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Inconsistent Yield Response of Forage Sorghum to Tillage and Row Arrangement

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Abstract: Forage sorghum is an alternative source for biofuel feedstock production and may also provide forage for livestock operations. Introducing biofuel feedstock as a dual-use forage to livestock operations has the potential to increase the adoption of biofuel feedstock production. However, additional technical agronomic information focusing on tillage, row arrangement, and harvest date for forage sorghum planted into pasturelands intended for dual use is needed. Three tillage treatments, disking and rototilling (RT), chisel plow (CP), and no tillage (NT), and two row arrangement treatments, single-row planting with 76.2 cm rows and twin rows of 17.8 cm on 76.2 cm centers, were tested for effects on forage sorghum yield in a 3-cut system. This study tested two sites in Booneville, AR, from 2010 to 2012. Several interactions with year were detected, likely due to large precipitation differences within and among years. The year greatly affected the yield, with greater ($p < 0.05$) yields in year 1 compared to years 2 and 3 in both locations. No till resulted in lower yields in some years and harvest dates, though no clear trend was detected among tillage treatments over years. Twin rows generally did not improve yield, except for the third harvest date at one location. No strong trends for tillage or row arrangement effects were observed in this study. Inconsistencies may have resulted from the strong influence of year or interactions of multiple factors, which may challenge producers interested in utilizing forage sorghum for biofuels and livestock feed.

Keywords: forage sorghum; tillage; twin row; biofuels; biomass



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1. Introduction

Cellulosic feedstocks from grain and forage sorghum (*Sorghum bicolor* L.) are acceptable sources for bioethanol production [1,2]. Sorghums are tolerant to drought stress [3], with greater growth and yield in arid environments compared to corn [4], also commonly used for bioethanol. Forage sorghums can also be grazed by or harvested for livestock, providing feed of adequate quality for cattle production [5,6]. With the potential for dual use, both biofuel and livestock feed, integrated crop–livestock operations may be significant in expanding the use of forage sorghum for biofuels. Forage sorghum could be planted with the intention to harvest for biofuel, but in the event of feed shortage, it could be redirected to livestock feed. However, additional agronomic evaluations of reduced tillage systems, seed bed preparation for transitioning from pasture to forage sorghum production, and planting strategies that optimize yield, such as single or twin row, are still needed.

Reduced tillage systems may be a priority for integrated farms. Marginal lands, or areas otherwise prone to soil erosion under tillage, are often relegated to grazing or forage acreage [7]. Reduced tillage results in greater residues on the soil surface, providing several soil health benefits, including improved soil structure, reduced soil erosion, and increased soil organic matter, while tillage may exacerbate these issues on marginal lands [8].

Sorghum yield responses to tillage vary widely by variety, previous field management, soil type, and climatic conditions. A 5 yr, no-till study in the southern high plains, with a

wheat–sorghum–graze rotation, observed reduced sorghum yields, likely due to increased soil water storage, and recommended tillage prior to sorghum planting [9], while an 18 yr study conducted in Nebraska determined that no-till plots had greater sorghum yields compared to tilled after wheat harvest in a wheat–sorghum–fallow rotation [10]. In short, in a two-year study in Alabama, sorghum grain yields were greater when no till planted into crimson clover or wheat than tilled systems [11]. Though yield responses may vary, economic evaluations generally agree that tillage systems require greater costs than no-till systems that are not always recouped by greater crop production [12].

Crop row arrangement impacts yield potential [13–16]. Increased corn yields of 2.7–10% have been observed with row spacing narrower than 76.2 cm under favorable growing conditions, while yields similar to those of wider rows (≥ 76.2 cm) have been observed under unfavorable growing conditions [16]. Greater yields in narrower rows (< 76.2 cm) may result from greater light interception [17] and greater space between plants in a row that reduce competition among plants [18]. Though, yield advantages are inconsistent, with some studies observing a yield reduction or no yield advantage [15,19,20].

The twin-row arrangement generally involves two rows planted close together, usually within 15–20-cm, with the twin rows 76.2 cm apart (76.2 cm centers). Twin rows have been shown to increase profitability and water conservation for soybean and cotton crops in areas with irrigation agriculture, such as the Mississippi River Valley Alluvial Aquifer [21]. Less information is available for dry land forage sorghum, but interactions may exist between row arrangement and arid environments, with advantages to wider rows when water is limited [22]. In Texas, sorghum yield under irrigation was greater with twin rows (30 cm) to single rows (96.5 cm) at the same population (161,000–198,000 plants ha^{-1} ; [23]). Novacek et al. [15] observed similar yields among twin rows (20 cm on 76 cm centers) under irrigation versus single rows (76 cm) in dry land conditions.

Before dual-use livestock feed and biofuel feedstock systems can be recommended for integrated farms, research is needed on successful forage sorghum establishment methods on pasture lands and row-planting configurations that may be beneficial in dry land environments. Our overall objective was to evaluate tillage type and single- and twin-row arrangements on forage sorghum yield in a 3-cut system for biofuel feedstock, considering its alternative use as livestock feed for integrated farms.

2. Materials and Methods

2.1. Description of Field Site and Experimental Layout

Two sites of 0.12 ha each at the USDA-ARS Dale Bumpers Small Farms Research Center near Booneville, AR, USA (35.1401° N, 93.9216° W), were selected for the study area, the “north location” (NL) and “south location” (SL). The previous management of the research site was common bermudagrass, continuously grazed by cow–calf pairs. The soil type on both sites was Leadvale silt loam (fine-silty, siliceous, semiactive, thermic Typic Fragiudult). Pre-study soil fertility analyses for NL indicated 20.3 and 97.0 ppm for P and K, respectively, and a pH of 6.25, and 39.3 and 73.3 ppm for P and K, respectively, and a pH of 6.25 for SL (University of Arkansas Diagnostic Laboratory, Fayetteville, AR, USA). The experimental design was a randomized complete block, 3×2 factorial design, with 3 tillage treatments and single- or twin-row arrangement and 4 blocks. Each site was divided into four $9.1 \text{ m} \times 18.3 \text{ m}$ blocks and contained 6 experimental units of $9.14 \text{ m} \times 3.05 \text{ m}$. Treatments were allocated randomly to one of six plots within each block in year one. Plot assignments remained the same for all three years, 2010–2012.

