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Research Article

Grain Sorghum Response to Row Spacing and Plant Populations in the Texas Coastal Bend Region

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Two grain sorghum (Sorghum bicolor L. Moench) studies were conducted in the Coastal Bend Region of Texas over a two-year period. In one study, sorghum growth and yield were compared when planted in a single row on beds or planted in twin rows on beds with different plant populations under dryland or irrigation. Above average rainfall occurred in May 2000 which resulted in twin rows at any plant population producing higher yields than the single row at lower plant population. In 2001, single-row plantings with either plant population (124,000–160,000 or 161,000–198,000 plants/ha) produced higher yield than twin rows planted at 161,000–198,000 plants/ha. Under irrigation, twin rows planted at 161,000–198,000 plants/ha produced higher yields than single row at the same population; however, no other yield differences were noted when row systems or plant populations were compared. In another study, 38 cm row spacings were compared with 76 cm row spacings under two plant populations. In 2000, when rains fell at an opportune time, no yield differences were noted; however, in 2001 with below average rainfall, the 76 cm plantings at 170,000–200,000 and 210,000–240,000 plants/ha produced higher yield than the 38 cm plantings at those same plant populations.

1. Introduction

Row spacing and plant populations are variables that can have a significant impact on the net returns of sorghum producers. Grain sorghum along the Texas Gulf Coast is commonly cultivated in rows 76–102 cm apart [1]. Recent technological developments in farming equipment and improved herbicides open new doors for using rows narrower than 76 cm or twin rows on a single bed in grain sorghum production. The use of narrow rows in grain sorghum production is not new. A number of previous studies published in the late 1950s and 1960s showed yield increases when grain sorghum was planted in narrow rows [2, 3].

Though optimal plant densities for grain sorghum differ from region to another, previous research has indicated that grain yields generally increase as plant populations increase [4–6]. At lower than suggested plant densities, grain sorghum head number per plant or seed number per head increased when compared to the recommended plant density [7–10]. In other crops, Grichar [11] reported variable results of the effects of different seeding rates in soybean (*Glycine max* L.). He reported that the effect of seeding rate on soybean yields varied from year to another depending on variety and rainfall received during the growing season. Brown et al. [12] showed a 34% yield increase in corn (*Zea mays* L.) grown on 51 cm rows compared with 102 cm rows. Fulton [13] reported that under conditions of adequate soil moisture, higher corn plant densities (54,360 plants/ha) produced greater yields than lower densities (39,540 plants/ha), and rows spaced at 50 cm produced higher yields than rows spaced 100 cm apart.

The row spacing in a crop can also impact crop yield potential [6, 14–16]. Weed-grain sorghum competition is intensified by open canopy structures [17], while narrow-row planting gives grain sorghum a competitive advantage over weeds [18]. Staggenborg [6] reported that crop row spacings of less than 76 cm would increase grain yield in areas with high yield potential with little risk of reduced yield in areas with lower yield potential. Grichar [19] reported that soybeans in a twin-row configuration yielded more than the single-row system 50% of the time. Reducing the distance between rows can also improve weed control by increasing crop competitiveness and reducing light transmittance to the soil [20–22]. Johnson et al. [23] reported that total weed densities were less when peanut (*Arachis hypogaea* L.) rows were spaced 30 cm apart compared with rows spaced 91 cm apart. Teasdale [24] showed that reduced row spacing and increased corn populations decreased weed growth in the absence of herbicides and shortened the time of canopy closure by one week. Significant yield increases were reported when grain sorghum was planted in double rows 38 cm apart on 97 cm beds [25]. This planting pattern increased grain yield 24% (1174 kg/ha) compared to single-row planting across two deficit-irrigation levels (76 and 152 mm of in-season irrigation) and two planting densities (148,000 and 222,000 plants/ha). Although the increase in yield was 26% with the higher level of irrigation and 22% with the lower level of irrigation, there were no significant differences between the two planting densities.

Seedlings in close proximity to each other express phytochrome-mediated responses by developing narrow leaves, long stems, and less massive roots [26]. Planting a crop in a pattern that reduces the spacing of plants within and between rows can increase plant biomass and leaf area index [27]. Work by Bullock et al. [27] showed that reduced row spacing increased the total interception of photosynthetic active radiation by the corn canopy and redistributed the radiation toward the top of the canopy.

