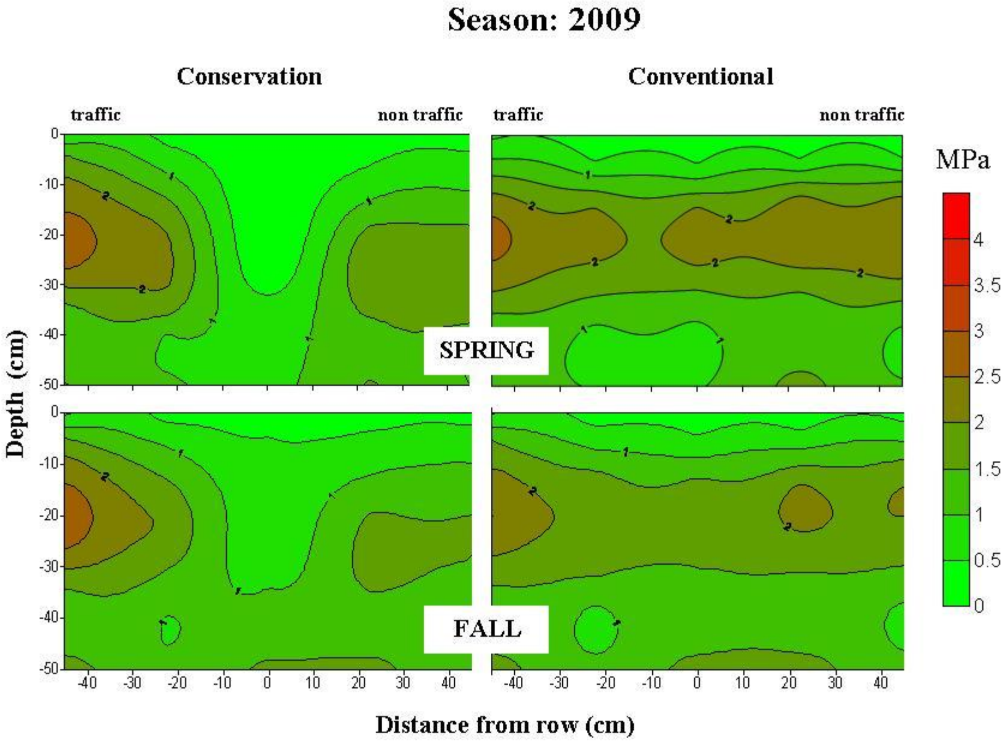


Figure 2-12: In row soil water content at 0.10 m deep affected by crop treatments for Marvyn loamy sand in 2008. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: weeks after planting, PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

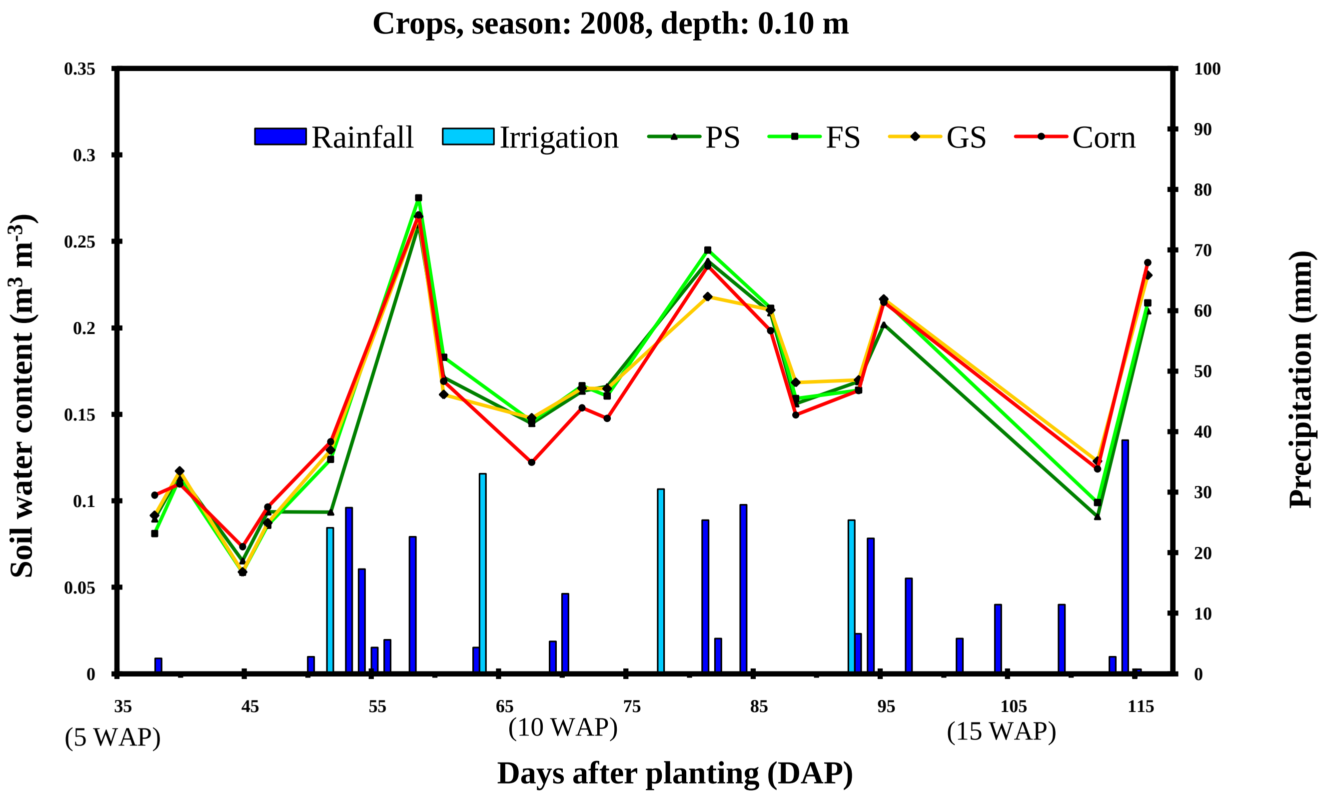


Figure 2-13: In row soil water content at 0.20 m deep affected by crop treatments for Marvyn loamy sand in 2008. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: weeks after planting, PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

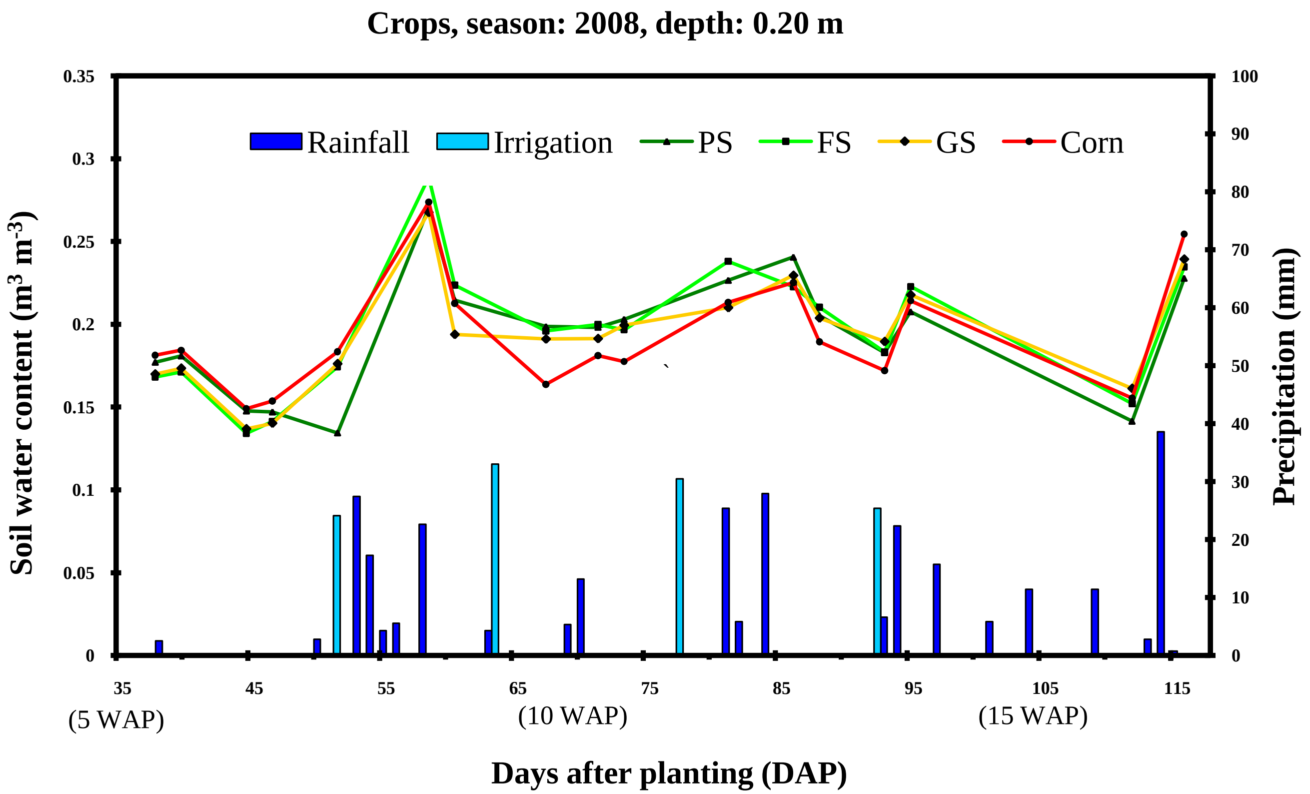


Figure 2-14: In row soil water content at 0.40 m deep affected by crop treatments for Marvyn loamy sand in 2008. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: weeks after planting, PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

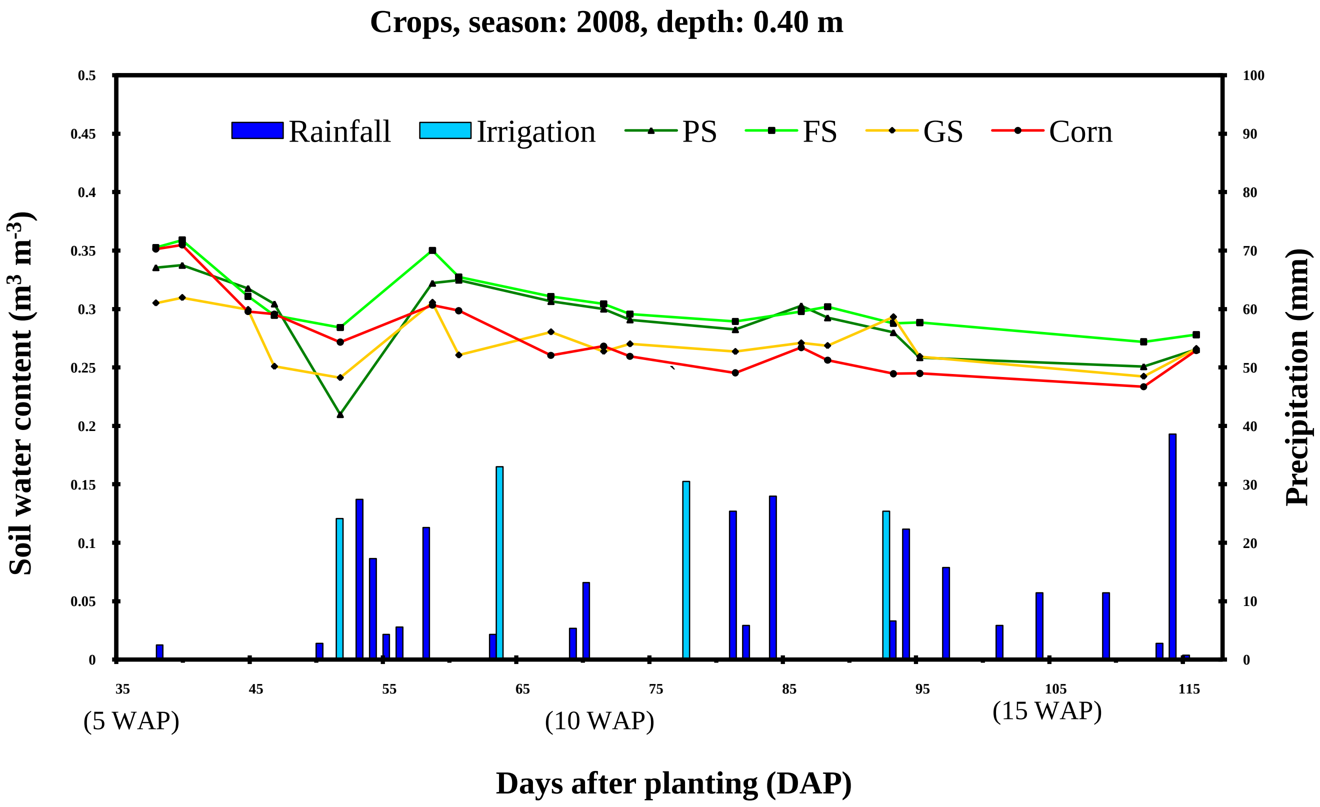


Figure 2-15: In row soil water content at 0.60 m deep affected by crop treatments for Marvyn loamy sand in 2008. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: weeks after planting, PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