2.2. Tillage and Planting Treatments

Three tillage treatments of different intensities were implemented prior to planting. The most intense tillage (RT), designed to leave the least amount of residue, was created by disking, followed by rototilling (Howard Rotovator 41–90, Napa, CA, USA). The medium-intensity tillage (CP), designed to leave partial residue, was accomplished with a chisel plow (W.T. Graham, Amarillo, TX, USA). The final treatment was no till (NT), designed to

leave the most amount of residue. Tillage was completed annually 1 d prior to planting for RT and CP.

Single-row planting with 76.2 cm rows was compared to twin-row arrangement of 17.8 cm on 76.2 cm centers. Single rows were planted with a no-till drill (John Deere 1590; Deere & Company, Moline, IL, USA). Twin rows were planted with a twin-row planter prototype (Hesston Manufacturing Co., Hesston, KS, USA). Each year, all plots received glyphosate [N-(phosphonomethyl) glycine] at a rate of 1.0 kg ae ha⁻¹ one week prior to planting and received 670 kg ha⁻¹ of 12-12-33 (N-P-K) fertilizer at planting and 67 kg ha⁻¹ of N when plants reached 30.5 cm or 30 d after planting. Forage sorghum cv. 'Enorma' was planted on NL for all three years. Forage sorghum cv. 'SCG BMR 105' was planted in SL in 2010, but the variety was unavailable thereafter and cv. 'Bundle King BMR' was planted in 2011 and 2012. The seeding rate for all forage sorghum varieties was 7.8 kg ha⁻¹. Planting dates on both sites were 5 June 2010, 14 June 2011, and 15 May 2012. Saturated soils prevented early planting in 2010 and 2011.

2.3. Data Collection

Forage sorghum was harvested three times per year in both locations. The first harvest date (H1) was determined based on seed supplier recommendations for estimated number of days from planting to maximum biomass production, as would be recommended for production for biofuel feedstock. The second date (H2) was approximately 30 d after the first harvest, and the final harvest (H3) was 30 d after the second harvest or just prior to a forecasted freeze. Each year, harvest dates were the same for NL and SL. Forage sorghum was harvested on 10 September, 21 October, and 4 November in year 1; 15 September, 13 October, and 20 October, in year two; and 16 August, 12 September, and 19 October, in year three. All plants within 1.5 m of two adjacent rows were harvested at 15.2 cm stubble height and weighed. A subsample of five plants was taken from the bulk sample, weighed, and dried at 55 °C until no further weight loss to determine dry matter for the bulk sample.

2.4. Statistical Analysis

Although the treatments and experimental design were replicated on both sites, NL and SL, two different forage sorghum varieties were used, and, therefore, sites were analyzed separately. Response variables were tested for normality with the UNIVARIATE procedure of SAS and met the assumptions of normality. The GLIMMIX procedure in SAS (Version 9.4; SAS Institute) was used to test the effects of year, tillage, row arrangement, and their interactions, with block as a random variable and harvest dates treated as repeated measures, on yield per harvest. For total yield, yields from each harvest per year were summed and analyzed with GLIMMIX procedure in SAS for effects of year, tillage, row arrangement, and their interactions with block as a random variable. For all variables, the LSMEANS option was used to generate individual treatment means. Significance was declared at $p \leq 0.05$.

2.5. Environmental Data

Temperature and precipitation for 2010–2012 and the 30 yr average (Figure 1) show slightly above-normal temperatures for all three years and highly variable precipitation. In 2010, precipitation was low in early spring and at planting, but above-average precipitation occurred in July and September, providing excellent growing conditions for forage sorghum. Drought occurred in both 2011 and 2012. In 2011, precipitation was abundant in April and May, but June, July, and September experienced lower-than-average rainfall. Historic drought occurred in 2012 beginning in April and extended throughout the growing season through September. Precipitation varied greatly over the three-year study.

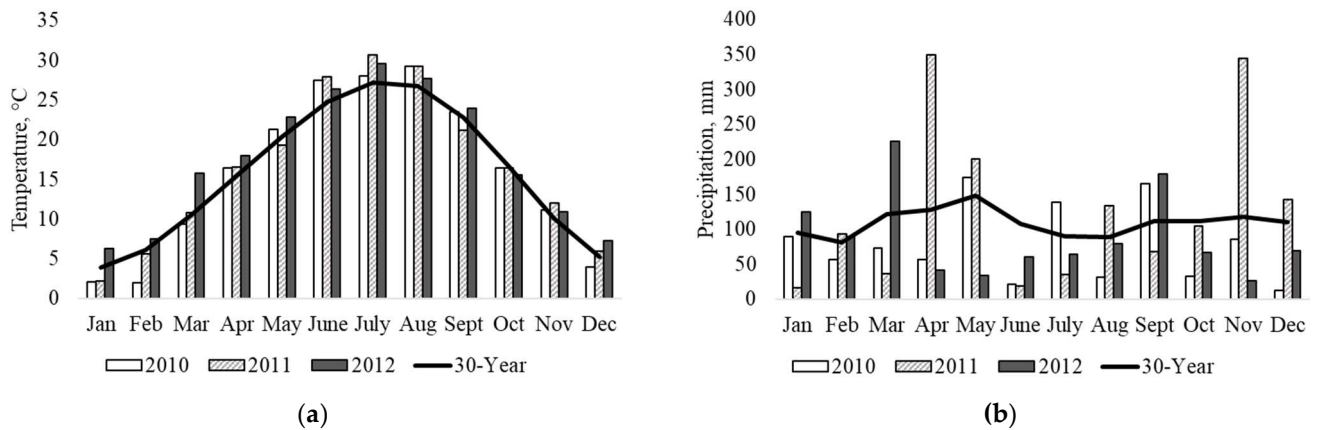


Figure 1. (a) Average monthly temperature and (b) total monthly precipitation near Booneville, AR, for 2010, 2011, 2012, and the 30-year average (1990–2020). Weather obtained from the National Climatic Data Center (NOAA; <https://www.ncdc.noaa.gov/cdo-web> accessed on 9 May 2024).