Until recently, profitability of grain sorghum production, as well as that of other crops, has been in decline as production costs continue to increase and crop prices remain low [28]. Although grain sorghum has a comparative advantage over other summer crops with regard to its adaptability to make use of limited soil moisture conditions, its dryland production is characterized by variable yield as crop performance depends highly on soil moisture availability [29]. Higher and more stable yields are obtained under irrigation, but at higher production costs [30]. An increased and more stable profitability of grain sorghum production is essential to improve and secure the sustainability of the farming industry in the region.

More research is needed in the Coastal Bend region of Texas to further understand the effects of narrow-row planting (row spacing as well as twin rows on a bed) on grain sorghum production and its interactions with planting density. Many producers question whether there is a different optimum plant density for grain sorghum grown in narrow rows. For these reasons, the objectives of this study were to determine (a) plant density and (b) row spacing on grain sorghum growth and yield.

2. Materials and Methods

Two different studies were conducted in the Coastal Bend region of Texas. The first study was conducted under irrigated conditions in 2000 and dryland conditions in 2000 and 2001 to determine grain sorghum response to twin rows planted on a bed compared to a single row planted on a bed using three different plant populations. This will be called Study 1. Another study was conducted under dryland conditions in 2000 and 2001 to determine grain sorghum response to two different row spacings (38 and 76 cm) and two different plant populations. This will be referred to as Study 2.

2.1. Research Sites. Study 1 was conducted at Texas AgriLife and Extension Center located approximately 3.2 km north of Corpus Christi (27.77°N and 97.51°W). This study was done under dryland conditions in both years but only under irrigation in 2000. Study 2 was conducted at Perry Foundation Farm located near Robstown (27.79°N and 97.51°W), which is approximately 13 km from Study 1 location. The soils at both locations were a Victoria clay (fine, montmorillonitic, and thermic Udic Pellusterts) with less than 1.0% organic matter and pH 7.5. Each year, the studies were moved to different locations within the same field.

2.2. Planting Dates and Plot Layout. In Study 1, in 2000 for both the dryland and irrigated study, Asgrow 459 was planted on March 25 and in 2001, Pioneer 84G62 was planted on March 13 at the dryland location. Due to issues with the irrigation system, the irrigated portion of this study was not planted in 2001. In Study 2, Pioneer 8313CG was planted on March 3, 2000, and Pioneer 84G62 was planted on March 7, 2001.

In both studies, a randomized complete block design with a 2 × 2 factorial treatment arrangement with 4 replicates was used. In Study 1, the two factors included two row configurations, single rows on a bed spaced 96.5 cm apart or twin rows spaced 30 cm apart on a bed. Beds were approximately 36–41 cm wide. In the dryland study, three plant populations (124,000–160,000, 161,000–198,000, 199,000–235,000 plants/ha) were planted in 2000 or two plant populations (124,000–160,000 and 161,000–198,000 plants/ha) in 2001. Under irrigation, the plant populations were the same as those for the 2000 dryland study. Row spacing and plant populations plots were 4 beds (9.8 m) wide and 47 m in length. In the irrigation study, water was applied with aboveground drip lines at panicle formation (122 mm) and at flowering (43 mm).

For Study 2, the two factors included two row spacings, 38 and 76 cm apart, and two plant populations of 170,000–200,000 and 210,000–240,000 plants/ha. Row spacing and plant populations plots were 16 rows for the wider spacing or 32 rows for the narrower spacing (12.7 m wide) and 152 to 170 m long.

For all studies, fertilizer was applied 45–60 days prior to planting based on the soil test recommendations provided by the Texas AgriLife Extension Service Soil and Plant Testing Laboratory. All treatments were planted on a flat seedbed. Grain sorghum was planted with a Monosem vacuum planter (Monosem ATI, Inc., 17135 West 116th Street, Leneka, KS 66219, USA) equipped with precision seed meters calibrated to deliver the desired seeding rate. Plant counts taking 4–6 wk after planting assured that each plot

Table 1: Monthly rainfall in the Corpus Christi area in 2000 and 2001.