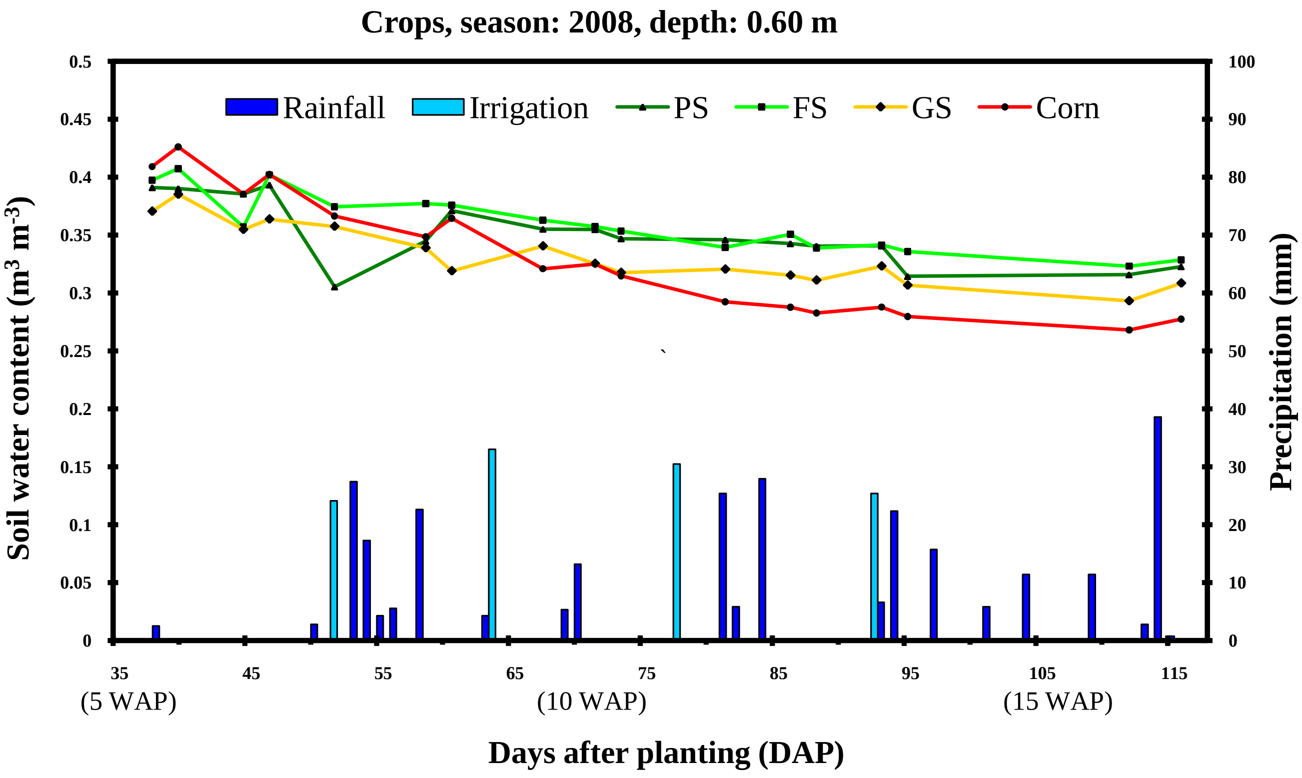


Figure 2-16: In row soil water content at 0.10 m deep affected by irrigation treatments for Marvym loamy sand in 2008. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: weeks after planting.

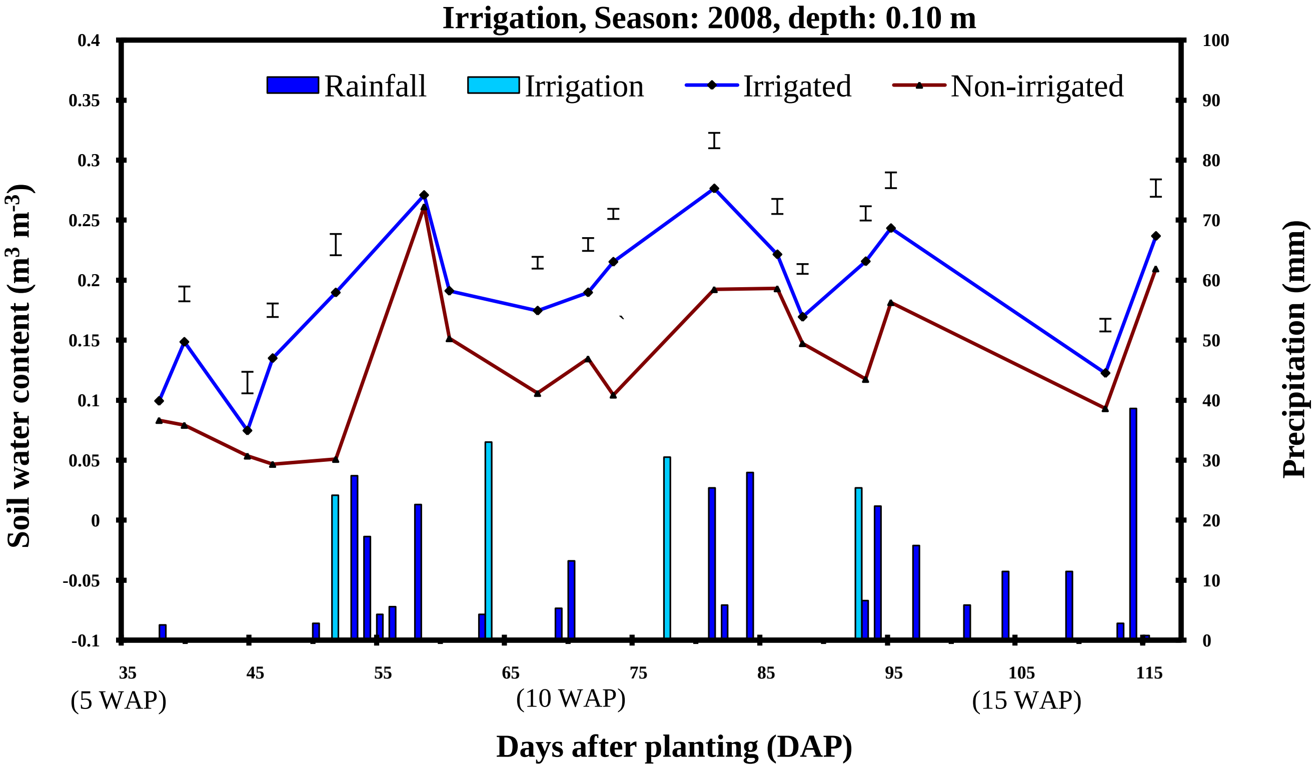


Figure 2-17: In row soil water content at 0.20 m deep affected by irrigation treatments for Marvyn loamy sand in 2008. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: Weeks after planting.

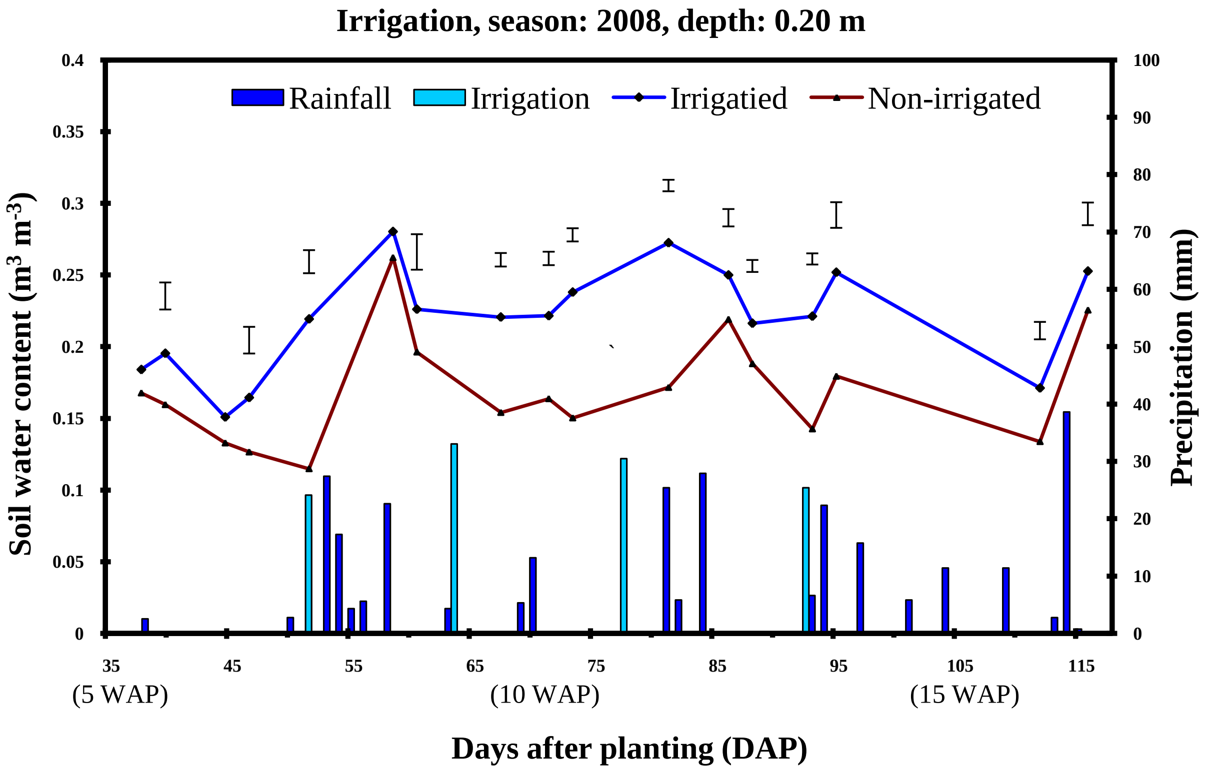


Figure 2-18: In row soil water content at 0.40 m deep affected by irrigation treatments for Marvyn loamy sand in 2008. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: Weeks after planting.

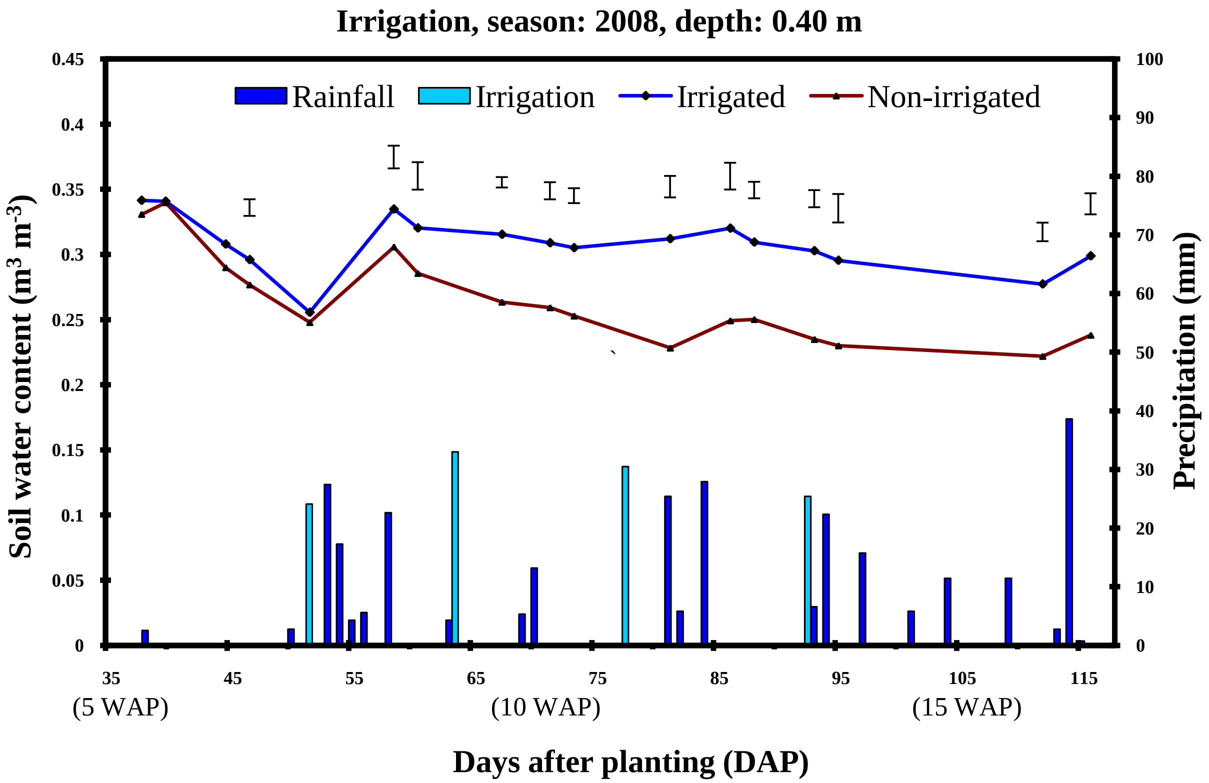


Figure 2-19: In row soil water content at 0.60 m deep affected by irrigation treatments for Marvyn loamy sand in 2008. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: Weeks after planting.