3. Results

3.1. North Location

Yield per harvest was affected by a year $\times$ harvest date $\times$ row arrangement interaction ($p = 0.003$; Figure 2a). In the three-way interaction, the greatest differences appear to be among years, with the greatest yields in 2010 when precipitation was greater. Yields from H1 were greater ($p < 0.05$) than all other harvest dates in 2010, 2011, and for 2012 except for yields from single rows for H3.

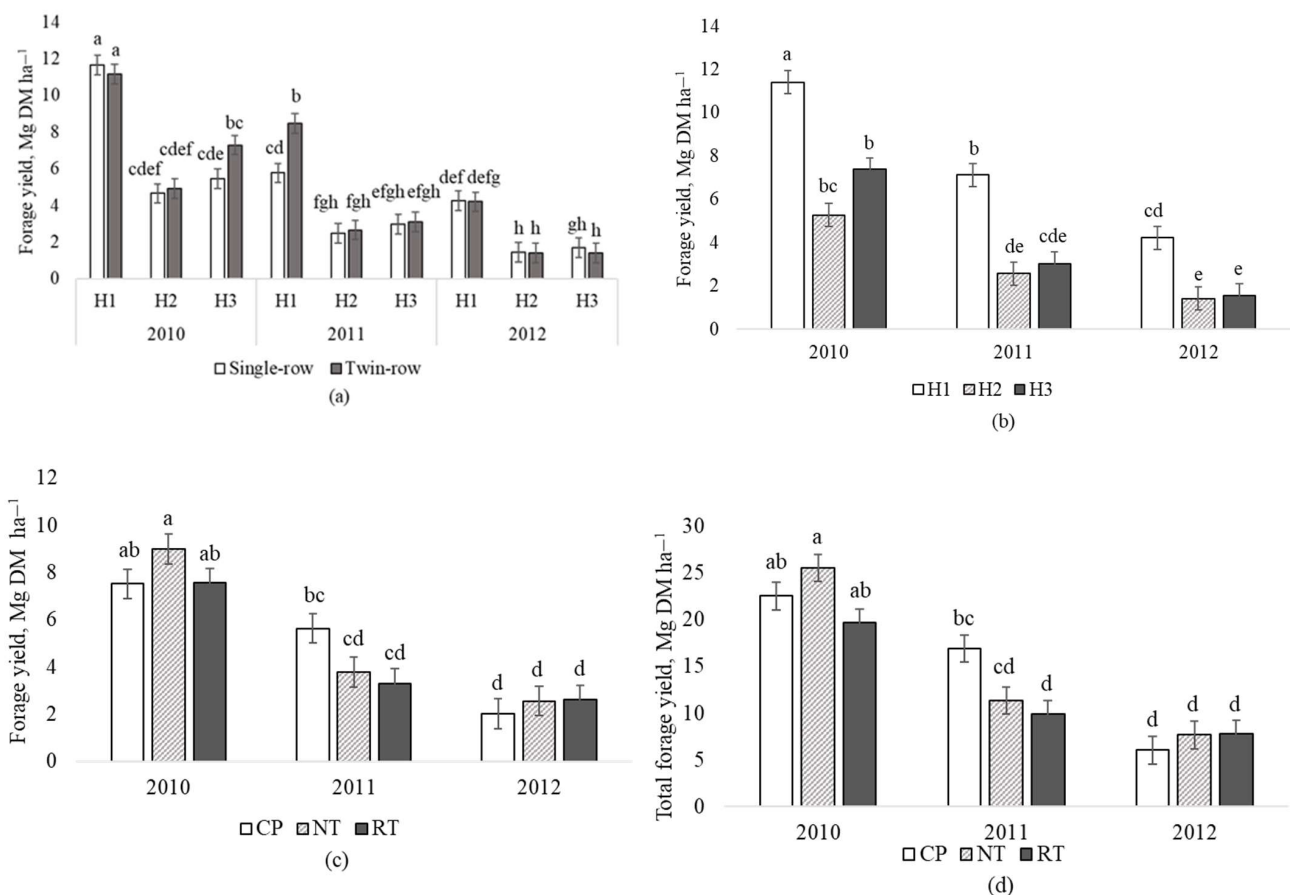


Figure 2. North Location: (a) Dry matter (DM) yields for forage sorghum planted in twin rows and single rows at harvest date 1 (H1), harvest date 2 (H2), and harvest date 3 (H3) for 2010, 2011, and 2012.

Effects of row arrangement $\times$ harvest date $\times$ year. $p < 0.01$. SEM = 0.53 Mg DM ha⁻¹. **(b)** Dry matter yields for forage sorghum from H1, H2, and H3 in 2010, 2011, and 2021. Effects of year $\times$ harvest date. $p < 0.01$. SEM = 0.54. **(c)** Dry matter yields for forage sorghum after chisel plow (CP), no-till (NT), or rototilling in 2010, 2011, and 2012. Tillage $\times$ year. $p < 0.01$. SEM = 0.63. **(d)** Total forage sorghum DM yields for CP, NT, and RT for 2010, 2011, and 2012. Tillage $\times$ Year $p < 0.01$. SEM = 1.47. Means without a common letter differ ($p < 0.05$).