Month	Monthly rainfall (mm)		
	2000	2001	62 yr average
February	15.5	18.5	45.7
March	93.5	51.6	35.6
April	26.0	0.8	47.2
May	121.9	34.8	71.8
June	66.3	77.2	81.8
July	0.3	26.4	59.7
August	24.4	142.8	76.2
Total	347.9	352.1	418.0

was within the desired plant populations. Atrazine (Aatrex (Drexel Chemical Company, Memphis, TN 38113, USA)) at 2.9 L/ha, *S*-metolachlor (Dual Magnum (Syngenta Crop Protection, Wilmington, DE 19810, USA)) at 1.22 L/ha, and glyphosate (Roundup Ultra (Monsanto Chemical Company, St. Louis, MO 63167, USA))at 1.22 L/ha were applied before emergence within two days after planting for weed control.

2.3. Data Collection and Analysis. In the single- and twin-row studies (Study 1), grain heads were hand harvested in early to mid-August, counted from 9.4 m of a center row, and threshed for grain yield determination. For the row spacing study (Study 2), grain was harvested using a commercial combine (John Deere 9600 (John Deere, Moline, IL 61265, USA)). Prior to harvest, the number of heads was counted in two 4.8 m section of center rows. Also, a sample was taken from each plot for measurement of moisture and 1000-grain weight. Crop weights were adjusted to 14% moisture.

Data were analyzed using PROC GLM with SAS (SAS Institute, Inc., Cary, NC, USA) and a model statement appropriate for a factorial design. Treatments means were separated by Fisher's protected least significant difference test at $P = 0.05$. Data for the two years were analyzed separately due to year-by-treatment interactions for all variables.

3. Results

3.1. Rainfall. Rainfall amounts in the Corpus Christi area were variable for the two years (Table 1). Rainfall in 2000 can be characterized as below average for February, April, June, and July and above average rainfall for March and May. In 2001, below average rainfall was received for February, April, May, and July. Total rainfall for the February through July growing season (plots were harvested early to mid-August) was below average for both years (Table 1).

3.2. Grain Sorghum Response to Single and Twin Rows and Plant Populations—Study 1

3.2.1. Heads/Plant. Under dryland conditions in 2000, the twin rows planted at 124,000–160,000 plants/ha produced fewer heads than the single row planted at 124,000–160,000 or 199,000–235,000 plants/ha (Table 2). The single row planted at 124,000–160,000 plants/ha produced a greater number of heads/plant than the twin rows planted at any populations.

In 2001, the twin rows planted at 161,000–198,000 plants/ha produced less heads/plant than either population planted on a single row or the twin rows planted at 124,000–160,000 plants/ha (Table 2). Mascagni and Bell [31] reported that under dryland conditions, the yield component that contributed the most to a twin-row yield response was heads/ha. They concluded that there may have been more tillering for twin rows since the intrarow spacing was greater than the single row for a given seeding rate.

Under irrigation, no differences in heads/plants were noted (Table 3). Mascagni and Bell [31] reported that under irrigation, the number of heads/ha had no effect on sorghum yield.

3.2.2. Number of Seed/Head. The number of seed/head account for 70% of the grain sorghum yield and therefore play an important role in yield determination [32]. In 2000, under dryland conditions, both single- and twin-row plantings at 199,000–235,000 plants/ha produced the lowest number of seed/head (Table 2). The twin rows planted at 124,000–160,000 plants/ha produced the greatest number of seed/head which was greater than for all row spacing and plant populations with the exception of the twin rows planted at 161,000–198,000 plants/ha. In 2001, the single row planted at 124,000–160,000 plants/ha produced the greatest number of seed/head (Table 2). No differences were noted with any other row spacings or plant populations.

Under irrigation, the twin rows planted at 124,000–160,000 plants/ha produced the greatest number of seed/head, and this was greater than any other plant populations (Table 3). The single row planted at 199,000–235,000 plants/ha produced the lowest number of seed/head.