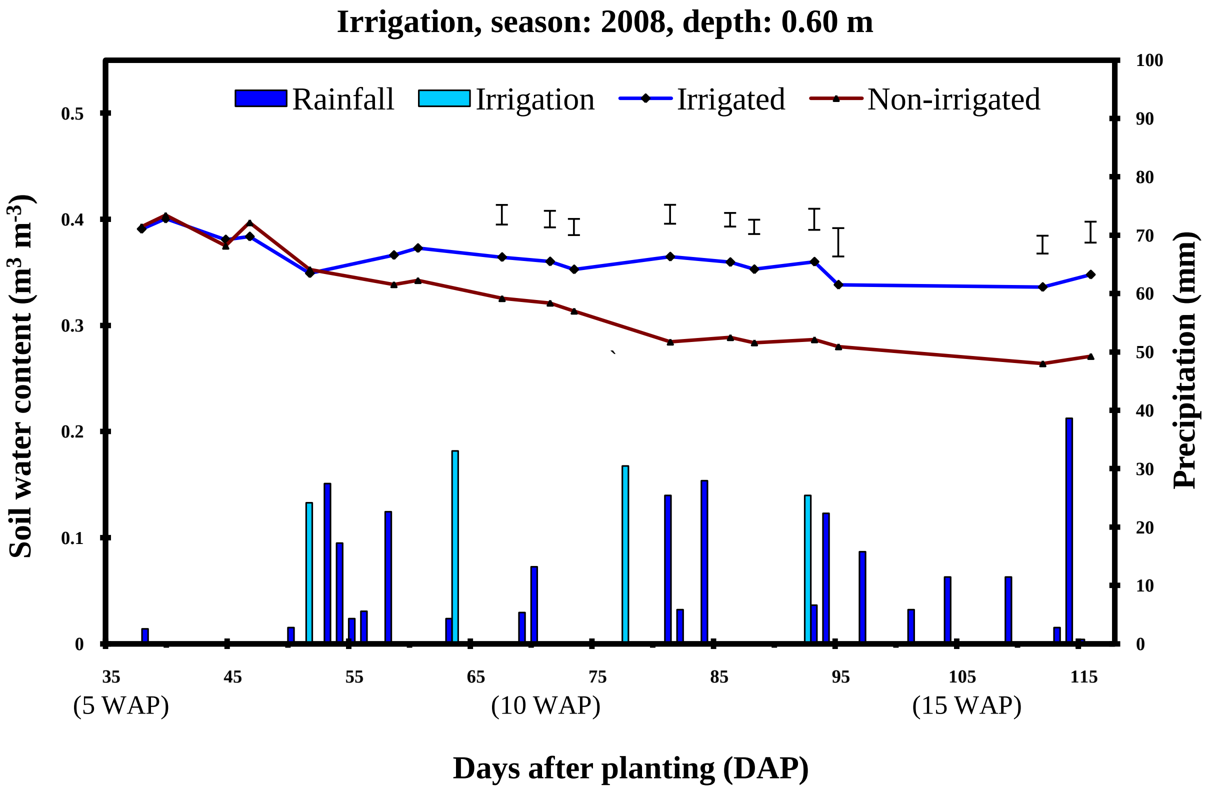


Figure 2-20: In row soil water content at 0.10 m deep affected by tillage treatments for Marvyn loamy sand in 2008. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: Weeks after planting

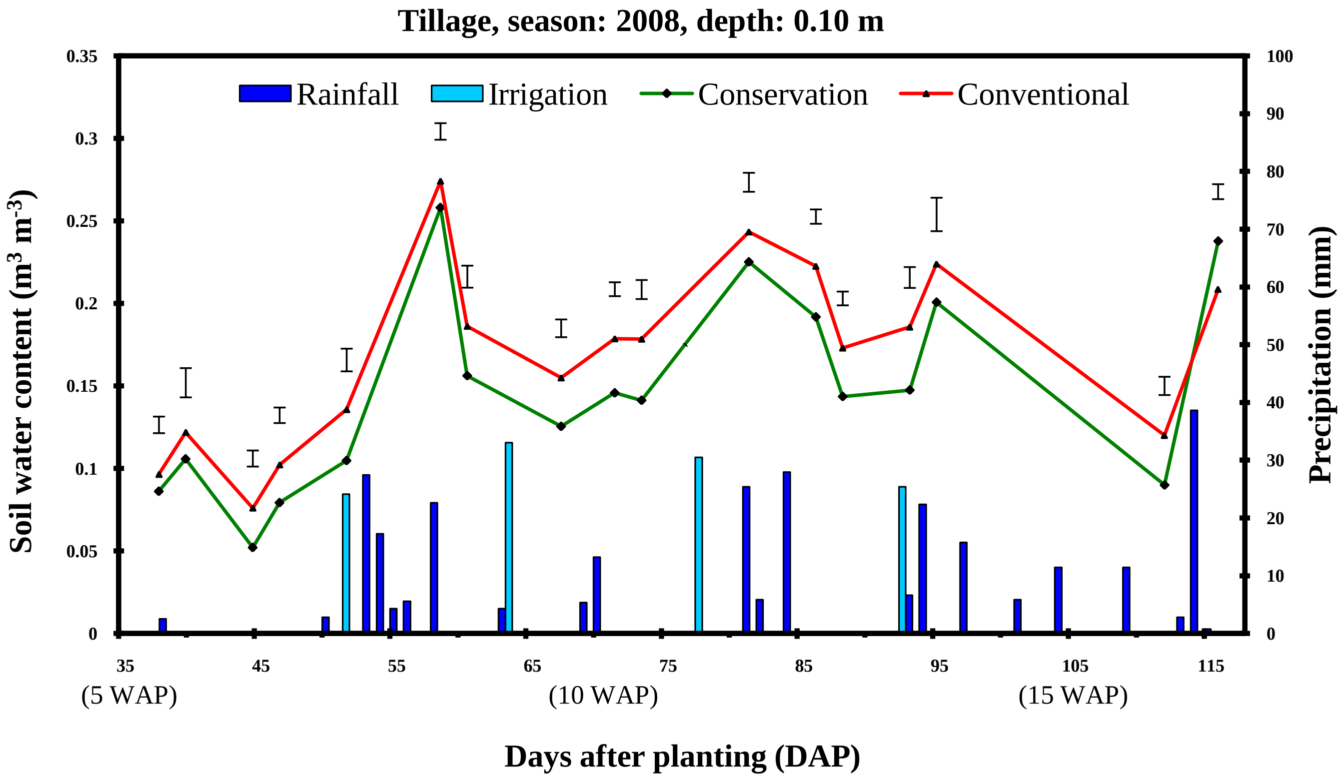


Figure 2-21: In row soil water content at 0.20 m deep affected by tillage treatments for Marvyn loamy sand in 2008. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: Weeks after planting.

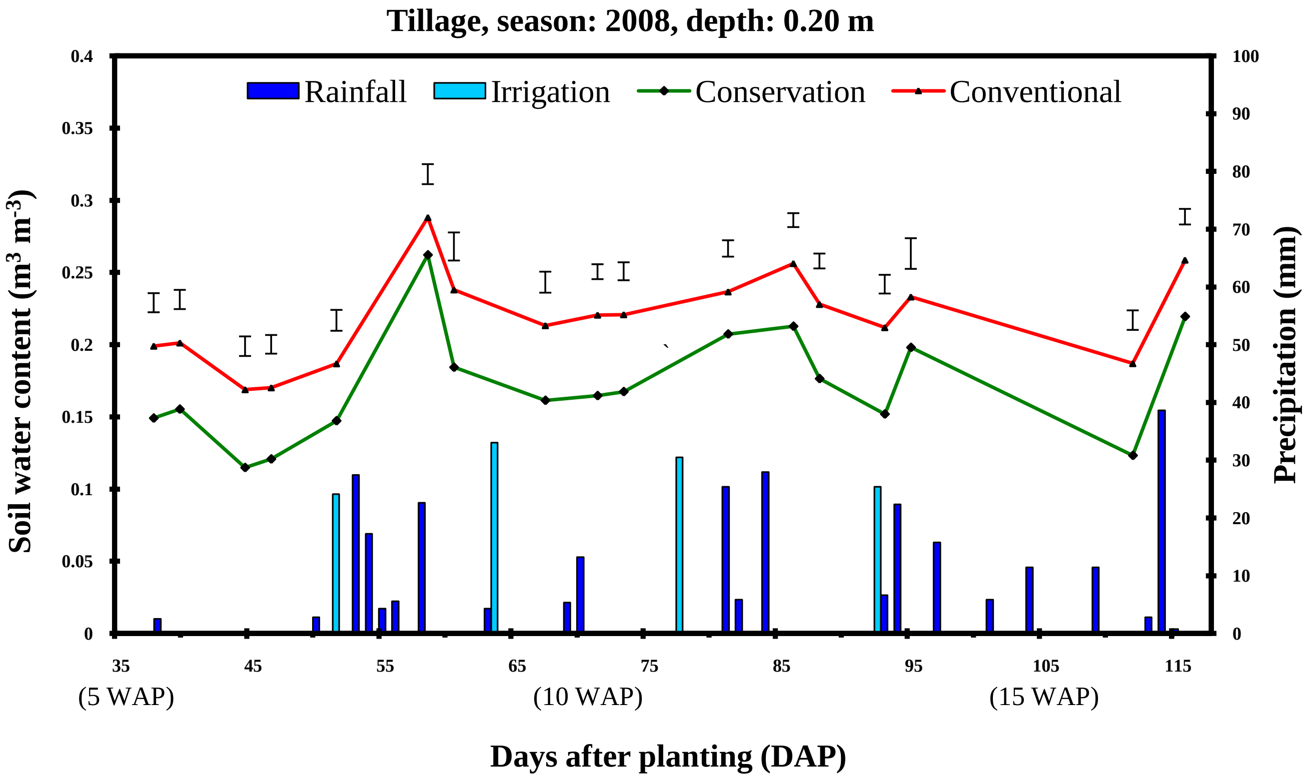


Figure 2-22: In row soil water content at 0.40 m deep affected by tillage treatments for Marvyn loamy sand in 2008. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: Weeks after planting.

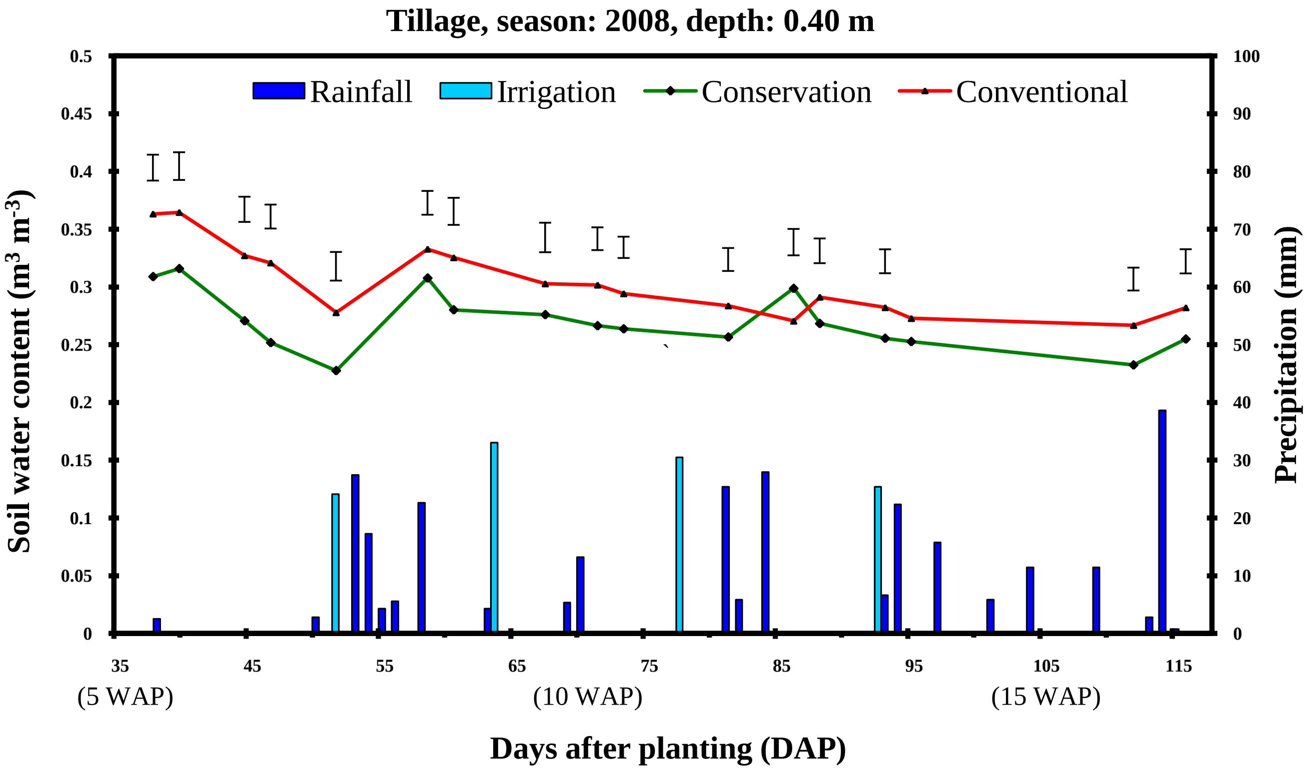


Figure 2-23: In row soil water content at 0.60 m deep affected by tillage treatments for Marvym loamy sand in 2008. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: Weeks after planting.