Multiple two-way interactions were detected for yield per harvest, year $\times$ harvest date ($p < 0.01$; Figure 2b) and year $\times$ tillage ($p < 0.01$; Figure 2c). The greatest ($p < 0.05$) yields were consistently observed in H1 across years (Figure 2b), while H2 and H3 did not differ within years. Yield per harvest (Figure 2c) was greatest ($p < 0.05$) in 2010 and for CP in 2011, likely due to a drought that occurred in 2011 and 2012.

Total yield, the sum of all harvests per year, was affected by a year $\times$ tillage interaction ($p < 0.01$; Figure 2d). The total yield differed greatly among years and generally decreased per year from 2010 to 2012 due to increasingly lower precipitation through the experiment. In 2011, total yields were greater ($p < 0.05$) for CP compared to RT, though NT did not differ from either tillage treatment; total yield did not differ by tillage treatments within the year for 2010 or 2012.

3.2. South Location

No three-way interactions were observed for SL, but two-way interactions were observed for harvest date $\times$ row arrangement ($p = 0.03$; Figure 3a), and several year interactions were observed, including year $\times$ tillage ($p < 0.01$; Figure 3b), year $\times$ row arrangement ($p < 0.01$; Figure 3c), and year $\times$ harvest date ($p < 0.01$; Figure 3d). Yield per harvest date was greater ($p < 0.05$) with the twin-row arrangement for H3 across years; other row arrangements and harvest dates did not differ. In 2010, no differences in yield per harvest were observed for tillage treatments (Figure 3b), but yields for NT were lower ($p < 0.05$) in 2011 and 2012, while CP and RT did not differ. The yield per harvest was not affected by row arrangement in 2010 or 2012 (Figure 3c), but the yield from twin rows was greater ($p > 0.05$) than single rows in 2011. However, the yields per harvest for single rows in 2011 were considerably lower ($p < 0.05$) than all years, including 2012 when drought was more severe. The harvest date and year affected the yield per harvest, yields for each harvest differed ($p < 0.05$) in 2010, with the greatest yields ranked from H2, H1, to H3, while yields in 2011 did not differ among harvest dates, and in 2012, yields were greater ($p < 0.05$) for H3, while H1 and H2 did not differ from each other.

The total yield was affected by year $\times$ row arrangement ($p < 0.01$) and year $\times$ tillage interactions ($p < 0.01$). The total yield was greatest in 2010 and for CP in 2012 (Figure 4). Tillage treatments did not affect the yields in 2010, though lower yields were observed for NT in 2011 and 2012. The CP and RT tillage treatments did not differ from one another in 2011 or 2012. No differences in row arrangement were observed for 2010 or 2012, but the yield for twin rows was greater ($p < 0.01$) than single rows in 2011.

