Growing Dryland Grain Sorghum in Clumps to Reduce Vegetative Growth and Increase Yield

Varaprasad Bandaru, B. A. Stewart,* R. L. Baumhardt, Satish Ambati, C. A. Robinson, and Alan Schlegel

ABSTRACT

Stored soil water and growing season precipitation generally support early season growth of grain sorghum (*Sorghum bicolor* L. Moench) in dryland areas but are insufficient to prevent water stress during critical latter growth stages. The objective of this study was to determine if growing plants in clumps affected early season growth and subsequent grain yield compared to uniformly spaced plants. We hypothesized that growing grain sorghum plants in clumps would result in fewer tillers and less vegetative growth so that more soil water would be available during the grain-filling period. Results from 3 yr at Bushland, TX, and 1 yr at Tribune, KS, showed that planting grain sorghum in clumps of three to six plants reduced tiller formation to about one per plant compared to about three for uniformly spaced plants. Grain yields were increased by clump planting by as much as 100% when yields were in the 1000 kg ha^{-1} range and 25 to 50% in the 2000 to 3000 kg ha^{-1} range, but there was no increase or even a small decrease at yields above 5000 kg ha^{-1}. Our results suggest that planting grain sorghum in clumps rather than spaced uniformly conserves soil water use until later in the season and may enhance grain yield in semiarid dryland environments.

Grain sorghum is a major crop grown under semiarid conditions in the USA and other parts of the world. In the U.S. southern Great Plains, dryland grain yields are generally low and highly variable because of sparse and erratic growing season precipitation. Average yields from 1972 to 2004 were 2530 kg ha^{-1} (CV 28) for southwest Kansas, 2280 kg ha^{-1} (CV 23) for the North Texas High Plains, and 1860 kg ha^{-1} (CV 28) for the South Texas High Plains (National Agricultural Statistics Database, 2005). Yields would be considerably lower if based on planted areas because only 90 (CV 8), 79 (CV 18), and 81% (CV 22) of the average planted areas actually were harvested for grain (National Agricultural Statistics database, 2005). The yields and percent of area harvested tend to decrease moving from north to south as drier conditions occur. A lack of water during the reproduction and grain-filling stages is common and the major cause of low grain sorghum yields in the U.S. southern Great Plains. Craufurd et al. (1993) reported that water stress during booting and flowering stages resulted in grain yield reductions of up to 85%. Strategies such as reduced plant populations, different spacing between rows, and skip row configurations have been used to enhance soil water contents later into the growing season (Blum and Naveh, 1976; Larson and Vanderlip, 1994).

Yield instability is another problem when growing grain sorghum in dryland regions. More consistent yields resulted in Australia when every third row or two rows of every four rows were left blank compared with uniformly spaced 1-m rows when yields were 2500 kg ha^{-1} or less (Routley et al., 2003). Yields were generally less for skip row configurations at higher yield levels. Soil water measurements confirmed that the positive effect of skip rows during dry years was due to conservation of soil water in the center of the skip areas for use by the crop after anthesis. Unger and Baumhardt (1999) summarized soil water storage data from 1939 through 1997 for Bushland, TX, and found that conservation tillage compared to conventional tillage during an 11-mo fallow period increased the average plant available soil water at planting from 100 to 170 mm. Stewart and Steiner (1990) further showed that sorghum grain yields were increased an average of 15 kg ha^{-1} for each additional millimeter of seasonal evapotranspiration at Bushland, so the amount of stored soil water is extremely important in this region for dryland crop production.

An adequate supply of stored soil water at seeding is essential for successful production of grain sorghum in the U.S. southern Great Plains and similar climatic regions where potential evapotranspiration (PET) far exceeds growing season precipitation. The stored soil water along with growing season precipitation generally provides an adequate supply of plant available water for early vegetative growth. However, water normally becomes limiting during the critical reproduction and grain-filling growth stages and severely reduces grain yield. An analysis of the growing season precipitation at Bushland, located in the North Texas High Plains, shows the challenge for producing high grain sorghum yields (Table 1). Substantially more of the PET is met by seasonal precipitation during the vegetative growth stages than the reproduction and grain-filling stages. Jones and Johnson (1996) showed in a 9-yr study that grain sorghum at Bushland used 84 mm, 22% of the ET, of stored soil water during the growing season. This analysis indicates that the amount of precipitation received coupled with use of stored soil water is sufficient to protect the plants from severe water stress early in the season. Therefore, the sorghum plants usually produce one or more tillers, particularly when the plant population is low.

Abbreviations: LAI, leaf area index; PET, potential evapotranspiration.

V. Bandaru, B.A. Stewart, S. Ambati, and C.A. Robinson, West Texas A&M Univ., P.O. Box 60278, Canyon, TX 79016; R.L. Baumhardt, USDA-ARS, Conservation and Production Res. Lab., P.O. Drawer 10, Bushland, TX 79012; and A. Schlegel, Southwest Research-Extension Center, Kansas State Univ., Rt. 1 Box 148, Tribune, KS 67679. Mention of a proprietary product name is for identification purposes only and does not imply endorsement or warranty to the exclusion of other products. Received 3 June 2005. *Corresponding author (bstewart@mail.wtamu.edu).

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677 S. Segoe Rd., Madison, WI 53711 USA

Table 1. Long-term average precipitation during various growth stages of grain sorghum seeded on 1 June at Bushland, TX.†

Crop stage	Days	PET	Precipitation	Pct./PET‡
		mm	mm	%
Day 1 to 3-leaf	23 (9)§	64 (11)	50 (87)	78
3-leaf to flag leaf	30 (7)	151 (9)	64 (65)	42
Flag leaf to flowering	21 (10)	131 (11)	37 (69)	28
Flowering to black layer	37 (11)	191 (8)	57 (71)	30
Total	111 (6)	537 (7)	208 (44)	39

† Source: 14 yr potential evapotranspiration (PET) data from Texas A&M University Research and Extension Center (2005).

‡ Percentage of potential evapotranspiration supplied by precipitation for the various growth stages.

§ Numbers in parentheses are CV values.