3.2.3. Grain Weight/Head. Under dryland conditions in 2000, the twin rows planted at 124,000–160,000 plants/ha produced the greatest grain weight/head (Table 2). This was greater than the single-row planting at 161,000 or greater plants/ha or the twin rows planted at 199,000 or greater plants/ha. In 2001, the single row planted at 124,000–160,000 plants/ha produced the greatest grain weight/head, and both single-row populations produced higher grain weight/head than either twin rows (Table 2). Karchi and Rudich [32] stated that yields were directly associated with number of heads per unit area and inversely associated with head weights.

3.2.4. Weight of 1000 Seed. Under dryland conditions, in neither year, there were not any differences in the weight of the 1000 seed with either row spacing or plant populations (Table 2). However, under irrigated conditions, the single-row planting at 124,000–160,000 seed/ha produced the highest weight, and this was greater than the weight of twin rows planted at any population (Table 3).

3.2.5. Yield. Under dryland conditions in 2000, the single-row planting at 124,000–160,000 plants/ha produced a lower

Table 2: Grain sorghum response to single and twin rows and plant populations under dryland conditions.

Rows	Plant populations (1000s/ha)	Heads/plant		Number of seed/head		Grain weight/head (g)		Weight of 1,000 seed (g)		Yield (kg/ha)	
		2000	2001	2000	2001	2000	2001	2000	2001	2000	2001
Single row	124–160	0.98	0.71	1610	776	40.3	23.8	25.0	18.9	4400	2140
	161–198	0.88	0.63	1436	592	33.1	14.0	23.1	19.8	5110	1910
	199–235	0.90	—	1272	—	34.0	—	26.9	—	5400	—
Twin rows	124–160	0.77	0.68	1937	531	48.1	10.4	24.8	19.6	5700	1810
	161–198	0.81	0.42	1650	542	40.4	10.1	24.5	18.7	5640	1430
	199–235	0.84	—	1449	—	34.4	—	23.8	—	5780	—
LSD (0.05)		0.12	0.13	316	150	11.2	2.3	NS	NS	1010	570

Table 3: Grain sorghum response to single and twin rows and plant populations under irrigated conditions in 2000.

Rows	Plant population (1000s/ha)	Heads/plant	Number of seed/head	Weight of 1,000 seed (g)	Yield (kg/ha)
Single row	124–160	0.86	1386	26.7	5980
	161–198	0.84	1206	25.7	5900
	199–235	0.89	1005	26.4	6040
Twin rows	124–160	0.82	1639	23.1	6390
	161–198	0.86	1393	24.0	6840
	199–235	0.88	1161	23.8	6730
LSD (0.05)		NS	222	2.0	880

yield than twin rows planted at any plant population (Table 2). This is atypical of what usually occurs. Rainfall was above normal in May (Table 1), and this contributed to the greater yield with the twin-row system. This rainfall occurred during panicle formation and early flowering. This growth stage is the period when the plants are especially sensitive to any type of stress as water deficits, and this stage is considered the most critical period for grain production [33]. In 2001, the single row planting at 124,000–160,000 plants/ha produced yields that were greater than the twin rows planted at 161,000–198,000 plants/ha. No other differences in yield were noted in 2001.

Under irrigated conditions, the twin rows planted at 161,000–198,000 plants/ha produced greater yield than the single row planted at the same plant population. No other differences in yield was noted with any row spacing or plant population (Table 3). Since irrigation was applied during panicle formation, the plant was not allowed to stress, which would have reduced the number of seeds/plant [33].

3.3. Grain Sorghum Response to Row Spacing and Plant Populations—Study 2

3.3.1. Heads/Plant. In 2000, no differences were noted in heads/plants when row spacing and plant populations were compared (Table 4). In 2001, the 76 cm row spacing planted at 210,000–240,000 plants/ha produced the greatest number of heads/plant, and this was greater than the 38 cm row spacing at either plant population or the 76 cm row spacing planted at the lower plant population.

3.3.2. Number of Seed/Head. No differences were noted in either year with any row spacing or plant population (Table 4).

3.3.3. Weight of 1000 Seed. In 2000, the 76 cm row spacing planted at 170,000–200,000 plants/ha produced the greatest weight, and this was greater than the 38 cm row spacing at either plant population (Table 4). In 2001, the 38 cm row spacing planted at 210,000–240,000 plants/ha produced the lowest weight, and trends were similar to those seen in 2000.