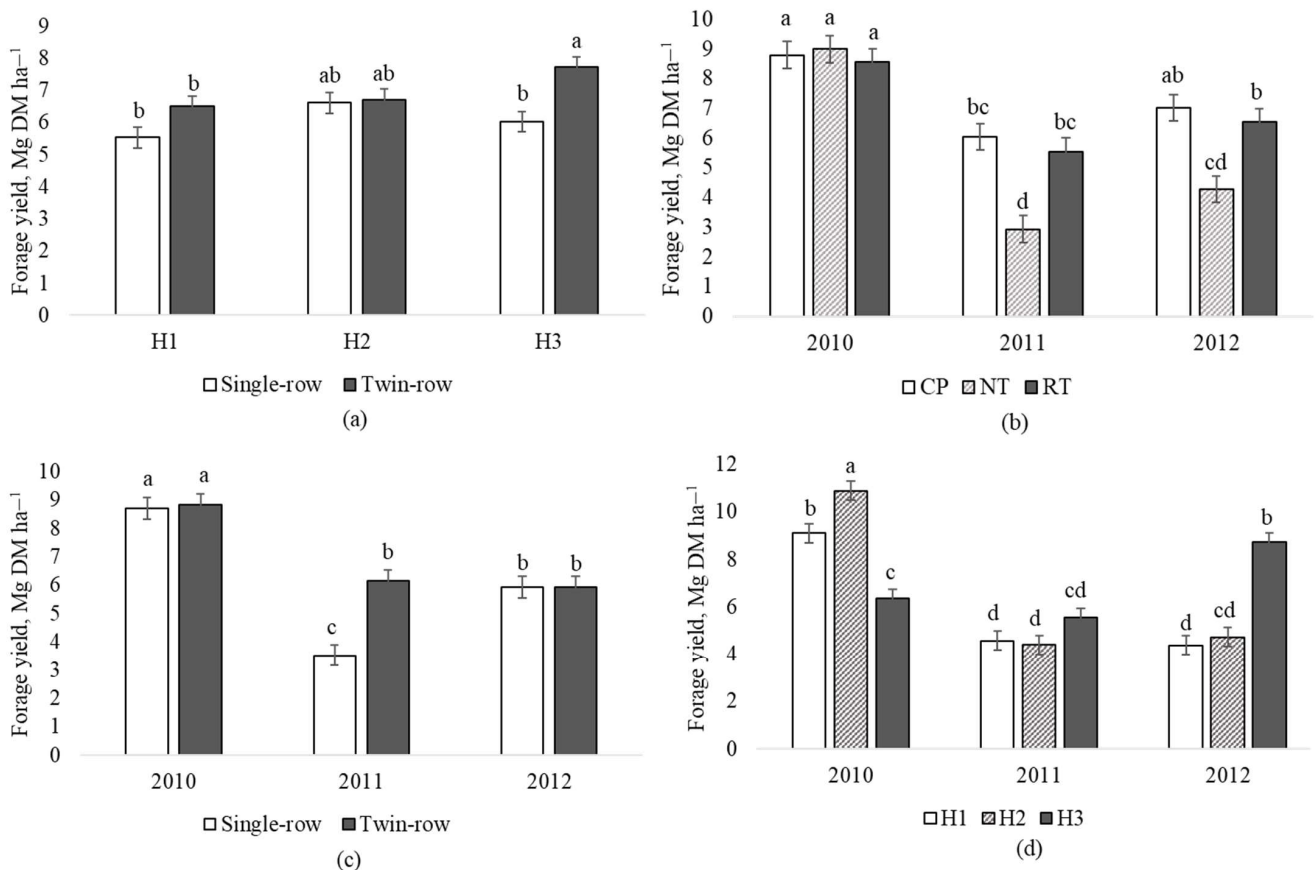


Figure 3. South Location: (a) Dry matter (DM) yields across years for forage sorghum planted in twin-row and single row at harvest date 1 (H1), harvest date 2 (H2), and harvest date 3 (H3). Effects of row arrangement $\times$ harvest date. $p = 0.03$. SEM = 0.32 Mg DM ha⁻¹. (b) Dry matter yields for forage sorghum after chisel plow (CP), no-till (NT), or rototilling in 2010, 2011, and 2012. Tillage $\times$ year. $p < 0.01$. SEM = 0.45. (c) Dry matter yields for forage sorghum planted in twin-row and single row in 2010, 2011, and 2012. Tillage $\times$ year. $p < 0.01$. SEM = 0.37. (d) Dry matter yields for forage sorghum from H1, H2, and H3 in 2010, 2011, and 2012. Effects of year $\times$ harvest date. $p < 0.01$. SEM = 0.40. Means without a common letter differ ($p < 0.05$).

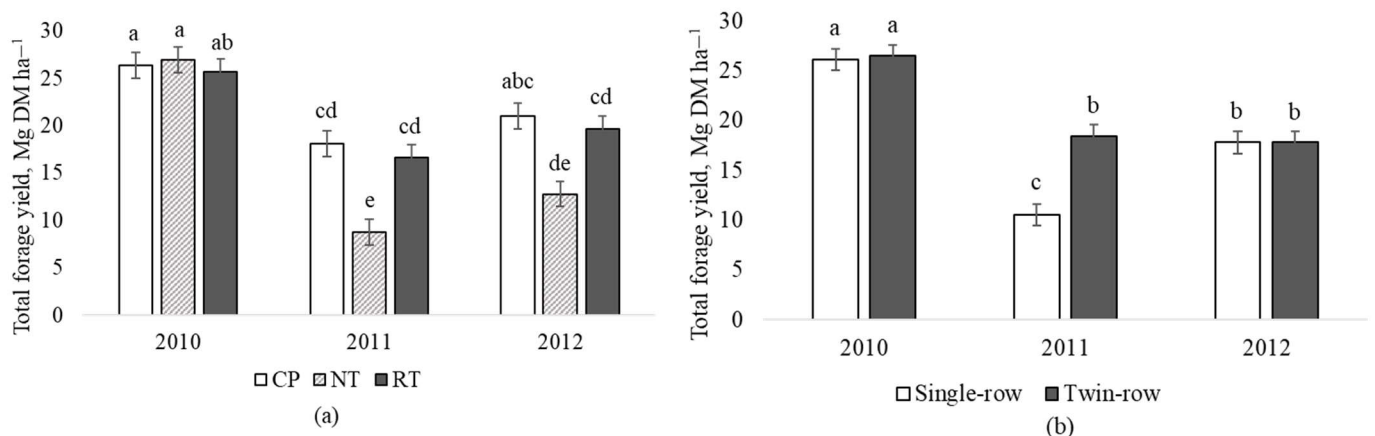


Figure 4. South Location: (a) Total dry matter (DM) yields for forage sorghum planted after chisel plow (CP), no-till (NT), or rototilling (RT) in 2010, 2011, and 2012. Tillage $\times$ year. $p < 0.01$. SEM = 1.35 Mg DM ha⁻¹. (b) Total dry matter (DM) yields for forage sorghum planted in twin-row and single in 2010, 2011, and 2012. Tillage $\times$ year. $p < 0.01$. SEM = 1.12 Mg DM ha⁻¹. Means without a common letter differ ($p < 0.05$).

4. Discussion

Due to the use of different forage sorghum varieties in NL and SL, locations were analyzed separately. However, the questions and results were similar, and, therefore, results from both locations will be discussed in this section together. Additionally, it is important that caution be used when interpreting data from SL. A different forage sorghum variety was used in 2010 than in 2011 and 2012, and though strongly diverse environmental conditions appear to have driven yield differences among years, the change in variety is a confounding factor with year, and it is unknown which factor most contributed to differences among treatments. Further, the variability in precipitation within and among years was a substantial factor in this study and may potentially mask impacts from other implemented factors.

No trends in tillage effects on forage sorghum yield were observed for NL. Forage sorghum yields were reduced with NT in 2011 and 2012 in SL. Differences in SL may be caused by the different forage sorghum variety used, and without soil moisture and temperature data, interpretations of the effects of tillage on forage sorghum yield are limited. Several studies have observed greater or equal yields for grain sorghum in no-till systems [24,25], while others observed greater productivity in tilled systems [26–28]. Soil moisture and temperature affect the timing of germination and plant emergence [29,30], and both soil moisture and temperature are influenced by tillage and crop residue. Surface residue cover in no-till systems can insulate the soil surface and prevent soil drying, thereby preserving soil moisture for seed germination and crop growth [31]. Generally, areas with low annual rainfall benefit from the moisture conservation provided in no-till systems [32,33]. However, tillage in clay-based or poorly drained soils may improve yield [27,34,35] by creating a seedbed with improved drainage and higher soil temperatures because of low surface residue [36]. Surface residues also have the potential to interfere with adequate seed to soil contact in no-till planting because of inadequate cutting by double-disk openers that cause “hair pinning” [37]. When hair pinning occurs, residues enter the planting channel with the seed, preventing adequate seed to soil contact [37].