Producers often establish only 50 000 to 100 000 sorghum plants ha^{-1} in dryland areas as a strategy to conserve more of the stored soil water for use during the reproduction and grain-filling growth stages. However, tiller numbers for plants tend to increase as the population declines and this negates most if not all of the anticipated benefit. Sorghum plants in the same maturity class with similar planting dates produce a set number of leaves that is unaffected by the plant population (Vanderlip, 1993). Therefore, reducing plant population may not reduce water use since tillers result which must produce leaves before a panicle is produced. Luebbe (1977) studied the main culms and the first two tillers of five genotypes, three parents, and two hybrids, and reported that the average numbers of leaves were 18.0, 13.5, and 12.7 for the main culms and the first two tillers, respectively. Lafarge and Hammer (2002) also showed that the number of leaves decreased with the succession of tillers and that tillers were fertile only as long as the number of leaves continued to increase. Under conditions of water stress, leaf development on tillers often ceases so the tillers do not produce panicles and the water and nutrients used to that point are of little or no value.

The hypothesis of this study was that growing sorghum plants in clumps would limit the formation of tillers and change the plant architecture so that less soil water would be used during the vegetative growth period. The objective was to compare clumps of plants to the same number of individually spaced plants and determine number of tillers produced, biomass and leaf area production during different growth stages, water use during vegetative and reproduction stages, grain yields, and harvest index values.

MATERIALS AND METHODS

Field experiments were conducted at the USDA Conservation and Production Research Laboratory in 2002, 2003, and 2004 at Bushland, TX (35°11′ N, 102°5′ W), and at the Southwest Research and Extension Center near Tribune, KS (38°30′ N, 101°47′ W), in 2004. Although the hypothesis and objective remained constant, the number of treatments and complexity of the experiments increased each year as results led to the need for additional approaches and information. Climatic data for the locations during the study years are presented in Table 2.

The soil at Bushland was Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) with a plant-available

Table 2. Growing season climatic data for experimental sites.

Month	Precipitation	Avg. precip.†	2002 Avg. temp.	2002 Avg. max. temp.	Highest temp.	Reference ET‡
	mm		°C			mm
			Bushland, TX, 2002			
May	2	68	19	28	35	232
June	17	75	25	33	38	265
July	52	68	25	32	37	224
Aug.	107	72	25	32	37	205
Sept.	38	49	20	27	32	149
Oct.	65	39	12	18	30	79
			Bushland, TX, 2003			
May	15	68	20	29	38	229
June	116	75	21	28	34	185
July	7	68	27	36	40	271
Aug.	41	72	26	34	41	215
Sept.	28	49	19	27	36	157
Oct.	28	39	16	24	32	121
			Bushland, TX, 2004			
May	11	68	21	29	37	249
June	109	75	22	31	40	216
July	39	68	24	31	37	203
Aug.	63	72	22	23	28	170
Sept.	95	49	20	22	26	154
Oct.	69	39	14	16	19	96
			Tribune, KS, 2004			
May	0	70	18	28	36	250
June	189	67	21	29	40	212
July	109	79	22	30	37	204
Aug.	91	53	21	29	37	181
Sept.	59	33	20	29	37	204
Oct.	20	27	12	20	29	91

† Average precipitation amounts are mean values for 58 yr at Bushland (Unger, 2001) and 30 yr at Tribune (Bond and Nolan, 2005).

‡ Reference evapotranspiration (ET) values for Bushland represent amounts of water a well-watered grass crop used (Texas A&M University Research and Extension Center, 2005) and those for Tribune were based on alfalfa (*Medicago sativa* L.) as the reference crop (Kansas State University Research and Extension, 2005).

water storage capacity of about 230 mm to a depth of 1.8 m (Unger, 1978). The average annual precipitation is 470 mm and the average annual PET is 1880 mm (Stewart, 1988). About 50% of the annual precipitation occurs during the summer months and the highest probability for precipitation is during the last few days in May (Stewart and Steiner, 1990). Quinby et al. (1958) reported that the favorable seeding season in the area begins about 15 May but higher yields result if planting is delayed until June. Subsequent research using a crop simulation model indicated that 5 June was the most optimum planting date (Baumhardt et al., 2005). One factor favoring a later seeding date is that plant-available stored water is usually increased by a delay in the seeding date (Stewart and Steiner, 1990). A large supply of stored available soil water is essential in most years to ensure an economic grain yield.

The soil at Tribune, KS, was a Richfield silt loam (fine, smectitic, mesic Aridic Argiustoll) with a pH of 7.4 and an organic matter content of 15 g kg^{-1} (Schlegel et al., 2002). The Richfield soil has a plant-available water holding capacity of about 250 mm. The average annual precipitation is 443 mm with 329 mm occurring from May through Oct. Grain sorghum is generally seeded during the last week of May or the first week of June.

2002 Bushland, TX, Experiment

The growth of grain sorghum plants in clumps was compared with uniformly spaced plants in plots arranged in a completely randomized design with the clump pattern replicated three times and the uniformly spaced pattern twice on a no-tillage field. The field had been fallowed for about 11 mo following the harvest of wheat (*Triticum aestivium* L.) in 2001. The grain sorghum hybrid 'Pioneer-8699' was not seeded until 10 July because of extremely dry conditions during May and June (Table 2). Kernels were seeded about every 17 cm in 75-cm rows with a tractor-mounted planter for a population of approximately eight plants m^{-2}. A hand seeder was used to plant about 10 kernels in clumps 1 m apart in rows for the clumped treatment. Emergence of plants spaced uniformly was only about four plants m^{-1} of row and lower than anticipated. Therefore, plants in the clumps were thinned to four to keep the population density of the clumps the same as for the equally spaced plants. The clumps were seeded in rows previously seeded with the tractor-mounted planter, so plants between clumps were removed by hand following emergence. The final population densities were approximately 5.3 plants m^{-2}.