3.3.4. Yield. In 2000, no differences in yield were noted with either row spacing or plant population (Table 4). In 2001, both 76 cm row spacings at either plant population produced higher yields than the 38 cm planting at either plant population. It has been reported that the yield response to narrow rows in corn and grain sorghum is affected by many environmental, spatial, and temporal field interactions [4–6, 13, 21]. It has also been suggested that a positive yield response to narrow rows is more likely to occur in the presence of environmental yield-limiting factors. Andrade et al. [22] reported that the narrow-row yield response was inversely proportional to the radiation interception achieved with wider rows. Under very favorable growing conditions, when radiation interception for wide rows was optimized, the yield response to narrowing the rows was minimized.

4. Summary

In the year when rainfall fell at the most opportune time (panicle formation), the twin rows produced higher yields

Table 4: Grain sorghum response to row spacing and plant populations under dryland conditions.

Row spacing (cm)	Plant population (1000s/ha)	Heads/plant 2000	Heads/plant 2001	Number of seed/head 2000	Number of seed/head 2001	Weight of 1,000 seed (g) 2000	Weight of 1,000 seed (g) 2001	Yield (kg/ha) 2000	Yield (kg/ha) 2001
38	170–200	0.93	0.79	744	1234	25.3	14.0	4610	1665
	210–240	0.91	0.81	702	969	24.8	13.3	4630	1726
76	170–200	0.95	0.80	846	1220	28.5	15.3	4666	2104
	210–240	0.96	1.03	772	733	27.4	15.7	4576	2104
LSD (0.05)		NS	0.18	NS	NS	2.1	2.4	NS	339

than single-row plantings. Under less rainfall, neither system (twin or single) produced yield differences within their respective plant population. Under irrigation, no differences in yield were noted between twin- and single-row plantings at 124,000–160,000 and 199,000–235,000 plants/ha; however, at 161,000–198,000 plants/ha, the twin-row plantings produced higher yields than the single-row planting. Comparing narrow-row plantings (38 cm) with a more conventional row spacing (76 cm), when rainfall occurred during panicle formation or beginning of flowering and the early boot stage, no yield difference between row spacing was noted; however, when rainfall was limiting, the narrow-row plantings produced less yield than conventional row spacing. Results for the differences in plant populations were mixed. The lower plant populations did not always produce the greater yields especially in dryer years.

Responses to narrow-row spacing in grain sorghum have been varied and inconsistent. Conley et al. [5] reported that grain yield response to row spacing was variable and dependent on environment. Welch et al. [34] reported that in the presence of adequate nitrogen, production of grain and residue increased with increasing populations. They concluded that under dryland conditions, optimum populations for both grain and residue production were between 100,000 and 150,000 plants/ha and that at populations of 100,000 plant/ha, grain and residue yields in 40 cm rows equaled or exceeded those in 102 cm rows. In contrast, Karchi and Rudich [32] in Israel reported, under dryland conditions, that greater yields resulted from narrow rows combined with lower plant populations. They found that the greater grain yields were primarily due to increased number of heads per unit area rather than to changes in head weight. They also stated that heads per unit area and the number of kernels per head were largely free of environmental effects.

Also, grain sorghum grown under dryland conditions and deficit irrigation is commonly exposed to water stress. The effect of water stress on yield, however, depends on its timing and intensity [35]. Narrow-row planting affects the canopy structure and, therefore, would affect the rate of development of soil water deficits and the timing of the onset of plant water stress. An early report regarding the interaction of soil moisture and row width indicated that the optimum row width increases as soil moisture becomes more limiting [29]. However, Steiner [36] concluded that narrow-row planting appeared to increase the transpiration component of evapotranspiration, thus increasing the production efficiency of dryland grain sorghum. Supporting Steiner's conclusions, Sanabria et al. [37] concluded that narrow-row, north-south planting patterns resulted in water conservation through enhanced stomatal control of transpiration under conditions of high evaporative demand.

References

[1] D. D. Fromme, C. J. Fernandez, W. J. Grichar, and R. L. Jahn, "Grain sorghum response to hybrid, row spacing, and plant populations along the upper Texas Gulf Coast," *International Journal of Agronomy*, vol. 2012, Article ID 930630, 5 pages, 2012.