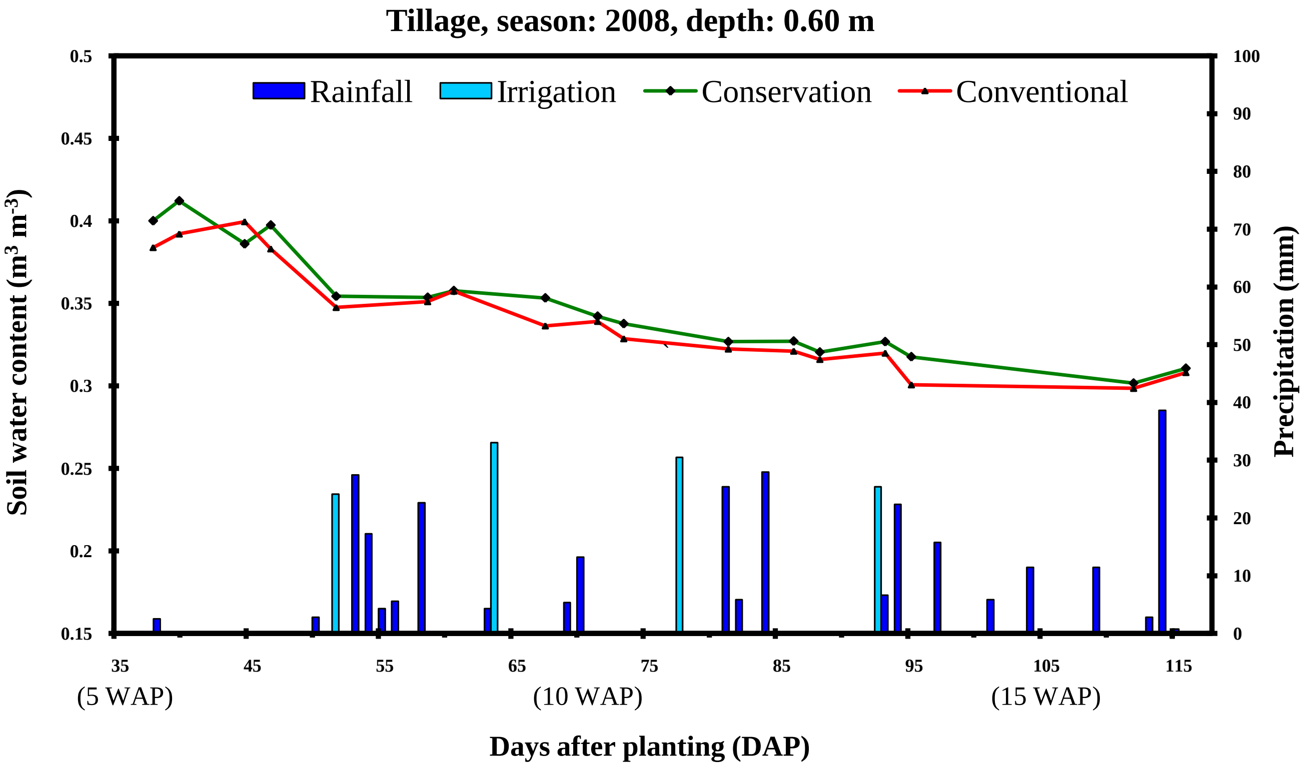


Figure 2-24: In row soil water content at 0.10 m deep affected by crop treatments for Marvyn loamy sand in 2009. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: Weeks after planting, PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

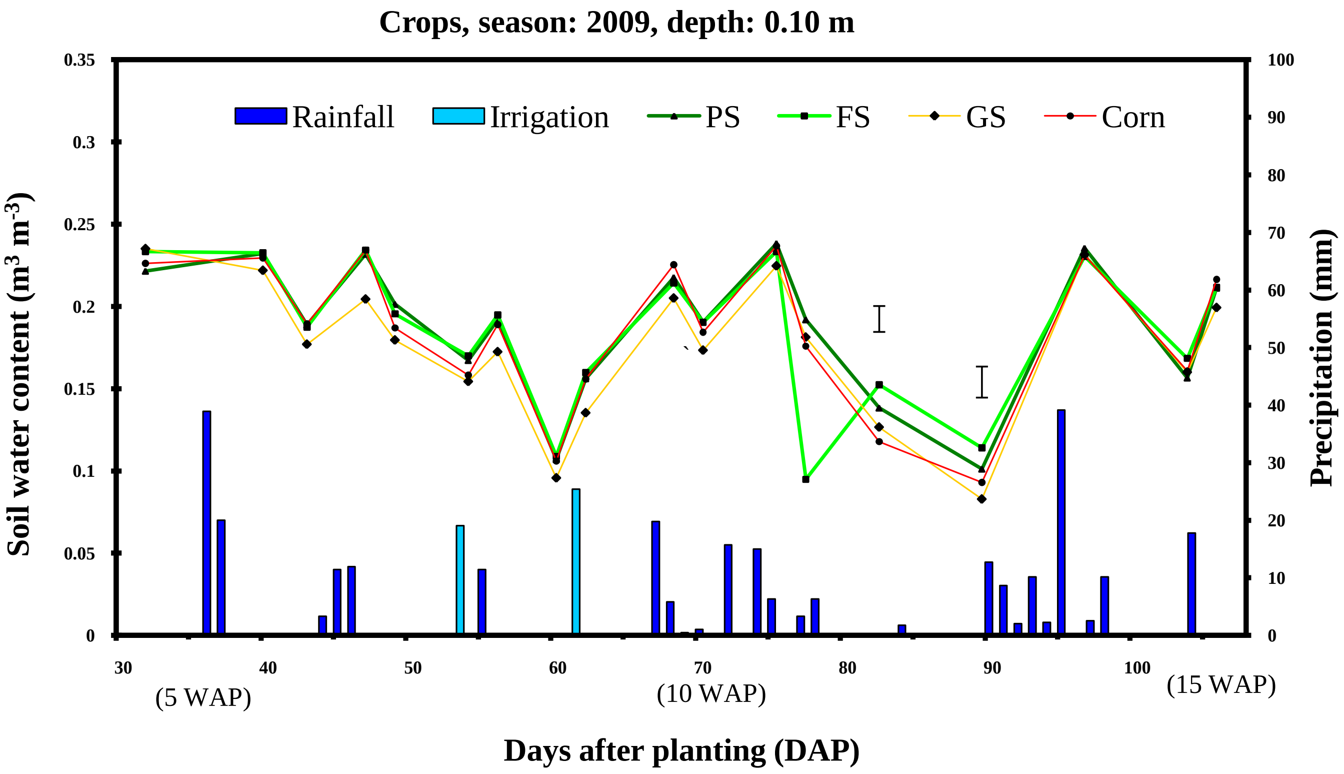


Figure 2-25: In row soil water content at 0.20 m deep affected by crop treatments for Marvyn loamy sand in 2009. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: Weeks after planting, PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

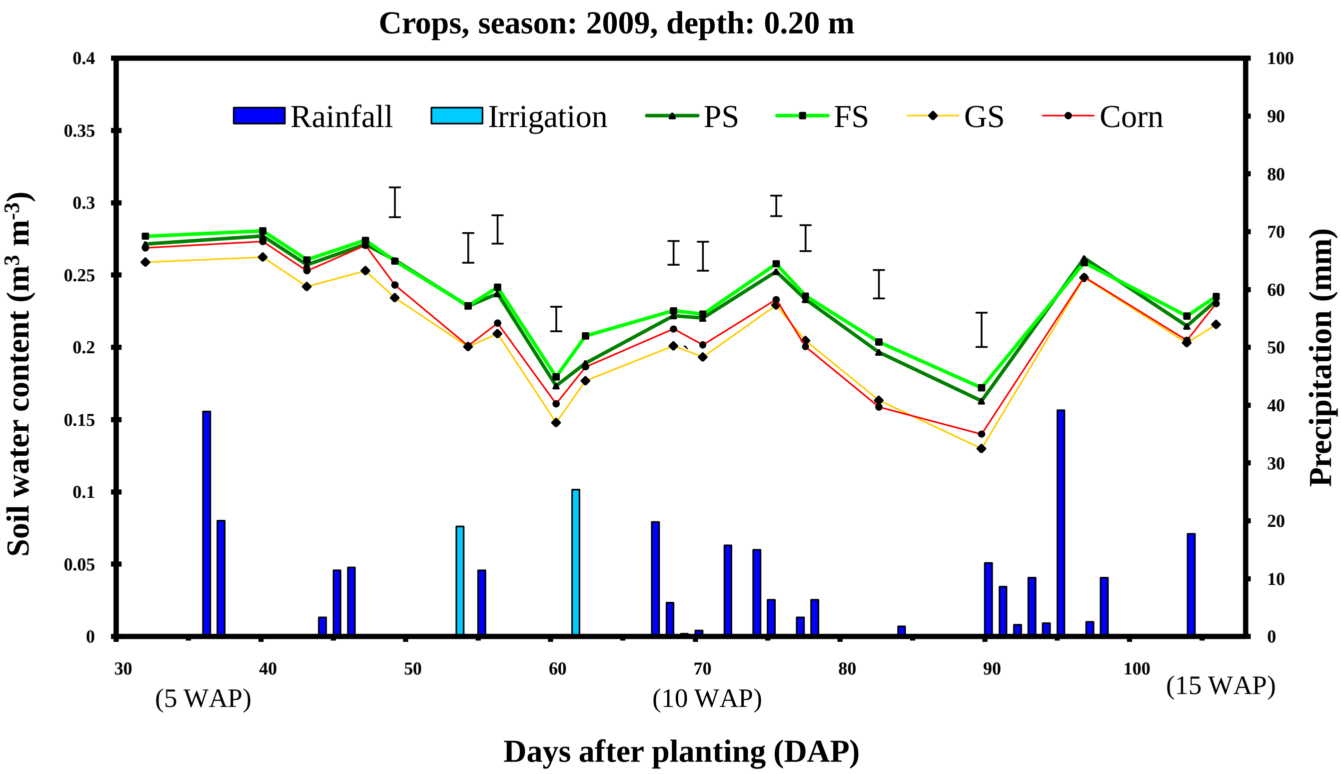


Figure 2-26: In row soil water content at 0.40 m deep affected by crop treatments for Marvyn loamy sand in 2009. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: Weeks after planting, PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

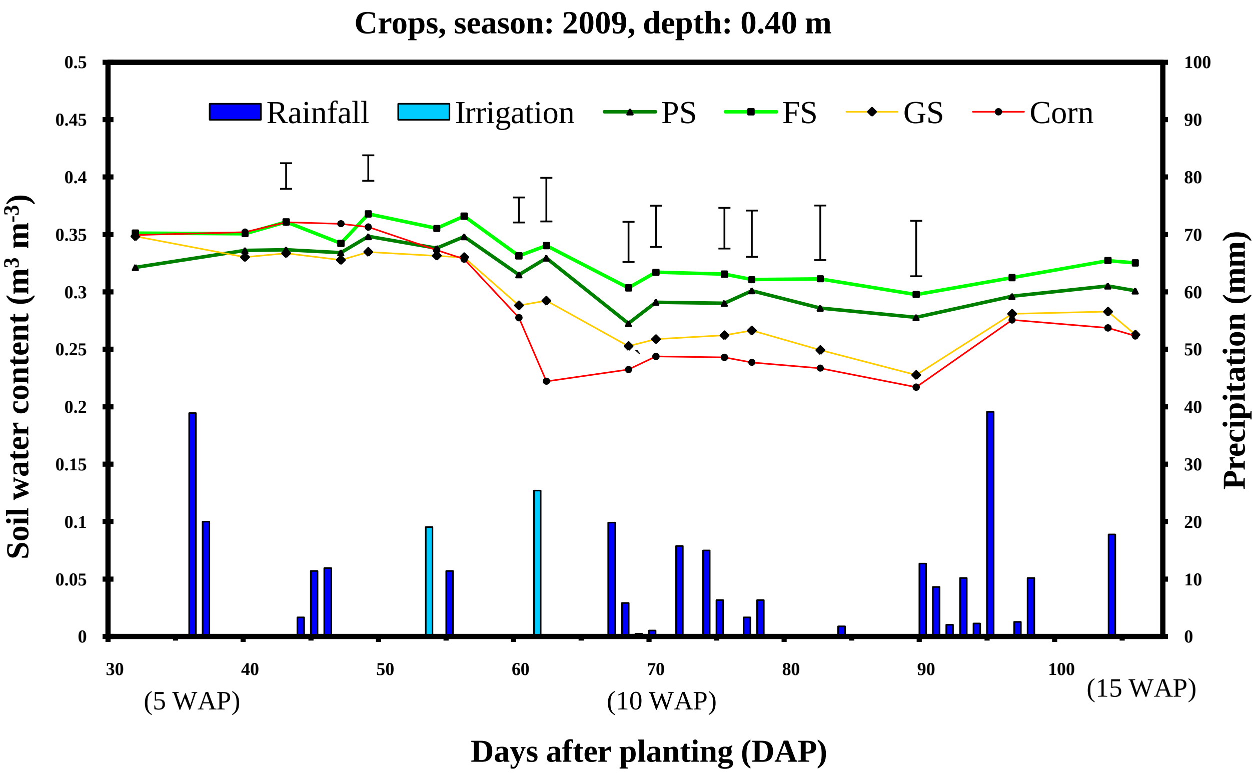


Figure 2-27: In row soil water content at 0.60 m deep affected by crop treatments for Marvyn loamy sand in 2009. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: Weeks after planting, PS: photoperiod sensitive sorghum (1990), FS: forage sorghum (SS506), GS: grain sorghum (NK300), Corn: Pioneer31G65.