Precipitation during the 2002 growing season was highly variable with only 19 mm in May and June compared to the long-term average of 143 mm (Table 2). July precipitation was 52 mm compared to an average of 68 mm. However, August and September precipitation was 145 mm, somewhat higher than the long-term average of 121. Thus, stand establishment was extremely challenging and water stress was severe during much of the growing season.

Tiller numbers and dates of panicle formation were determined during the growing season for six plants in the center of the plot (two middle rows with three plants per row). At harvest, plant height, aboveground biomass, and grain yield were determined. Sixteen clumps were sampled and results compared to 12 samples of four equally spaced plants m^{-1}. Treatment comparisons were by an unpaired *t* test.

2003 Bushland, TX, Experiment

Kernels were seeded in clumps and spaced uniformly within nine rows that were 75 cm apart in subplots randomly allocated in 50 by 14 m main plots consisting of the sorghum hybrids 'Pioneer-87G57' and 'NC+5C35'. Subplot dimensions were 50 by 7 m. Wheat straw was applied at two rates (none and spread at the rate of 1.2 Mg ha^{-1} and then covered with a plastic net to prevent movement by wind to simulate surface mulch similar to a no-tillage field) on 25 by 7 m sub-subplots that were randomly allocated within subplots. The main plots, subplots, and sub-subplots were arranged in a split-split plot with treatments replicated three times. The experiment was conducted on land that had been fallowed for 11 mo following the harvest of wheat in 2002. The field had been tilled several times during the fallow period so there were few or no plant residues remaining on the soil surface. Sorghum was seeded around the experimental site as a fetch crop to minimize the effect of hot, dry winds moving across the plots.

Pioneer-87G57 and NC+5C35 were the hybrids used. The two sorghum hybrids that were used both are classed as early maturing (63 d to half-bloom for Pioneer 87G57 and 58 for NC+5C35) and adapted to growing conditions in the southern Great Plains. Atrazine (2-chloro, 4-ethyl amino-6-isopropylamino-1,3,5 triazine) was applied at 2.4 kg a.i. ha^{-1} as a preemergence herbicide using a field sprayer to control grass and broadleaf weeds. No fertilizer was applied because the area had been fallowed for 11 mo and experience has shown that there is usually adequate fertility following fallow for dryland crop production.

Plots were seeded on 12 June using a tractor-mounted planter. The clump treatments were seeded using a hand planter and 12 or more kernels were planted and then the plants were thinned after emergence to six plants per clump. Final plant densities for all plots were about eight plants m^{-2}.

Soil water content was determined gravimetrically on 30-cm increments to a 1.8-m depth at seeding and at harvesting. Soil water content at seeding was assumed uniform after fallow so 10 soil samples cores were taken randomly throughout the plot area using a tractor-mounted hydraulic soil sampler. At harvesting, 42 samples (two samples from each plot) were collected. Previously determined soil bulk densities were used to convert water contents to a volumetric basis.

Leaf area and aboveground biomass amounts were determined at 35 and 60 d following seeding. For treatments having equally spaced plants within the rows, six contiguous plants (approximately 1 m of row) were taken as a sample and two samples were collected from each plot. For the clump treatments, two clumps were collected from each plot. After measuring leaf area with a leaf area meter (Licor 3100, LI-COR, Lincoln, NE), biomass was determined after oven drying at 70°C to a constant mass. Tiller numbers were determined 32 d after seeding, and panicle numbers were determined 55 d after seeding. At physiological maturity (18 October), three representative 2-m length samples were hand harvested from the interior rows of each plot. Samples were oven-dried for 1 wk at 60°C, weighed to determine biomass, and then threshed to measure grain weight. Grain yield was adjusted to a moisture content of 130 g kg^{-1}.

Leaf temperatures were measured at hourly intervals between 0930 and 1630 h at 42 and 55 d after seeding (before and after formation of panicles). A hand-held infrared thermometer was held above the plant canopy at an angle of about 15° below the horizontal so that plant parts, but no soil, were viewed.

Hybrids, seeding pattern, and straw main and interacting effects were evaluated using the General Linear Models ANOVA procedure from the Statistical Analysis System software (SAS Institute, 1998). When main effects were significant, treatment means for dependent plant characteristics were separated using a protected LSD separation using $P = 0.05$.

2004 Bushland, TX, Experiments

Five plant configurations were included in six field experiments at this location. Plants were spaced uniformly every 25 cm in a row (SP-25), every 25 cm in a row with all tillers removed (SP-25-TR), every 38 cm in a row (SP-38), clumped every 75 cm in a row with three plants in a clump (C3-75), and clumped every 100 cm in a row with four plants in a clump (C4-100, Fig. 1). Two kernels were seeded by hand every 25 cm in the SP-25 and SP-25-TR treatments, and every 38 cm in the SP-38 treatment, while five kernels were seeded for the C3-75 and seven for the C4-100 treatments per clump. Plants were thinned following emergence to the desired population. Final plant densities for the SP-25, C3-75, C4-100, and SP-25-TR treatments were equal at 5.4 plants m^{-2}, and 3.6 for the R-38 treatment.

The experiments were conducted on a bench-terraced watershed with a 1 to 2% slope and constructed on a field of Pullman clay loam. Wheat was harvested from the area in July 2003. Half of the area (120 by 32 m) then was chem-fallowed while the other half was stubble-mulch fallowed for 11 mo. Runoff from the upper two-thirds of the watershed collected on the level bench. Some of the runoff from the upper one-third of the watershed infiltrated into the soil while moving over the middle-third and never reached the level bench. Soil water contents were variable across the watershed with the upper-third having the least water, the lower-third (level-benched area) having the most, and the middle-third having intermediate levels. A soil moisture probe (Robinson, 2003) was pushed into the soil profile at various locations to verify different amounts of stored water at time of seeding in 2004, but water contents were not determined gravimetrically.

The sorghum hybrid Pioneer-8699 was used to establish the five plant configurations in both the stubble-mulched and no-tilled areas. That hybrid was used because it is early maturing (65 d before reaching half-bloom) and can yield well under water stress conditions.