Tillage is an important consideration for introducing dual-purpose biofuel production on integrated farms, especially those that have significant acreage in pasture. Pasture-land is generally relegated to non-productive or highly erodible landscapes [7] better suited to conservation tillage or NT establishment. Although NT may have resulted in lower yields in some years, producers will need to weigh the environmental benefits (reduced soil erosion, reduced soil compaction, increased microbial activity [38]) to the potential for more successful establishment and greater yields with tillage in some years. Tillage also has important economic considerations, with greater costs associated with tillage that are not always recouped with increased yields [12]. Short-term mixed results from no-till establishment may discourage some integrated farms from adoption, but analysis of long-term studies indicates no statistical difference in long-term yields from no till compared to conventional tillage for corn, soybean, and wheat [39]. The long-term data also indicate that profits per area tend to be greater for no till compared to conventional tillage due to lower farm operation costs with no till [39].

For NL, no clear trends were observed for the effects of row arrangement on yield, though twin rows produced greater yields in 2011 for H1. For SL, twin rows increased the yield in 2011, and for H3, across years. When planted at the same population density, twin rows allow for more intra-row spacing, reducing interspecies competition [18], potentially resulting in greater yields. Twin rows also allow for greater capture of solar radiation [15,17,40] and weed suppression [41]. Snider et al. [42] observed greater forage sorghum yields with 19.05 cm spacing compared to 38.1 cm and 76.2 cm at two different sites, one each in Alabama and Arkansas, over three years. Snider et al. [42] concluded that the greater yield was a result of increased stem density. Wider row spacing may improve the yield in crops in dry lands, while twin rows have been shown to have greater yields than single rows with high-quality soils and under optimal growing conditions [15,22,43,44]. Fernandez et al. [23] observed greater sorghum grain yields in the twin-row configuration

compared to single rows under irrigation, but no difference in non-irrigated plots, indicating that narrow row spacing may be advantageous under optimal conditions but not different from single rows under conditions of limited soil moisture. It is possible that the increased yields for twin rows in H1 in 2011 for NL were a result of twin rows, taking advantage of early adequate moisture provided by heavy April and May precipitation, and single rows were unable to compensate when drought began in July and extended through the fall, resulting in similar yields in H2 and H3.

In SL, twin rows produced greater forage sorghum yields in 2011 but not in 2010 or 2012. Although forage sorghum varieties can vary greatly in response to planting density [45], potentially, the twin-row arrangement was ideal for the variety planted in 2011, and conditions were such that the yield advantage could be expressed, but not in 2012 because of severe drought conditions. Additionally, for SL, twin rows from H3 outyielded single rows at H3 across years. Generally, in studies conducted throughout the Midwest, single-row and twin-row arrangements have not resulted in a yield advantage in corn grain systems [40,46]. However, greater solar radiation reception has been observed in corn planted in twin rows up to the V9 growth stage but not at earlier or later growth stages [47]. Similarly, greater solar radiation capture was observed in early canopy closure in twin rows, though the radiation interception advantage declined at later vegetative stages and with increasing plant density [40]. Potentially, forage sorghum in the twin-row configuration experienced accelerated regrowth due to increased solar radiation reception, which may have been particularly important for H3 with decreasing day length. However, this is speculative as the response is likely very variety dependent and NL did not follow a similar trend.

The total yield was exceptional for both experiments in 2010, averaging 22.6 Mg DM ha⁻¹ for NL and 26.3 Mg DM ha⁻¹ for SL. However, the yield at each harvest may be a more important factor to consider for dual-use biofuel feedstock and livestock feed systems. When considering a variety for dual use, the regrowth potential may be the greater benefit as it provides more management flexibility. Forage sorghum yield can be spread across multiple cuttings and, considering weather and feed inventory, the producer can keep forage for livestock feed or sell for biofuel feedstock without assuming major yield losses in following cuttings. For example, in NL, greater forage sorghum yields at H1 indicate the correct estimation for peak biomass production, the first cutting could be sold as a biofuel feedstock, and regrowth could be reserved for livestock feed. For SL, yields at harvest differed by year and are also likely confounded by the change in variety. However, it appears that peak biomass may have occurred later for the variety in 2010, based on the greater yield in H2 in SL. If that is consistently true, a producer could graze early in the season and sell the regrowth for biofuel feed stock. Further, if historic drought occurs, such as in 2012, the producer may also choose to keep all forage for livestock, buffering the impacts of drought on the livestock operation.

5. Conclusions

Our findings, while variable, support the literature that suggests no-till establishment can result in reduced yields in some instances, but not consistently, and twin rows, overall, do not result in a greater yield advantage, as compared to single-row arrangements. Differences in forage sorghum yield at different harvest dates also indicate the potential of dual-use forage sorghum. Forage sorghum in a multi-harvest system provides flexibility to sell biofuel feedstock when growth is optimal or redirect to livestock feed if environmental conditions result in low forage inventory. Overall, despite the potential of forage sorghum, the lack of clear trends across both studies indicates the influence of multiple factors and interactions that cause inconsistencies in the forage sorghum yield, which may challenge producers interested in dual-use forage sorghum systems.