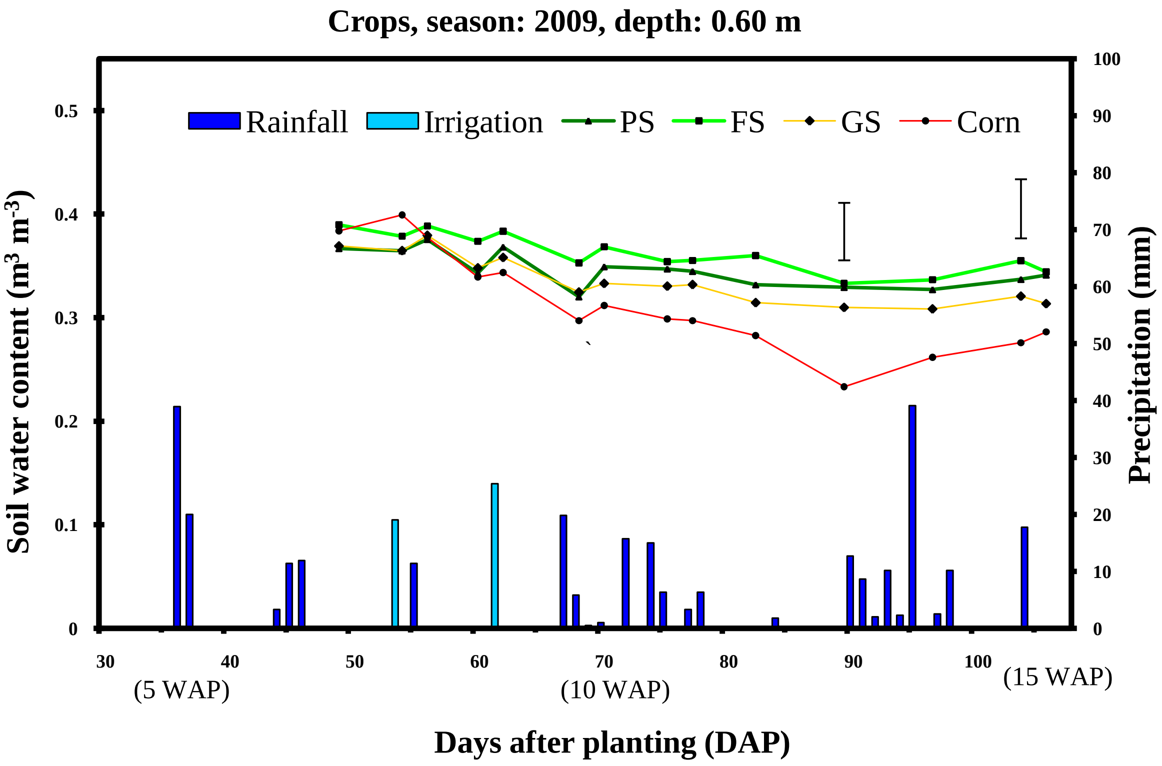


Figure 2-28: In row soil water content at 0.10 m deep affected by irrigation treatments for Marvyn loamy sand in 2009. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: Weeks after planting.

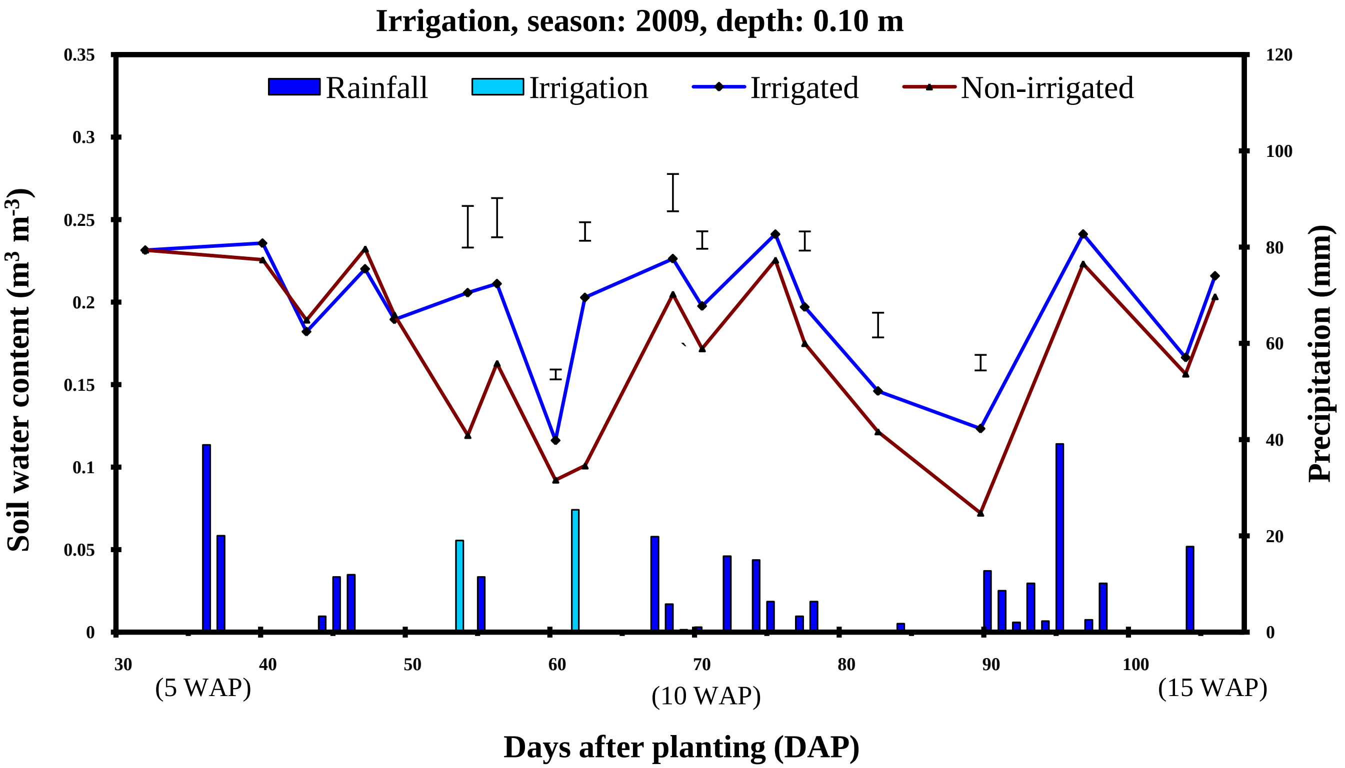


Figure2-29: In row soil water content at 0.20 m deep affected by irrigation treatments for Marvyn loamy sand in 2009. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: Weeks after planting.

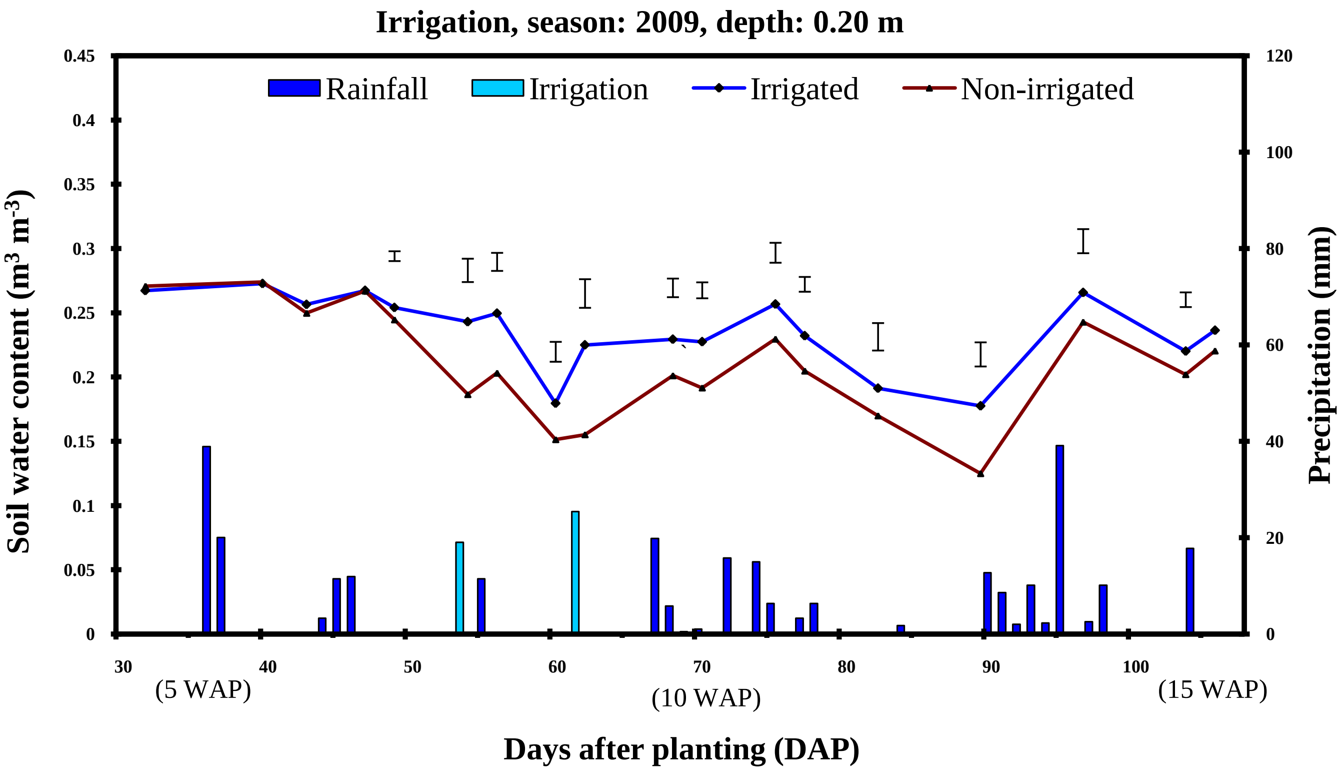


Figure 2-30: In row soil water content at 0.40 m deep affected by irrigation treatments for Marvyn loamy sand in 2009. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: Weeks after planting.

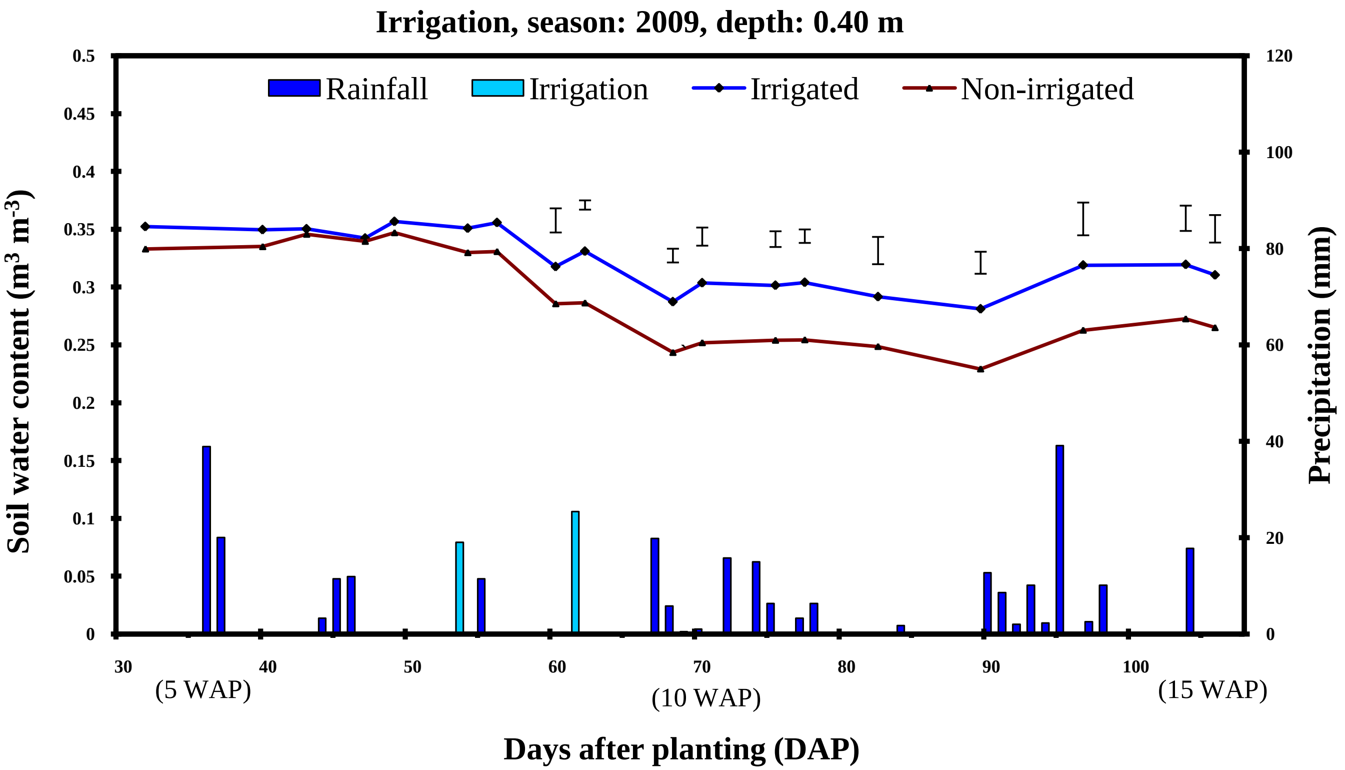


Figure 2-31: In row soil water content at 0.60 m deep affected by irrigation treatments for Marvyn loamy sand in 2009. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: Weeks after planting.