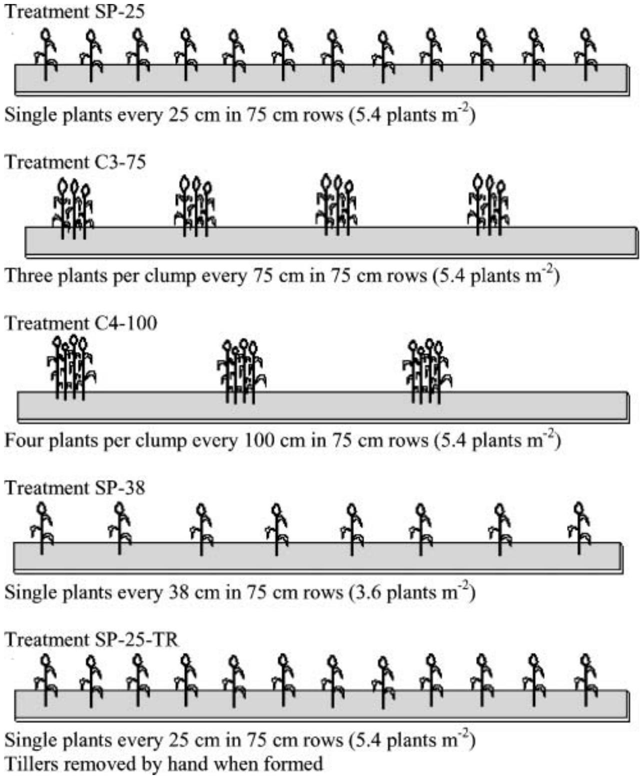

Fig. 1. Schematic showing plant geometries for the treatments used in the 2004 experiments at Bushland, TX, and Tribune, KS.

The stubble mulch and no-tillage areas were end to end, and the three slope position areas were side by side. The experimental design considered each combination of position and tillage as a separate experiment containing the five plant configurations and three replications. Treatment plots (10.7 m wide and 8 m long) were randomly assigned within replications. There were 15 plots in each experiment and a total of 90 for the six experiments. While general comparisons can be made between tillage areas and slope positions of the various experiments, statistical differences are valid only for the individual experiments.

No fertilizer was applied because plant nutrients generally are not limiting after fallow at Bushland. Herbicides were not used to prevent any possible movement with runoff from the sloping area down to the bench area that could injure plants. Weeds were satisfactorily controlled by hand hoeing. One replication of each experiment on the no-tilled area was seeded on 11 June but additional seeding was delayed because of dry soil conditions until 23 June, following favorable rainfall.

After thinning the plants, aluminum access tubes were installed to a depth of 2 m in the SP-25, C4-100, and SP-25-TR treatments for determining soil water by a neutron meter. Rainfall events and scheduling problems prevented installation immediately following seeding as previously planned. For the SP-25 and SP-25-TR treatments, access tubes were placed halfway between two plants within a row. For the C4-100 treatment, two access tubes were installed. One was 13 cm from a clump (the same distance from the plants as for the SP-38 and SP-25-TR treatments) and the second was 38 cm from the clump and half the distance from another clump since the clumps in alternate rows had been staggered to achieve symmetrical distribution. Volumetric soil water content was measured on 29 July, 18 August, 14 September, and 4 October.

Samples were taken in a uniform manner for all plant measurements. A subsample of four contiguous plants was taken in treatments having equally spaced plants (SP-25, SP-25-TR, and SP-38) within the rows and three samples were taken randomly from each plot. For the clump treatments (C3-75 and C4-100), three clumps were sampled for C4-100 and four clumps for C3-75. Thus, 12 plants were sampled for all treatments. The area used by 12 plants was the same for all treatments except for the SP-38 that used 1.5 times more area. Data were converted to a common unit area. Tiller numbers were determined 30 d after seeding. Plants were sampled 40 d after seeding for LAI and dry matter. After measuring LAI, dry mass of leaves and stems was determined after oven drying at 60°C to a constant mass. Leaf temperatures were measured at hourly intervals between 0800 and 1700 h 38 d after seeding in the same manner as described for the 2003 Study. At physiological maturity, plots were harvested by hand and samples were oven-dried for 1 wk at 60°C. Samples were threshed and dry weights of biomass and grain were determined. Grain yields were adjusted to a moisture content of 130 g kg^{-1}.

The data were analyzed using the mixed procedure for SAS (SAS Institute, 1998). For each experiment, the planting geometry treatments were considered fixed factors and replications were considered random factors. Plant characteristics analyzed included number of tillers, number of panicles, grain yield, and harvest index values. A $P = 0.05$ significant level was used to separate treatments.

2004 Tribune, KS, Experiments

Two field experiments were established in a 120 m long by 20 m wide area that had been fallowed since wheat was harvested in July 2003. Half of the area (120 m long and 10 m wide) was tilled in April 2004 to establish seedbeds with and without crop residues on the surface for separate experiments. The five plant configurations used at Bushland in 2004 (Fig. 1) were established in both tilled and untilled areas by hand planting Pioneer-87G57 on 28 June and thinning to the desired populations after the plants emerged. The treatments were arranged as a randomized complete block and replicated three times in the tilled and untilled field experiments, and the data were analyzed using PROC GLM. Each treatment plot was 7.5 m long and 6 m wide. There were 15 plots in each tillage area for a total of 30 plots.

Glyphosate (N-(phosphomethyl) glycine; 0.84 kg a.i. ha^{-1}) was applied four times to the area during the fallow period (twice after wheat harvest and twice in the spring before planting) for weed control and 90 kg N ha^{-1} was applied on 26 Feb. 2004. Before seeding, glyphosate (0.84 kg a.i. ha^{-1} acid equivalent), atrazine (1.1 kg ha^{-1} a. i.), and S-metolachlor (2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-[(1*S*)-2-methoxy-1-methylethyl]acetamide; 1.4 kg a.i. ha^{-1}) were applied.

Samples were collected in the same manner as for Bushland and tillers were counted 28 d after seeding. Leaf areas were not determined at Tribune and there were no soil water measurements. Plots were harvested by hand at physiological maturity on 27 October and samples dried for 1 wk at 60°C. Later, samples were threshed and grain and biomass amount determined. Harvest index values were based on oven dry weights, but grain yields were adjusted to a moisture content of 130 g kg^{-1}.