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References

1. Szambelan, K.; Nowak, J.; Frankowski, J.; Szwengiel, A.; Jeleń, H.; Burczyk, H. The comprehensive analysis of sorghum cultivated in Poland for energy purposes: Separate hydrolysis and fermentation and simultaneous saccharification and fermentation methods and their impact on bioethanol effectiveness and volatile by-products from the grain and the energy potential of sorghum straw. *Bioresour. Technol.* **2018**, *250*, 750–757. [[PubMed](#)]
2. Batog, J.; Frankowski, J.; Wawro, A.; Lacka, A. Bioethanol production from biomass of selected sorghum varieties cultivated as main and second crop. *Energies* **2020**, *13*, 6291. [[CrossRef](#)]
3. Safian, N.; Naderi, M.R.; Torabi, M.; Soleymani, A.; Salemi, H.R. Corn (*Zea mays* L.) and sorghum (*Sorghum bicolor* (L.) Moench) yield and nutritional quality affected by drought stress. *Biocatal. Agric. Biotechnol.* **2022**, *45*, 102486. [[CrossRef](#)]
4. Bhattarai, B.; Singh, S.; West, C.P.; Ritchie, G.L.; Trostle, C.L. Effect of deficit irrigation on physiology and forage yield of forage sorghum, pearl millet, and corn. *Crop Sci.* **2020**, *60*, 2167–2179. [[CrossRef](#)]
5. Dann, H.M.; Grant, R.J.; Cotanch, K.W.; Thomas, E.D.; Ballard, C.S.; Rice, R. Comparison of brown midrib sorghum-sudangrass with corn silage on lactational performance nutrient digestibility in Holstein dairy cows. *J. Dairy Sci.* **2008**, *91*, 663–672. [[CrossRef](#)] [[PubMed](#)]
6. McCuiston, K.C.; McCollum, F.T., III; Greene, L.W.; MacDonald, J.; Bean, B. Performance of stocker cattle grazing 2 sorghum-sudangrass hybrids under various stocking rates. *Prof. Anim. Sci.* **2011**, *27*, 92–100. [[CrossRef](#)]
7. Wu, L.; Wu, L.; Bingham, I.J.; Misselbrook, T.H. Projected climate effects on soil workability and trafficability determine the feasibility of converting permanent grassland to arable land. *Agric. Syst.* **2022**, *203*, 103500. [[CrossRef](#)]
8. Kumar, K.; Goh, K. Crop residues and management practices: Effects on soil quality. Soil nitrogen dynamics, crop yield, and nitrogen recovery. *Adv. Agron.* **2000**, *68*, 197–319.
9. Baumhardt, R.L.; Schwartz, R.C.; MacDonald, J.C.; Tolk, J.A. Tillage and cattle grazing effects on soil properties and grain yields in a dryland wheat-sorghum-fallow rotation. *Agron. J.* **2011**, *103*, 914–922. [[CrossRef](#)]
10. Wicks, G.A.; Smika, D.E.; Hergert, G.W. Long-term effects of no-tillage in a winter wheat (*Triticum aestivum*)-sorghum (*Sorghum bicolor*)-fallow rotation. *Weed Sci.* **1988**, *36*, 384–393. [[CrossRef](#)]
11. Bishnoi, U.R.; Mays, D.A.; Fabasso, M.T. Response of no-till and conventionally planted grain sorghum to weed control method and row spacing. *Plant Soil* **1990**, *129*, 117–120. [[CrossRef](#)]
12. Varner, B.T.; Epplin, F.M.; Strickland, G.L. Economics of no-till versus tilled dryland cotton, grain sorghum, and wheat. *Agron. J.* **2011**, *103*, 1329–1338. [[CrossRef](#)]
13. Porter, K.B.; Jensen, M.E.; Sletten, W.H. The effect of row spacing, fertilizer and planting rate on the yield and water use of irrigated grain sorghum 1. *Agron. J.* **1960**, *52*, 431–434. [[CrossRef](#)]
14. Grichar, W.J. Row spacing, plant populations, and cultivar effects on soybean production along the Texas Gulf Coast. *Crop Manag.* **2007**, *6*, 1–6. [[CrossRef](#)]
15. Novacek, M.J.; Mason, S.C.; Galusha, T.D.; Yaseen, M. Twin rows minimally impact irrigated maize yield, morphology, and lodging. *Agron. J.* **2013**, *105*, 268–276. [[CrossRef](#)]
16. Licht, M.A.; Parvej, M.R.; Wright, E.E. Corn yield response to row spacing and plant population in Iowa. *Crop Forage Turfgrass Manag.* **2019**, *5*, 1–7. [[CrossRef](#)]
17. Andrade, F.H.; Calviño, P.; Cirilo, A.; Barbieri, P. Yield responses to narrow rows depend on increased radiation interception. *Agron. J.* **2002**, *94*, 975–980. [[CrossRef](#)]
18. Bullock, D.G.; Nielsen, R.L.; Nyquist, W.E. A growth analysis comparison of corn grown in convention and equidistant plant spacing. *Crop Sci.* **1988**, *28*, 254–258. [[CrossRef](#)]
19. Farnham, D.E. Row spacing, plant density, and hybrid effects on corn grain yield and moisture. *Agron. J.* **2001**, *93*, 1049–1053. [[CrossRef](#)]
20. Lee, C.D. Reducing row widths to increase yield: Why it does not always work. *Crop Manag.* **2006**, *5*, 1–7. [[CrossRef](#)]
21. Quintana-Ashwell, N.; Anapalli, S.S.; Pinnamaneni, S.R.; Kaur, G.; Reddy, K.N.; Fisher, D. Profitability of twin-row planting and skip-row irrigation in a humid climate. *Agron. J.* **2022**, *114*, 1209–1219. [[CrossRef](#)]