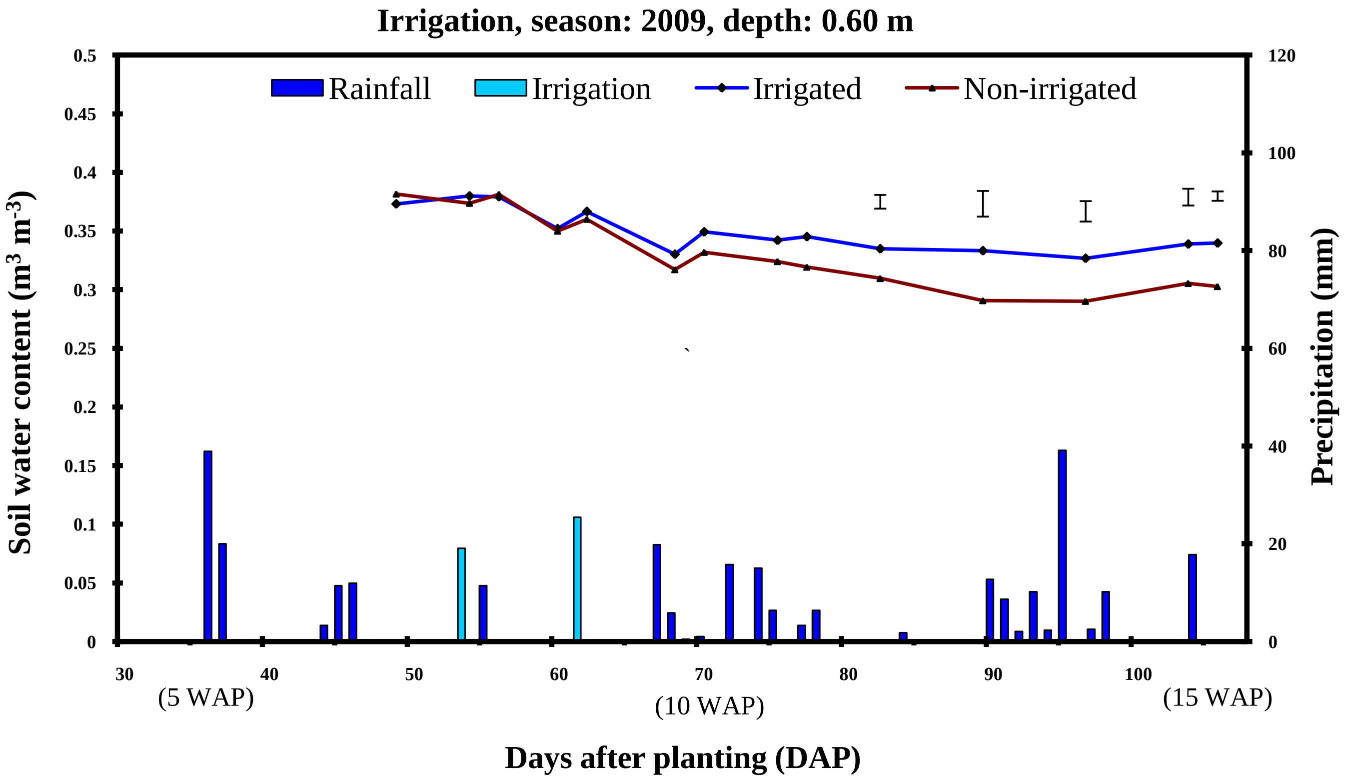


Figure 2-32: In row soil water content at 0.10 m deep affected by tillage treatments for Marvyn loamy sand in 2009. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: Weeks after planting.

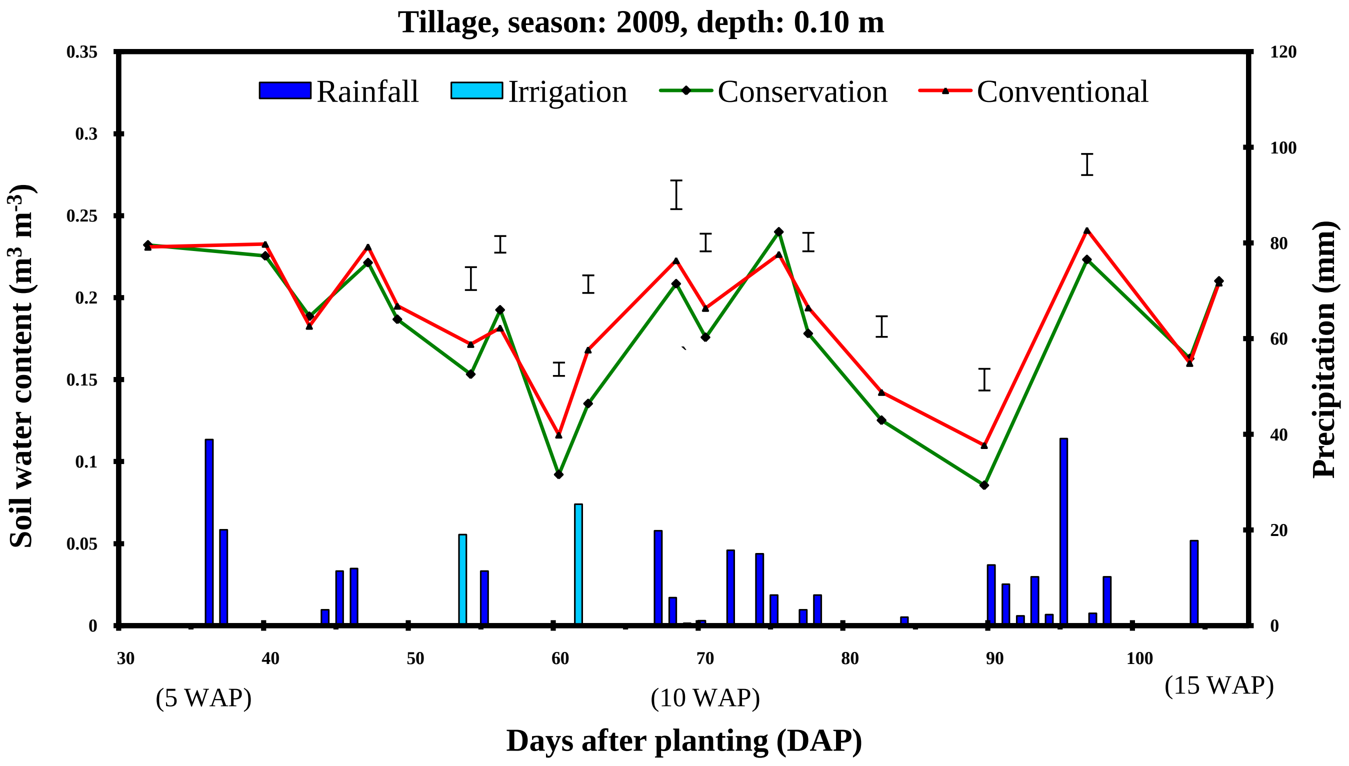


Figure 2-33: In row soil water content at 0.20 m deep affected by tillage treatments for Marvyn loamy sand in 2009. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: Weeks after planting.

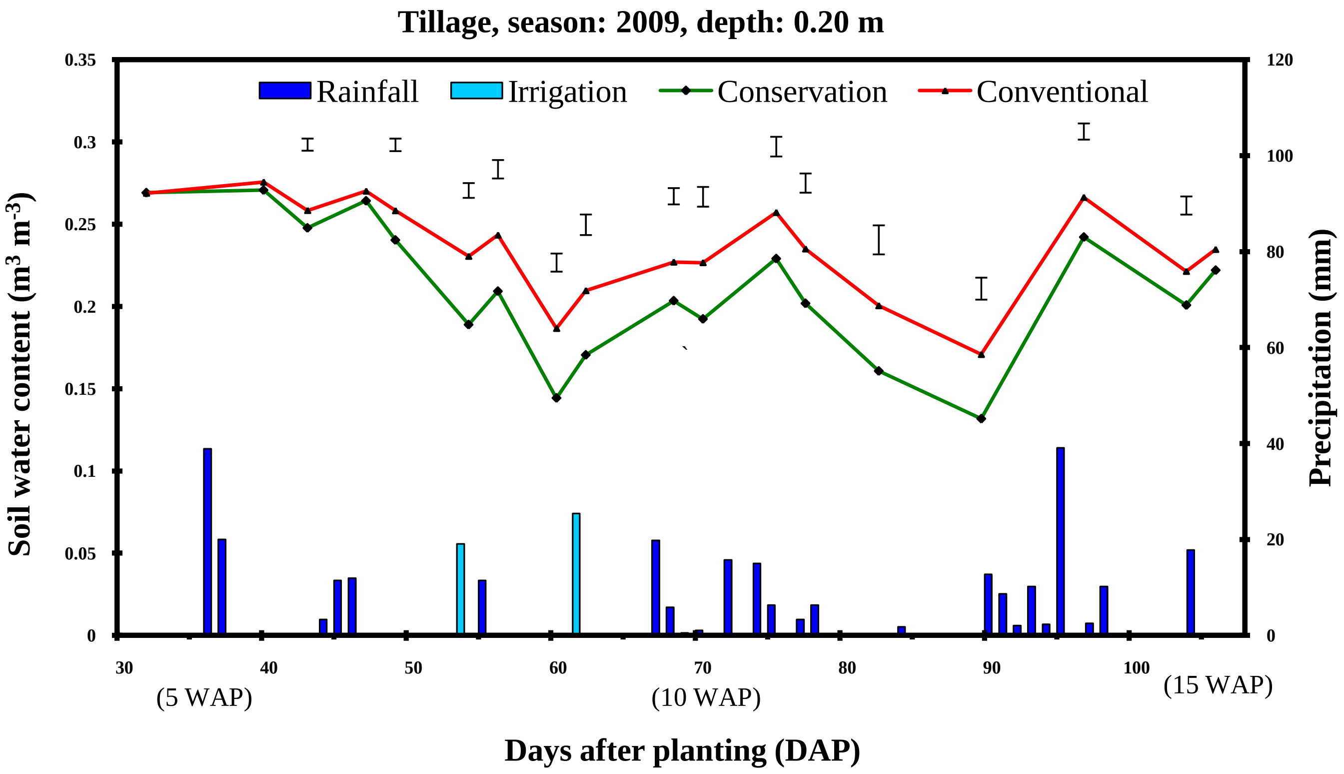


Figure 2-34: In row soil water content at 0.40 m deep affected by tillage treatments for Marvyn loamy sand in 2009. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: Weeks after planting.