RESULTS AND DISCUSSION

2002 Bushland, TX, Experiment

Several primary tillers were produced initially, followed by secondary and tertiary tillers later in the season. Uniformly spaced plants developed three tillers per plant while plants in clumps had only one tiller (Table 3). However, the clumped plants produced 2230 kg ha^{-1} compared to only 1288 kg ha^{-1} for the normal spaced plants. The yields generally were lower than anticipated for the region and were attributed to the lack of growing season precipitation and an insufficient supply of stored soil water during critical growth stages. The harvest index of the clumps was twice that of the uniformly spaced plants and was mainly responsible for the increased yield of grain. Clumps also hastened maturity. Plants in the clumps reached the 50% bloom stage 5 d earlier than the uniformly spaced plants, and planting in clumps could be an important factor for increasing water use efficiency.

2003 Bushland, TX, Experiment

Precipitation during June was more than 50% higher than average (Table 2) resulting in favorable growing conditions during initial plant development. However, precipitation for the remainder of the growing season was <50% of the average and led to extreme water stress at anthesis and during grain-filling growth stages. There were approximately three tillers for every plant when the plants were spaced approximately 17 cm apart within rows spaced 75 cm apart. In comparison, plants growing in clumps of six plants spaced 1 m apart in rows spaced 75 cm apart averaged less than one tiller per plant. The large difference in tiller production resulted in significant differences in the amounts of aboveground biomass produced during the first 35 and 60 d of growth (Table 4). At the end of 35 d, the uniformly spaced plants produced from 50 to 90% more biomass than the clumped plants. Although the differences were smaller for the samples taken 65 d after seeding, amounts of aboveground biomass for the evenly spaced plants were 20 to 40% greater than amounts for the clumped plants. Leaf area index (LAI) values followed similar trends. There were no significant differences in either biomass production or LAI values for the different hybrids or for maintaining straw mulch on the soil surface (Table 4).

Table 3. Mean tillers per plant, maximum plant height, grain yields, and harvest index for grain sorghum plants grown in clumps compared with the same number of plants in uniformly spaced rows for the 2002 Bushland, TX, experiment.

Variable	Uniformly planted rows	Clump planting	*t* test of treatment differences
Tillers per plant	**2.8**	**1.3**	*
Plant height, cm	**84**	**89**	**NS**
Grain yield, kg ha^{-1}	**1289**	**2226**	*
Harvest index, grain/biomass	**0.24**	**0.44**	*

*** Significantly different at the 0.05 probability level according to an unpaired *t* test.**

Precipitation was only 20% of the reference ET in 2003 (Table 2). These arid conditions resulted in severe water stress and greatly reduced yields. There were significantly more panicles produced by plants in clumps than by uniformly spaced plants (Table 4) and the panicles were formed about 5 d sooner for the plants in clumps. However, even the clumps produced fewer panicles than the potential. Considering that there were eight plants m^{-2} and about five additional tillers m^{-2} for the clump treatments, there was a potential for about 13 panicles m^{-2} and there were only about 6.5 produced. For the uniformly spaced plants, there were about 25 tillers m^{-2} in addition to the 8 m^{-2} for the main stalks so there was a potential of about 33 panicles m^{-2} but only 4.5 to 6.0 were produced. There were significantly more panicles produced on the plots covered with straw indicating that there was less water stress.

Grain yields were from 70% to more than 100% greater for the clump treatments compared to those with uniformly spaced plants (Table 4). Grain yields were higher because more of the dry matter produced was partitioned into grain than into nongrain material resulting in a greater harvest index. All harvest index values were low, but particularly low for uniformly spaced plants, indicating that the plants were severely stressed. Prihar and Stewart (1990) reported that the harvest index for grain sorghum has a genetic potential of about 0.53 when produced under little or no stress, and that the harvest index value decreases sharply with increasing stress. The amounts of aboveground biomass at harvest remained significantly lower for the clumps compared to uniformly spaced plants in all cases except for Pioneer 87G57 grown on soil without straw, and the grain yields and harvest index values were significantly greater for clumps in every comparison.

There were 504 mm of soil water in the 1.8 m soil profile at seeding time. At harvest, the amounts of soil water were 441 mm for the clump treatments and 434 mm for the uniformly spaced plant treatments. Amounts at

Table 4. Mean values of grain sorghum measurements in the 2003 Bushland, TX, experiment as a function of hybrid, straw cover, and planting geometry at a constant density of eight plants m^{-2}.

Treatment†	Straw	No straw	Straw	No straw	Straw	No straw
	Tillers per plant—20 d		Biomass—35 d, kg ha^{-1}		Leaf area index—35 d	
Pioneer 87G57						
Clumps	0.6bA‡	0.6bA	503bA	570bA	0.44bA	0.45bA
Spaced plants	3.2aB	3.1aA	963aA	996aA	0.77aA	0.82aA
NC+5C35						
Clumps	0.7bA	0.6bA	542bA	580bA	0.44bA	0.50aA
Spaced plants	3.2aA	3.0aA	830aA	897aA	0.72aA	0.76aA
	Biomass—60 d, kg ha^{-1}		Leaf area index—60 d		Panicles m^{-2}	
Pioneer 87G57						
Clumps	2827bA	2687bA	1.05bA	1.03bA	6.9aA	6.9aA
Spaced plants	3929aA	3697aA	1.70aA	1.50aA	6.0bA	4.3bB
NC+5C35						
Clumps	2625bA	2717bA	1.13bA	1.04bA	6.7aA	6.2aB
Spaced plants	3157aA	3440aA	1.50aA	1.48aA	4.9bA	4.3bB
	Grain, kg ha^{-1}		Harvest index§		Biomass	
Pioneer 87G57						
Clumps	1370aA	1135aB	0.33aA	0.28aB	3637aA	3523aA
Spaced plants	795bA	544bB	0.15bA	0.13bB	4604bA	3708aB
NC+5C35						
Clumps	1269aA	1007aB	0.33aA	0.27aB	3254aA	3352aA
Spaced plants	772bA	607bB	0.17bA	0.13bB	4010bA	4064bA

† Treatments consisted of two hybrids and two planting geometries (evenly spaced plants every 17 cm and clumps of six plants every 1 m, both in 75-cm rows).