22. Lyon, D.J.; Pavlista, A.D.; Hergert, G.W.; Klein, R.N.; Shapiro, C.A.; Knezevic, S.; Mason, S.C.; Nelson, L.A.; Baltensperger, D.D.; Elmore, R.W.; et al. Skip-row planting patterns stabilize corn grain yields in the central Great Plains. *Crop Manag.* **2009**, *8*, 1–8. [CrossRef]
23. Fernandez, C.J.; Fromme, D.D.; Grichar, W.J. Grain sorghum response to row spacing and plant populations in the Texas Coastal Bend Region. *Int. J. Agron.* **2012**, *2012*, 238634. [CrossRef]
24. Sainju, U.M.; Whitehead, W.F.; Singh, B.P.; Wang, S. Tillage, cover crops, and nitrogen fertilization effects on soil nitrogen and cotton and sorghum yields. *Eur. J. Agron.* **2006**, *25*, 372–382. [CrossRef]
25. Tarkalson, D.D.; Hergert, G.W.; Cassman, K.G. Long-term effects of tillage on soil chemical properties and grain yields of dryland winter wheat-sorghum/corn-fallow rotation in the Great Plains. *Agron. J.* **2006**, *98*, 26–33. [CrossRef]
26. Bordovsky, D.G.; Choudhary, M.; Gerard, C.J. Tillage effects on grain sorghum and wheat yields in the Texas Rolling Plains. *Agron. J.* **1998**, *90*, 638–643. [CrossRef]
27. Sweeney, D.W. Twenty years of grain sorghum and soybean yield response to tillage and N fertilization of a claypan soil. *Crop Forage Turfgrass Manag.* **2017**, *3*, 1–7. [CrossRef]
28. Matowo, P.R.; Pierzynski, G.M.; Whitney, D.A.; Lamond, R.E. Long term effects of tillage and nitrogen source, rate, and placement on grain sorghum production. *J. Prod. Agric.* **1997**, *10*, 141–146. [CrossRef]
29. Kaspar, T.C.; Erbach, D.C.; Cruse, R.M. Corn response to seed-row residue removal. *Soil Sci. Soc. Am. J.* **1990**, *54*, 1112–1117. [CrossRef]
30. Schneider, E.C.; Gupta, S.C. Corn emergence as influenced by soil temperature, matric potential, and aggregate size distribution. *Soil Sci. Soc. Am. J.* **1985**, *49*, 415–422. [CrossRef]
31. Fortin, M.C. Soil temperature, soil water, and no-till corn development following in-row residue removal. *Agron. J.* **1993**, *85*, 571–576. [CrossRef]
32. Wang, X.B.; Cai, D.X.; Hoogmoed, W.B.; Oenema, O.; Perdok, U.D. Developments in conservation tillage in rainfed regions of North China. *Soil Tillage Res.* **2007**, *93*, 239–250. [CrossRef]
33. Hansen, N.C.; Allen, B.L.; Baumhardt, R.L.; Lyon, D.J. Research achievements and adoption of no-till, dryland cropping in the semi-arid U.S. Great Plains. *Field Crops Res.* **2012**, *132*, 196–203. [CrossRef]
34. DeFelice, M.S.; Carter, P.R.; Mitchell, S.B. Influence of tillage on corn and soybean yield in the United States and Canada. *Crop Manag.* **2006**, *5*, 1–17. [CrossRef]
35. Al-Kaisi, M.M.; Archontoulis, S.V.; Kwaw-Mensah, D.; Miguez, F. Tillage and crop rotation effects on corn agronomic response and economic return at seven Iowa locations. *Agron. J.* **2015**, *107*, 1411–1424. [CrossRef]
36. Mahboubi, A.A.; Lal, R. Long-term tillage effects on changes in structural properties of two soils in central Ohio. *Soil Tillage Res.* **1998**, *45*, 107–118. [CrossRef]
37. Creamer, N.G.; Dabney, S.M. Killing cover crops mechanically: Review of recent literature and assessment of new research results. *Am. J. Altern. Agric.* **2022**, *17*, 32–40.
38. Lal, R. Soil carbon sequestration and aggregation by cover cropping. *J. Soil Water Conserv.* **2015**, *70*, 329–339. [CrossRef]
39. Che, Y.; Rejesus, R.M.; Cavigelli, M.A.; White, K.E.; Aglasan, S.; Knight, L.G.; Dell, C.; Hollinger, D.; Lane, E.D. Long-term economic impacts of no-till adoption. *Soil Secur.* **2023**, *13*, 100103. [CrossRef]
40. Robles, M.; Ciampitti, I.A.; Vyn, T.J. Dynamics of maize plant responses to a twin-row spatial arrangement at multiple plant densities. *Agron. J.* **2012**, *104*, 1747–1756. [CrossRef]
41. Begna, S.H.; Hamilton, R.I.; Dwyer, L.M.; Stewart, D.W.; Smith, D.L. Effects of population density and planting pattern on the yield and yield components of leafy reduced-stature maize in a short-season area. *J. Agron. Crop Sci.* **1997**, *179*, 9–17. [CrossRef]
42. Snider, J.L.; Raper, R.L.; Schwab, E.B. The effect of row spacing and seeding rate on biomass production and plant stand characteristics of non-irrigated photoperiod-sensitive sorghum (*Sorghum bicolor* (L.) Moench). *Ind. Crops Prod.* **2012**, *37*, 527–535. [CrossRef]
43. Karlen, D.L.; Camp, C.R. Row spacing, plant population, and water management effects on corn in the Atlantic Coastal Plain. *Agron. J.* **1985**, *77*, 393–398. [CrossRef]
44. Thapa, S.; Xue, Q.; Stewart, B.A. Alternative planting geometries reduce production risk in corn and sorghum in water-limited environments. *Agron. J.* **2020**, *112*, 3322–3334. [CrossRef]
45. Caravetta, G.J.; Cherney, J.H.; Johnson, K.D. Within-row spacing influences on diverse sorghum genotypes: I. Morphology. *Agron. J.* **1990**, *82*, 206–210. [CrossRef]
46. Rusk, R.; Sievers, J.L. Comparison of Twin Row and 30-in. Row Corn. *Iowa State Univ. Res. Demonstr. Farms Prog. Rep.* **2010**, 268. Available online: http://lib.dr.iastate.edu/farms_reports/268 (accessed on 7 July 2024).
47. Barr, R.L.; Mason, S.C.; Novacek, M.J.; Wortmann, C.S.; Rees, J.M. Row Spacing and Seeding Rate Recommendations for Corn in Nebraska G2216. University of Nebraska-Lincoln Extension. 2013. Available online: <http://extensionpublications.unl.edu/assets/pdf/g2216.pdf> (accessed on 7 July 2024).

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