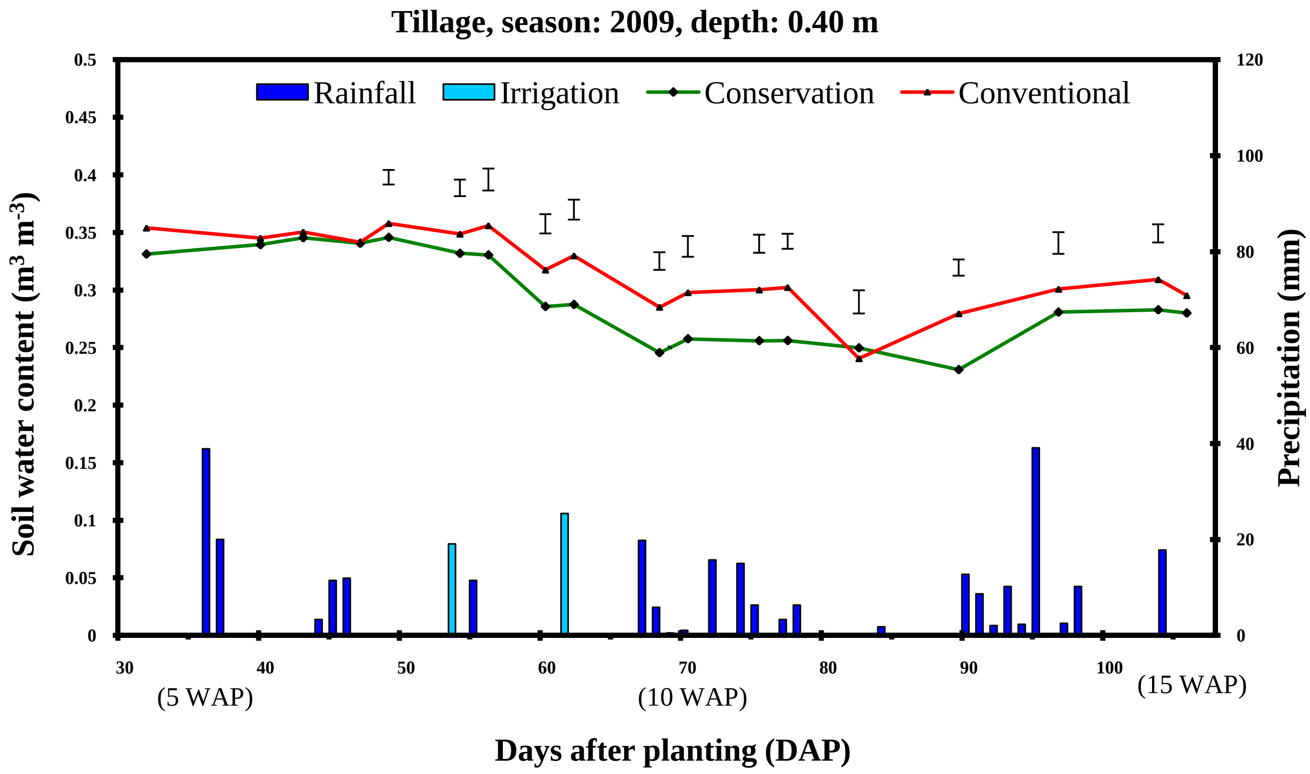
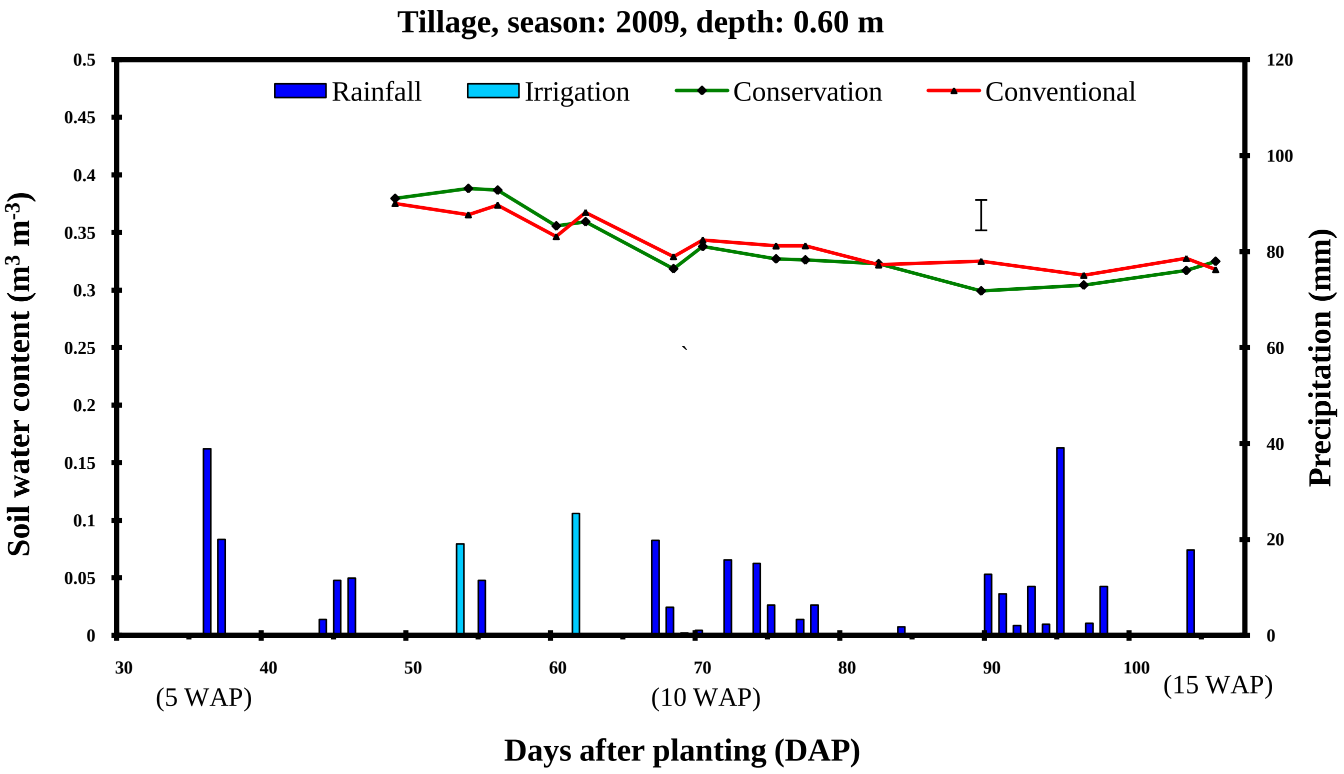


Figure 2-35: In row soil water content at 0.40 m deep affected by tillage treatments for Marvyn loamy sand in 2009. Vertical error bars denote significant differences – Difference of L.S. means S.E.$_{(0.10)}$. WAP: Weeks after planting.



III. RAPIDLY DRYING SOGHUM BIOMASS FOR POTENTIAL BIOFUEL PRODUCTION

ABSTRACT

The Southern U.S. has an ideal climate that may aid in growing large amounts of biomass potentially suitable for biofuel; however, short-term droughts during the growing season may reduce yields. Sorghum (*Sorghum bicolor* L.) may have great potential as an energy crop, because it is capable of high biomass yields and is drought tolerant. Sorghum could be integrated into a conservation system as part of a crop rotation. However, sorghum biomass has relatively high moisture content and should be conditioned and dried before transported to reduce costs. Sorghum-sudan hybrid was harvested with two different headers on a self-propelled windrower: a Massey Ferguson 9145 (sickle) and a Massey Ferguson 9185 (disc). The disc header was comprised of two pairs (rear / front) of metal conditioner rollers which compressed the biomass, thus improving the drying process. The roller pairs were used with three different pressures (0, 3500 and 7000 kPa), and with different gaps (0 and 0.02 m). Sorghum biomass samples were collected after harvest and moisture content (%) evaluated daily until they remained constant. Results revealed that the higher pressures and smaller gaps resulted in faster drying of biomass. Thus, the best settings for the disc header were “7000 kPa – 0 m” or “7000 kPa – 0.02 m” which showed, respectively, moisture content levels of 13.6 % and 16.8 % after 14 days. However, when the disc header was set to “0 kPa - 0.02 m”, the moisture content was significantly higher (43.2%). These results indicate sorghum was adequately dried for bailing in Southeastern U.S. condition, when using MF 9185 set with both “0 m gap front and rear, 7000 kPa” and “0.02 gap front / 0 m gap rear, 7000 kPa”.

Keywords: moisture, conditioning, bailing, windrowers, settings.

1. INTRODUCTION

Growing domestic biomass for bioenergy may help to reduce the amount of oil imported by the United States. The Southeastern U.S. has an ideal climate that may aid in growing large amounts of biomass; however, short-term droughts during the growing season over the last several years have dramatically reduced production. For these reasons, sorghum may be a reasonable alternative as an energy crop in this region, because it is considered drought resistant (Habyarimana et al., 2004). Sorghum can extract water from deep soil layers with most coming from depths of 0.45 - 1.35 m (Farre and Faci, 2006).

Additionally, sorghum has been considered a potential bioenergy crop, mostly from a cellulosic standpoint, providing a total maximum dry matter yield of 30.15 tons ha^{-1} in a short time (120 days) and with a maximum mean daily growth rate of 22 g day^{-1} (Loomis and Williams, 1963).

Therefore, sorghum could be integrated into a conservation system as part of a crop rotation with typical cash crops where part of its biomass would be used as a soil cover and any additional amount of biomass would be harvested for potential biofuel production. While much emphasis has been placed on perennials for biofuel production, annual crops, such as sorghum would provide a major source of biomass for cellulosic ethanol production. These annual crops for bioenergy production have largely been ignored in the Southeastern U.S.

However, sorghum biomass has relatively high moisture content and should be dried before transported to reduce costs. Cundiff and Worley (1992) found that freshly harvested sorghum stalks had 48 to 76% of fresh weight and contained 42–75 % of whole-plant nonstructural carbohydrate. Thus, sorghum biomass needs to be dried to a moisture content of 15–20 % for storage. Moisture content higher than 20 % results in molds and bacteria growth that decreases biomass quantity and quality. On the other hand, moisture content lower than 15 % results in leaf loss decreasing biomass quantity (Wilcke et al., 1998).

Therefore, the objective of this study was: 1) Compare the drying of sorghum biomass under two different headers on a self-propelled windrower, 2) determine the best setting of the disc header including setting the pressures and gaps, 3) evaluate if adequate drying could be obtained for baling sorghum within a relatively short time period in southeastern U S. conditions.

2. MATERIAL AND METHODS

In order to compare the drying of sorghum biomass, an experiment was conducted at the E.V. Smith Research Station, Shorter, AL (85º:53’50” W, 32º:25’22” N) in April, 2008. The soil at the experimental field was classified as Lynchburg loamy sand (fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults). The total field was previously used for with corn (*Zea Mays* L.) silage before planting sorghum.

2.1. Crop

The sorghum evaluated in this experiment was the Sweet Graze BMR (Brown Midrib Sorghum Sudangrass). It is described as tolerant to drought (500 mm rainfall requirement during growing season), high sugar content, high forage quality, low lignin content, and with little cold tolerance (Pogue Agri Partners Inc., 2010).

Conventional tillage was applied to the entire experimental area. Seeding rate of 28 kg ha^{-1} and N rate of 65 kg ha^{-1} was applied during planting. Other applications, such as nutrients and herbicides were obtained by following the Auburn University Extension recommendations. Only natural rainfall was used.

2.2. Self-propelled Windrowers

Two different headers on a self-propelled windrower were compared: a Massey Ferguson 9145 and a Massey Ferguson 9185 (AGCO Company, Duluth, GA), which are a sickle and a disc header, respectively. Figure 3-1 illustrates both windrowers.

The disc header was comprised of two pairs (rear / front) of metal conditioner rollers which compressed the biomass, thus improving the drying process. The roller pairs were used with three different pressures (0, 3500 and 7000 kPa), and with different gaps (0 and 0.02 m) combined in 7 different configurations. However, the sickle header was also comprised of 2 pairs (rear/front) of conditioners, the front pair being metal and the rear pair being rubber. Table 3-1 showed all settings applied to both windrowers.

2.3. Field description

The total number of experimental plots was 32 which were composed of 8 different treatments and 4 replications. The treatments were: the 7 different gap/pressure settings of Massey Ferguson 9185 (disc), and the standard setting of Massey Ferguson 9145 (sickle) which were represented in Table 3-1.

All plots and borders were 5 m wide and 30 m long in which 4 rows were spaced apart by 0.9 m. Each block was separated by borders.

2.4. Biomass samples

The total dry aboveground matter produce by the evaluated sorghum was approximately 6.3 Mg ha^{-1} and was established by collecting 0.25 m^2 samples from the all plots before harvesting. Sorghum was harvested on October 16, 2008. Biomass samples were collected after harvest and moisture content (%) was evaluated until it remained constant. Samples were collected daily in early afternoon, except for rainy days and subsequent wet days. However, biomass samples were collected 8 times from October, 16th to October 30th, where the collection days were: October 16th, 20th, 21th, 22th, 23th, 28th, 29th, and 30th. All plots were disturbed using a Frontier TD10E hay Tedder (Deere & Company, Moline, IL) on October 28th in order to achieve faster biomass drying.

Three handfuls of biomass subsamples were taken randomly from each plot, and placed in bags where the wet biomass weight was recorded. Biomass samples were dried at 55° C until constant weight was achieved. Wet-basis moisture content -M_{wb}(%) was calculated using the following formula:

$$M_{wb}(\%) = \frac{m_{H2O}}{m_{H2O} + m_{dm}} x100$$

Where:

M_{wb} (%)= wet-basis moisture content, m_{H2O} = mass of moisture in kg, and m_{dm} = mass of dry matter in kg.

2.5. Statistical Analysis

Statistical analyses were performed in a randomized complete block design (RCB) with eight different treatments as shown in Table 3-1. The predetermined significance level was $P \leq 0.10$ and Fisher's least-significant-difference test (LSD) was performed for means comparisons. The data were analyzed with GLM procedure using software SAS 9.1 (SAS Inst. Inc., Cary, NC)

3. RESULT AND DISCUSSIONS

3.1. Effect of different MF 9185's roller pressures on sorghum moisture content.

Results showed that higher pressures applied on rollers tended to speed the biomass drying process dry sorghum biomass faster than lower pressures (Figure 3-2). For all sampled days, rollers set to 7000 kPa were significantly more effective in drying biomass than rollers set to 0 kPa. This difference in pressure treatments was highest on October 30 (29.8 % vs. 15. 2 %, $P = 0.0025$).

Different results were found when comparing 3500 and 7000 kPa pressures. No significant differences were found between those applied pressures on October 22, 23, 28 and 29. Controversially, October 21 and 30 showed significant differences between different applied pressures. And, the last sampled day (October 30) had the highest difference between 3500 and 7000 kPa (24.2 % vs 15.2 %, $P = 0.0460$).

3.2. Effect of different MF 9185's roller gaps on sorghum moisture content.

Sorghum biomass tended to dry faster when rollers were contacting each other (Fig. 3 -3). Comparing two different gap sets: "O m gap front/rear" vs. "0.02 m gap front / 0 m gap rear", all sampled days showed numerically low moisture content values for "0 m gap front and rear" treatments. But, they were significant different on October 23, 28 and 30. Additionally, the last sampled day (October 30) showed averages of 19.8 % and 26.4 %, respectively for "0 m gap front/rear" and "0.02 m gap front / 0 m gap rear" treatments (*P* = 0.0712).

3.3. Interaction of different MF 9185's roller gaps and pressures on sorghum moisture content.

3.3.1. Day: 10/16/2008

Different moisture contents among treatments were observed 5 hours after harvest on October 16. Treatment 8 showed minimum moisture content (63.5 % ±0.02) followed by treatments 3 (63.8 % ±0.03), 2 (64.8 % ± 0.02), 5 (66.2 % ±0.03) and 6 (66.1 % ± 0.04), which showed no significant differences among each other. Treatment 1 (67 % ± 0.02) was considered not significantly different from treatments 2, 3, 5, and 6. Treatments 4 (69.8 % ±0.16) and 7 (70.7 % ±0.02) showed highest moisture content (Figure 3-4). The average temperature during October 16th was 20.5 ºC (AWIS Weather Services, Inc., 2010).