‡ Small letters that are different in a column indicate significant differences by LSD mean separation at the $P < 0.05$ level; large letters that are different in a row indicate significant differences according to a protected LSD mean separation ($P < 0.05$ level).

§ Harvest index based on dry weight of grain divided by dry weight of aboveground biomass.

harvest were considerably higher than during much of the growing season because of rainfall just before harvesting. The measurements indicate that the clump treatments and uniformly spaced plant treatments used similar amounts of water from the soil profile. The time of water extraction, however, likely differed since the aboveground biomass was greater for the uniformly spaced plants than for the clumps at 35 and 65 d after seeding (Table 4). This indicates that the uniformly spaced plants used more soil water compared with the clumps during the first 65 d of the growing season resulting in more soil water being available for grain fill by clumped plants.

Additional evidence that the uniformly spaced plants used more water than the clumps early in the season is differences observed in leaf temperatures (Fig. 2). The average leaf temperature during the hottest part of the day was about 2°C higher for evenly spaced plants compared to clump plants when determined 42 d after seeding. After 60 d, the difference was even greater at about 4°C. Either there was less available water for the uniformly spaced plants, or the clumps had a lower demand because of less LAI and biomass. Visual observations also showed that water stress appeared sooner and more severe on the uniformly spaced plants. Additional plant available water for the clumps during the critical growth stages late in the season is believed to be the main reason that the clump treatments had higher harvest indexes and increased grain yields compared to treatments with uniformly spaced plants.

2004 Bushland, TX, Experiments

Weather conditions during 2004 were more favorable for grain sorghum production than for 2002 and 2003 (Table 2). The June through September precipitation was 306 mm, 42 mm above the long-term average and resulted in higher grain yields than for the previous years. Results from the experiments on the stubble mulched and no-tilled areas were similar (Tables 5 and 6). This was likely due to the fact that there was not much plant residue on the soil surface of the no-tilled plots because of the drought-induced low yield of the preceding wheat crop. Furthermore, much of the residue that was produced had decomposed during the 11-mo fallow period that preceded grain sorghum seeding.

Planting geometry had a significant effect on the number of tillers produced. The SP-25 treatment represents a commonly used geometry for dryland grain sorghum in the southern Great Plains. Plants produced approximately two tillers per plant. Although the experiments located on different positions cannot be compared statistically, there was a trend for plants on the middle and bench position experiments to produce more tillers than those growing on the upper position (Tables 5 and 6). Therefore, it seems that the number of tillers produced was influenced by soil water conditions. Tiller numbers were affected by the distance between plants as shown by comparing the results of the SP-25 and the SP-38 treatments for the various experiments. For the stubble-mulch tillage experiments, the SP-38 treatment with 38 cm between plants produced about three tillers per plant compared to about two for the SP-25 treatment with 25 cm between plants (Table 5). The results were similar for the experiments on the no-tillage area (Table 6). Both clump treatments in the stubble-mulch and no-tillage plots produced fewer tillers than the SP-25 and SP-38 treatments, but there were generally fewer tillers for the C4-100 treatment than for the C3-75 treatment. There were also fewer tillers produced in the clump treatments for the upper and middle slope position experiments than for the experiment on the bench

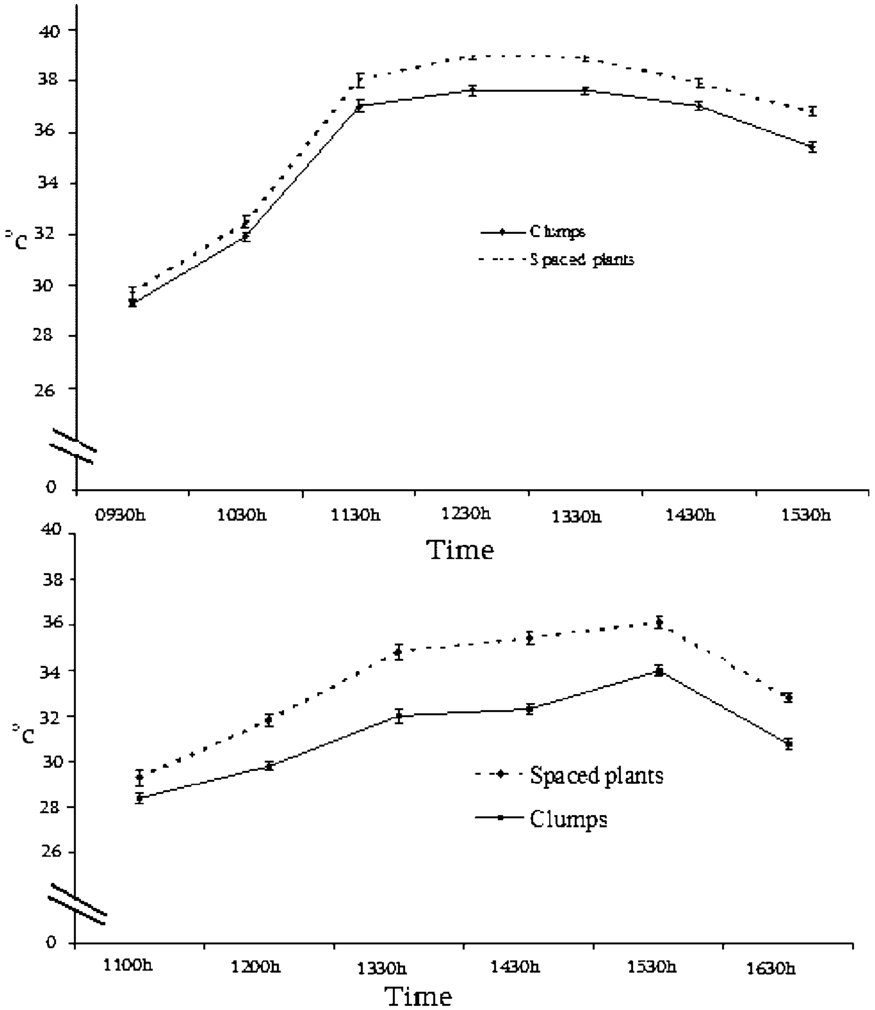

Fig. 2. Comparison of grain sorghum leaf temperatures of evenly spaced plants and clumps 42 d (top) and 60 d (bottom) after seeding, Bushland, TX, 2003.

position indicating that soil water conditions played an important role in tiller formation.