[2] K. B. Porter, M. E. Johnson, and W. H. Stetten, "The effect of row spacing, fertilizer, and planting rates on yield and water use of irrigated grain sorghum," *Agronomy Journal*, vol. 52, pp. 431–433, 1960.

[3] F. C. Stickler and S. Wearden, "Yield and yield components of grain sorghum as affected by row width and stand density," *Agronomy Journal*, vol. 57, pp. 564–567, 1965.

[4] O. R. Jones and G. L. Johnson, "Row width and plant density effects on Texas High Plains sorghum," *Journal Production Agriculture*, vol. 4, pp. 613–621, 1991.

[5] S. P. Conley, W. G. Stevens, and D. D. Dunn, "Grain sorghum response to row spacing, plant density, and planter skips," *Crop Management*, 2005.

[6] S. A. Staggenborg, "Grain sorghum response to row spacings and seeding rates in Kansas," *Journal of Production Agriculture*, vol. 12, no. 3, pp. 390–395, 1999.

[7] T. J. Gerik and C. L. Neely, "Plant density effects on main culm and tiller development of grain sorghum," *Crop Science*, vol. 27, pp. 1225–1230, 1987.

[8] T. A. Lafarge and G. L. Hammer, "Predicting plant leaf area production: shoot assimilate accumulation and partitioning, and leaf area ratio, are stable for a wide range of sorghum population densities," *Field Crops Research*, vol. 77, no. 2-3, pp. 137–151, 2002.

[9] T. A. Lafarge and G. L. Hammer, "Tillering in grain sorghum over a wide range of population densities: modelling dynamics of tiller fertility," *Annals of Botany*, vol. 90, no. 1, pp. 99–110, 2002.

[10] Y. O. M'Khaitir and R. L. Vanderlip, "Grain sorghum and pearl millet response to date and rate of planting," *Agronomy Journal*, vol. 84, pp. 579–582, 1992.

[11] W. J. Grichar, "Planting date, cultivar, and seeding rate effects on soybean production along the Texas Gulf Coast," *Crop Management*, 2007.

[12] R. H. Brown, E. R. Beaty, W. J. Ethredge, and D. D. Hays. ", "Influence of row width and plant population on yield of two varieties of corn (*Zea mays* L.)," *Agronomy Journal*, vol. 62, pp. 767–770, 1970.

[13] J. M. Fulton, "Relationships among soil moisture stress, plant populations, row spacing, and yield of corn," *Canadian Journal Plant Science*, vol. 50, pp. 31–38, 1970.

[14] B. A. Besler, W. J. Grichar, S. A. Senseman, R. G. Lemon, and T. A. Baughman, "Effects of row pattern configurations and reduced (1/2x) and full rates (1x) of imazapic and diclosulam for control of yellow nutsedge (*Cyperus esculentus*) in peanut," *Weed Technology*, vol. 22, no. 3, pp. 558–562, 2008.

[15] A. Limon-Ortega, S. C. Mason, and A. R. Martin, "Production practices improve grain sorghum and pearl millet competitiveness with weeds," *Agronomy Journal*, vol. 90, no. 2, pp. 227–232, 1998.

[16] H. H. Bryant, J. T. Touchton, and D. P. Moore, "Narrow rows and early planting produce top grain sorghum yields," *Highlights Agriculture Research Alabama Agricultural Experiment Station*, vol. 33, article 5, 1986.

[17] A. P. Everaarts, "Effects of competition with weeds on the growth, development and yield of sorghum," *Journal of Agricultural Science*, vol. 120, no. 2, pp. 187–196, 1993.

[18] R. H. Walker and G. A. Buchanan, "Crop manipulation in integrated weed management systems," *Weed Science*, vol. 30, pp. 17–24, 1982.

[19] W. J. Grichar, "Row spacing, plant populations, and cultivar effects on soybean production along the Texas Gulf Coast," *Crop Management*, 2007.