MF 9185 showed similar biomass moisture content to MF 9145 when set at 3500 or 7000 kPa; but MF 9185 had higher moisture content when set to 0 kPa. Therefore, higher pressures exposed more plant tissues to the atmosphere than low pressures which resulted in faster biomass drying over a short period of time.

3.3.2. Day: 10/23/2008

Seven days after harvest, treatment 3 (27.7 % ±0.053) and 2 (28.5 % ±0.062) showed reduced values of moisture content followed by treatments 8 (30.9 % ±0.065), 6 (31.6 % ±0.068) and 1 (33.4 % ±0.045), which showed no significant differences among each other. Treatment 5 (34.4 % ±0.075) was considered not significantly different from 1, 6 and 8. Thus, treatments 4 (43.8 % ±0.07) and 7 (56.5 % ±0.03) showed the highest moisture content, but they were not statistically different from each other (Fig. 3-5). All previous sampling days including October 20, 21 and 22 showed the same trend as October 23. Thus, the average temperature was 17.0 ºC during those 7 days, and 8 mm of precipitation was recorded on October 18th (AWIS Weather Services, Inc., 2010).

However, MF 9185 showed similar biomass moisture content to MF 9145 when rollers set to any pressure with 0 m gap, and when rollers submitted on 7000 kPa with 0.02 m gap in front roller. Additionally, moisture content was higher in MF 9185 plots than MF 9145 ones when rollers set with 0 and 3500 kPa or had at least a 0.02 m gap.

On October 28, the biomass moisture content had an average increment of 0.07% in all experimental plots due to 57 mm of precipitation on October 24 (AWIS Weather Services, Inc., 2010). Consequently, the sorghum biomass in all experimental plots was fluffed with the tedder to improve biomass drying.

3.3.3. Day: 10/30/2008

Fourteen days after harvest, biomass from treatment 3 (13.6 % ±0.037) and 6 (16.8 % ±0.054) showed minimum moisture content followed by treatments 2 (21.8 % ±0.044), 1 (24.0 % ±0.058), 8 (24.1 % ±0.039) and 5 (26.6 % ±0.042), which were not significantly different among each other. Treatment 4 (35.6 % ±0.048) was considered not significantly different from 5. Thus, treatments 7 (43.2 % ±0.021) showed the highest moisture content. (Figure 3-6). The sampled previous day (October 29) showed the same trend as October 30. Thus, the average temperature from October 24 to 30 was 11.7 ºC (AWIS Weather Services, Inc., 2010).

However, biomass harvested from plots where the MF 9185 was used for harvesting showed 13.6 % and 16.8 % of moisture content for treatments 3 and 6, respectively. It has been recommended that moisture content of biomass samples fall between 15.0 – 20.0 % of moisture content (Wilcke et al., 1998). Therefore, MF 9185 was able to dry sorghum biomass when rollers were set on 7000 kPa with “0 m gap front/rear” and “0.02 m gap front / 0 m gap rear”. Additionally, MF 9145 exceeded the recommended values by still containing 24.1 % moisture after 14 days.

4. CONCLUSION

1. MF 9185 windrower dried sorghum biomass faster when higher pressures were applied on conditioner rollers. Therefore, pressures of 7000 kPa caused reduced moisture content values as compared to 0 and 3500 kPa after 15 days of harvest.

2. No gap between the rollers on the MF 9185 conditioner dried sorghum biomass faster than 0.02 m gap.

3. MF 9185 windrower was considered more efficient in drying sorghum biomass than MF 9145 when conditioner rollers were set with “0 gap front/rear, 7000 kPa”. The settings “0 m gap front and rear, 7000 kPa” and “0.02 gap front / 0 m gap rear, 7000 kPa” reduced moisture content to values lower than 20%, which was considered the maximum moisture content value for storing biomass.

Therefore, high biomass crops such as sorghum were successfully dried for baling in southeastern U.S. condition, when using MF 9185 set with both “0 m gap front and rear, 7000 kPa” and “0.02 gap front / 0 m gap rear, 7000 kPa”.

5. REFERENCES

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Table 3-1: Settings applied in both self-propelled windrowers. Massey Ferguson 9185 (disc header) and Massey Ferguson 9145 (sickle header).

Self –propelled Windrowers	Treatment Number	Pressure (KPa)	Gap (m) front	rear
Massey Ferguson 9185 – disc header				
	1	0	0	0
	2	3500	0	0
	3	7000	0	0
	4	0	0.02	0
	5	3500	0.02	0
	6	7000	0.02	0
	7	0	0.02	0.02
Massey Ferguson 9145 – sickle header				
	8	standard	standard	

Table 3-2: Daily average temperature and precipitation during drying period (AWIS Weather Services, Inc., 2010).

Dates	**Average Temperature (ºC)**	**Precipitation (mm)**
10/16/2008	20.5	0
10/17/2008	22.7	0
10/18/2008	17.2	8
10/19/2008	14.4	0
10/20/2008	12.7	0
10/21/2008	13.3	0
10/22/2008	16.6	0
10/23/2008	18.3	0
10/24/2008	15.5	57
10/25/2008	13.8	0
10/26/2008	13.8	0
10/27/2008	16.1	0
10/28/2008[*]	8.3	0
10/29/2008	6.1	0
10/30/2008	8.3	0
10/31/2008	12.2	0

[*] Plots disturbed using a Frontier TD10E hay Tedder.

Figure 3-1: Massey Ferguson 9185 – disc header (A); and Massey Ferguson 9145 – sickle header (B).

Figure 3-2: Sorghum moisture content (wet basis, %) for different disc header pressures for all sampled days.

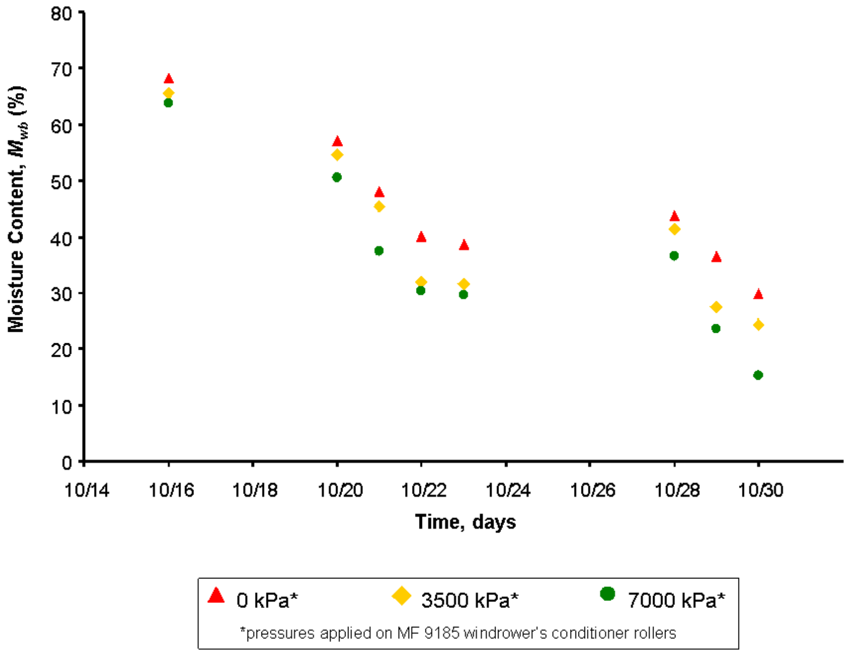

Figure 3-3: Sorghum moisture content (wet basis, %) for different disc header gaps in all sampled days.

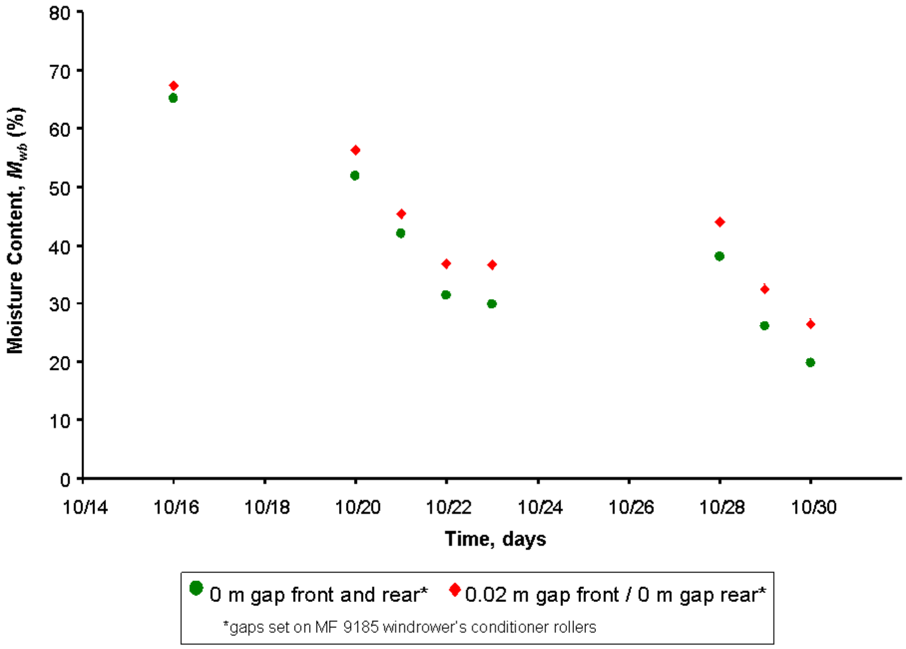

Figure 3-4: Sorghum moisture content (wet basis, %) for all treatments on October 16, 2008.

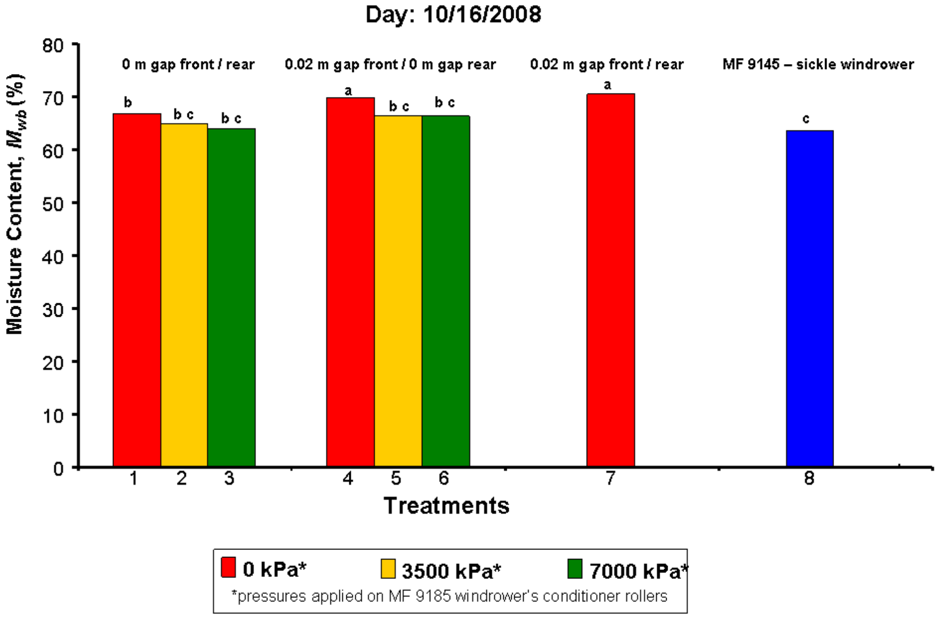

Figure 3-5: Sorghum moisture content (wet basis, %) for all treatments on October 23, 2008.

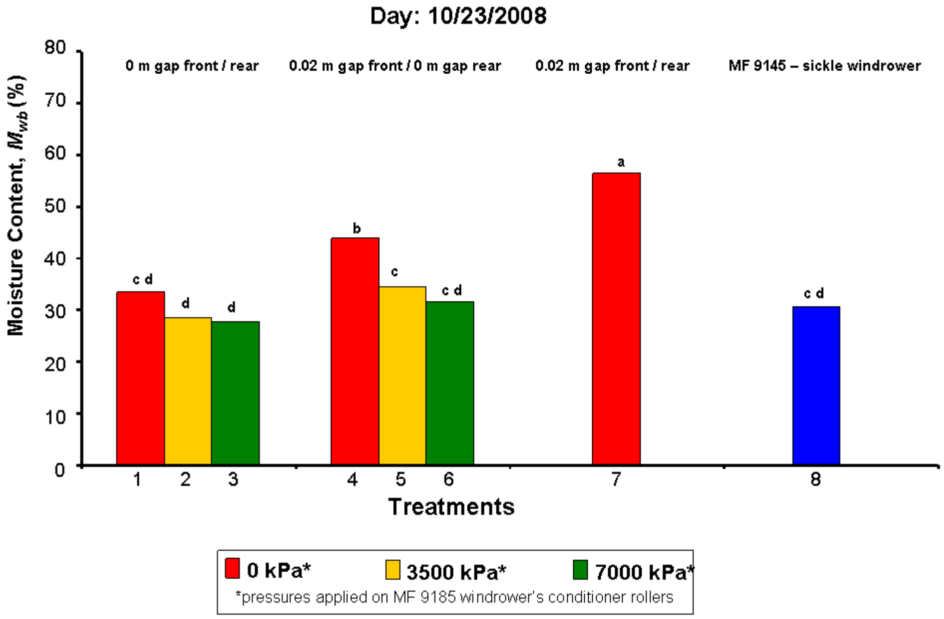

Figure 3-6: Sorghum moisture content (wet basis, %) for all treatments on October 30, 2008.