Tillering is a complex phenomenon and it is not clear why clumping reduced the number of tillers so dramatically. Studies have shown that the production of tillers is reduced as the ratio of red to far red light is decreased (Deregibus et al., 1983; Casal et al., 1985; Davis and Simmons, 1994). In our study, clumped plants did not receive as much light at the base as individually spaced plants. Also, when there were four plants per clump, C4-100, there were fewer tillers produced than when there were three plants per clump (C3-75). This suggests that the amount of light at the base decreases as the number of plants in a clump increases.

Tillering is also affected by plant C balance, in particular the availability of assimilates (Mitchell, 1953; Ong and Marshall, 1979). Lafarge et al. (2002) stated that assimilate supply is reduced by conditions of low light interception, resulting from low incident radiation, a short photoperiod, high planting density, or defoliation. Gerik and Neely (1987) also showed that plant density affected the assimilate supply and tiller development of grain sorghum. The competition of several plants together in a clump would certainly reduce the assimilate supply and this may have also been a primary reason for fewer tillers on clumped plants. Our observations strongly support a light effect because even when tillers were separated by only 2 to 3 cm, there were more tillers produced than when plants were touching one another.

Aboveground biomass and leaf area produced during the initial 42 d of growth were closely related to tiller production (Tables 5 and 6). Treatment SP-25 produced approximately 75% more dry matter and leaf area than the C4-100 treatment. The SP-25-TR treatment that had the tillers removed as they were formed produced essentially the same amounts of dry matter and leaf area as the C4-100 treatment, supporting the hypothesis that the increased dry matter and leaf area for the SP-25 treatment was the result of more tillers.

Although there were large differences among treatments in number of tillers and amounts of aboveground biomass and leaf area after 42 d, the differences in the number of panicles produced by each treatment were smaller. The exception was SP-25-TR that had all tillers removed so that the number of panicles could not exceed the number of plants. There were more panicles produced in experiments located on the bench and middle slope positions than on the upper position, showing

Table 5. Mean values of measurements for grain sorghum as affected by five planting geometries in 75-cm rows in experiments located on the upper (Upper), middle (Middle), and bench (Bench) positions of a stubble-mulched bench-terraced field at Bushland, TX, in 2004.†

Planting geometry‡	Tillers plant^{-1} 28 DAP§	Biomass 42 DAP	Leaf area index values 42 DAP	Panicles m^{-2}	% Tillers with panicles¶	Grain	Harvest index values	Aboveground biomass
	no. plant^{-1}	kg ha^{-1}		no. m^{-2}	%	kg ha^{-1}		kg ha^{-1}
Upper								
SP-25	1.8a#	2880a	1.31a	8.1a	28	2385c	0.28c	7472ab
C3-75	0.7b	1900c	1.01b	7.7a	65	2976b	0.36b	7251b
C4-100	0.3b	1617d	0.87c	6.2b	46	3563a	0.41a	7623a
SP-38	3.1a	2284b	1.30a	8.0a	40	2702bc	0.30c	7901a
SP-25-TR	removed	1518d	0.85c	5.4c	n.a.	2964b	0.39a	6667c
Middle								
SP-25	2.0a	2758a	1.41a	10.6a	48	3180c	0.34c	8204ab
C3-75	1.1b	1919c	1.12c	9.5b	69	4013a	0.41ab	8586a
C4-100	0.5c	1732d	0.90d	8.1b	109	3952a	0.44a	7879b
SP-38	2.6a	2303b	1.37b	10.0a	70	3610ab	0.38b	8333a
SP-25-TR	removed	1609e	0.88d	5.4c	n.a.	3563bc	0.40b	7814b
Bench								
SP-25	2.3a	3015a	1.44a	12.0a	53	4743a	0.41b	10 148a
C3-75	1.2b	2150c	1.18c	9.9bc	69	4902a	0.46a	9 348bc
C4-100	0.8c	1806d	0.93d	8.8c	79	4810a	0.46a	9 172c
SP-38	2.9b	2408b	1.42b	10.8b	71	4911a	0.41b	10 507a
SP-25-TR	removed	1694e	0.91e	5.4d	n.a.	4274b	0.42b	9 620b

† Separate but identical experiments were conducted on three positions that had different amounts of stored soil water at time of seeding and different amounts of runoff or run-on during the cropping season.

‡ Planting geometries were SP-25 (plants every 25 cm), C3-75 (clumps of 3 plants every 75 cm), C4-100 (clumps of 4 plants every 100 cm), SP-38 (plants every 38 cm), and SP-25-TR (plants every 25 cm with tillers removed by hand) in 75 cm rows.

§ Days after planting (DAP).

¶ Percentages were obtained by dividing number of plants plus number of tillers; values above 100 are due to experimental error.

Means in columns for a position on the benched terrace followed by the same letter are not significantly different according to a protected LSD mean separation ($P < 0.5$ level); each position represents a separate experiment and cannot be compared statistically.

the importance of water for producing panicles. The most significant point was that many of the tillers in all treatments and all experiments did not produce a panicle (Tables 5 and 6), and the percentage of tillers that did produce panicles was lowest for the experiments located on the upper slope. Only 28% of the tillers for the SP-25 treatment in the experiment on the upper slope of the stubble-mulched area produced panicles (Table 5), and it was clearly evident from observations that many of the panicles produced little or no grain. Therefore, the water and nutrients consumed for tiller growth were not used efficiently because these resources were used early in the growing season during the vegetative growth stages and were therefore not available during the critical reproduction and grain-filling growth stages. For the clump treatments, C3-75 and C4-100, the numbers of tillers produced were fewer, but the percentages that produced panicles were much greater than for the SP-25 and SP-38 treatments that had plants equally spaced.