[20] B. E. Tharp and J. T. Kells, "Effect of glufosinate-resistant corn (*Zea mays*) population and row spacing on light interception, corn yield, and common lambsquarters (*Chenopodium album*) growth," *Weed Technology*, vol. 15, pp. 413–418, 2001.

[21] K. D. Thelen, "Interaction between row spacing and yield: why it works," *Crop Management*, 2006.

[22] F. H. Andrade, P. Calviño, A. Cirilo, and P. Barbieri, "Yield responses to narrow rows depend on increased radiation interception," *Agronomy Journal*, vol. 94, no. 5, pp. 975–980, 2002.

[23] W. C. Johnson, E. P. Prostko, and B. G. Mullinix, "Improving the management of dicot weeds in peanut with narrow row spacings and residual herbicides," *Agronomy Journal*, vol. 97, no. 1, pp. 85–88, 2005.

[24] J. R. Teasdale, "Influence of narrow row/high population corn (*Zea mays*) on weed control and light transmittance," *Weed Technology*, vol. 9, no. 1, pp. 113–118, 1995.

[25] C. J. Fernandez, T. Foutz, and R. Schawe, "Increasing irrigated grain sorghum yield through double-row planting," in *4th Australian Sorghum Conference*, A. K. Borrell and R. G. Hensell, Eds., Department of Primary Industries-Queensland Government, Grains and Research Development Corporation, Queensland, Australia, 2001.

[26] M. J. Kasperbauer and D. L. Karlen, "Plant spacing and reflected far-red light effects on phytochrome-regulated photosynthate allocation in corn seedlings," *Crop Science*, vol. 34, no. 6, pp. 1564–1569, 1994.

[27] D. G. Bullock, R. L. Nielsen, and W. E. Nyquist, "A growth analysis comparison of corn growth in conventional and equidistant plant spacing," *Crop Science*, vol. 28, pp. 254–258, 1988.

[28] H. C. Dethloff and G. L. Nall, "AGRICULTURE," Handbook of Texas Online, Texas State Historical Association, 2012, http://www.tshaonline.org/handbook/online/articles/ama01.

[29] P. L. Brown and W. D. Shrader, "Grain yields, evapotranspiration and water use efficiency of grain sorghum under different cultural practices," *Agronomy Journal*, vol. 51, pp. 339–343, 1959.

[30] C. Stichler, M. McFarland, and C. Coffman, "Irrigated and dryland grain sorghum production," 2012, http://publications.tamu.edu/CORN_SORGHUM/PUB_Irrigated%20and%20Dryland%20Grain%20Sorghum%20Production.pdf.

[31] H. J. Mascagni and B. Bell, "Plant patterns for different grain sorghum hybrids," *Louisiana Agriculture Magazine*, 2005, http://www.Isuagcenter.com/en/communications/publications/agmag/Archive/2005/Winter/Plant+Patterns+for+Different+Grain+Sorghum+Hybrids.htm.

[32] Z. Karchi and Y. Rudich, "Effects of row width and seedling spacing on yield and its components in grain sorghum grown under dryland conditions," *Agronomy Journal*, vol. 58, pp. 602–604, 1966.

[33] J. Kelley, "Chapter 1: growth and development," Grain Sorghum Handbook, MP 297, http://www.uaex.edu/Other_areas/publications/PDF/MP297/.

[34] N. H. Welch, E. Burnett, and H. V. Eck, "Effect of row spacing, plant population, and nitrogen fertilization on dryland grain sorghum production," *Agronomy Journal*, vol. 58, pp. 160–163, 1966.

[35] M. M. Jones and H. M. Rawson, "Influence of rate of development of leaf water deficits upon photosynthesis, leaf conductance, water use efficiency, and osmotic potential in sorghum," *Physiologia Plantarum*, vol. 45, no. 1, pp. 103–111, 1979.

[36] J. L. Steiner, "Dryland grain sorghum water use, light interception, and growth responses to planting geometry," *Agronomy Journal*, vol. 78, pp. 720–726, 1986.

[37] J. R. Sanabria, J. F. Stone, and D. L. Weeks, "Stomatal response to high evaporative demand in irrigated grain sorghum in narrow and wide row spacing," *Agronomy Journal*, vol. 87, no. 5, pp. 1010–1017, 1995.