Table 6. Mean values of measurements for grain sorghum as affected by five planting geometries in 75-cm rows in experiments located on the upper (Upper), middle (Middle), and bench (Bench) positions of a no-tilled bench-terraced field at Bushland, TX, in 2004.†

Planting geometry‡	Tillers plant^{-1} 28 DAP§	Biomass 42 DAP	Leaf area index values 42 DAP	Panicles m^{-2}	% Tillers with panicles¶	Grain	Harvest index values	Aboveground biomass
	no. plant^{-1}	kg ha^{-1}		no. m^{-2}	%	kg ha^{-1}		kg ha^{-1}
Upper								
SP-25	2.2a#	2716a	1.30a	9.2a	33	2270b	0.29c	6866ab
C3-75	0.5c	1831c	1.10b	8.3b	106	2891a	0.38a	6673b
C4-100	0.5c	1622d	0.86c	7.7b	78	3011a	0.40a	6603b
SP-38	2.6b	2234b	1.29a	9.2a	61	2742a	0.33b	7288a
SP-25-TR	removed	1550d	0.85c	5.4c	NA	2645ab	0.40a	5800c
Middle								
SP-25	2.3a	2924a	1.40a	10.3a	41	2690a	0.32a	7374ab
C3-75	0.7c	1897c	1.11c	8.7b	84	3338ab	0.40a	7320ab
C4-100	0.6c	1754d	0.90d	8.4b	103	3479a	0.42a	7266b
SP-38	2.7a	2352b	1.37b	10.3a	70	2954bc	0.33b	7852a
SP-25-TR	removed	1634e	0.88d	5.4c	NA	2904c	0.39a	6561c
Bench								
SP-25	2.3a	3047a	1.45a	11.4a	50	4812a	0.41b	10 295a
C3-75	0.9c	2088c	1.20c	9.1b	75	4968a	0.46a	9 474b
C4-100	0.8c	1880d	0.93d	8.7b	84	4807a	0.46a	9 167b
SP-38	2.8b	2478b	1.42b	11.5a	80	5070a	0.42b	10 588a
SP-25-TR	removed	1786d	0.92d	5.4c	NA	4222b	0.46a	8 051c

† Separate but identical experiments were conducted on three positions that had different amounts of stored soil water at time of seeding and different amounts of runoff or run-on during the cropping season.

‡ Planting geometries were SP-25 (plants every 25 cm), C3-75 (clumps of three plants every 75 cm), C4-100 (clumps of four plants every 100 cm), SP-38 (plants every 38 cm), and SP-25-TR (plants every 25 cm with tillers removed by hand) in 75-cm rows.

§ Days after planting (DAP).

¶ Percentages were obtained by dividing number of plants plus number of tillers; values above 100 are due to experimental error.

Means in columns for a position on the benched terrace followed by the same letter are not significantly different according to a protected LSD mean separation ($P < 0.5$ level); each position represents a separate experiment and cannot be compared statistically.

Grain yields were relatively high for experiments located on the bench position (Tables 5 and 6) because this position received runoff from experiments located on other slope positions. There were no differences in yields between the clump treatments C3-75 and C4-100, and the spaced plant treatments SP-25 and SP-38 for experiments on the bench. However, the yield of the SP-25-TR treatment that had tillers removed was reduced. This reduction was likely caused by an insufficient number of panicles for the yield level achieved with the favorable water conditions.

The results were vastly different for experiments on the upper slope position where water was very limited. For these experiments, the clump treatments produced more grain than the SP-25 treatment (Tables 5 and 6). The C4-100 treatment produced more grain than the C3-75 treatment for the experiment on the stubble mulch areas and there was a similar trend for the no-tillage experiment. The SP-38 treatment had one-third fewer plants ha^{-1} than the SP-25 treatment and showed a trend on both tillage areas to produce more grain than the SP-25 treatment. The clumps also produced higher yields when compared to the uniformly spaced plants for the experiments conducted on the middle slope position, although the percentage increase was not as great.

The increased grain yields for the clump treatments were the result of a higher harvest index (weight grain/weight aboveground biomass) and not because of increased biomass production (Tables 5 and 6). Amounts of total biomass were equal or lower in the clump treatments than the spaced plant treatments, but harvest index values for the clump treatments were higher than the SP-25 treatment, and particularly large for plants in experiments on the drier slope position. This further corroborates our hypothesis that less soil water was partitioned by the clumps for vegetative growth and more was available during the critical reproductive and grain-filling stages. In comparison, uniformly spaced plants produced many tillers that used more soil water during vegetative growth. However, many of these tillers could not be sustained by the remaining soil water during the reproductive growth stages.

The SP-25-TR treatment was included primarily to compare plants without tillers to the C4-100 treatment that contained plants with few or no tillers but growing together. Observations from the 2002 and 2003 studies suggested that plants growing together benefited from leaves of one plant shading leaves of another plant, and reducing exposure to wind, both of which result in less water loss. It was also observed that clump plants grew upward in a tight bunch while uniformly spaced plants grew outward so there was less sunlight and wind striking the leaves of the clump plants.

Leaf canopy temperatures also suggested that more soil water was available later in the season for the clump treatments (Fig. 3). The SP-25 treatment in particular had a higher canopy temperature indicating more water stress. Many studies have shown that leaf temperatures increase during the day as a function of increasing water deficits (Gates, 1964; Wiegand and Namken, 1966; Pallas et al., 1967; Van Bavel and Ehrler, 1968; Slatyer, 1969; Stevenson and Shaw, 1971; Jackson et al., 1977). Water stress was also observed a few days earlier during the growing season for the SP-25 plots than for the clump treatments. Visual water stress symptoms were less apparent for the SP-38 treatment when compared to the SP-25 treatment.

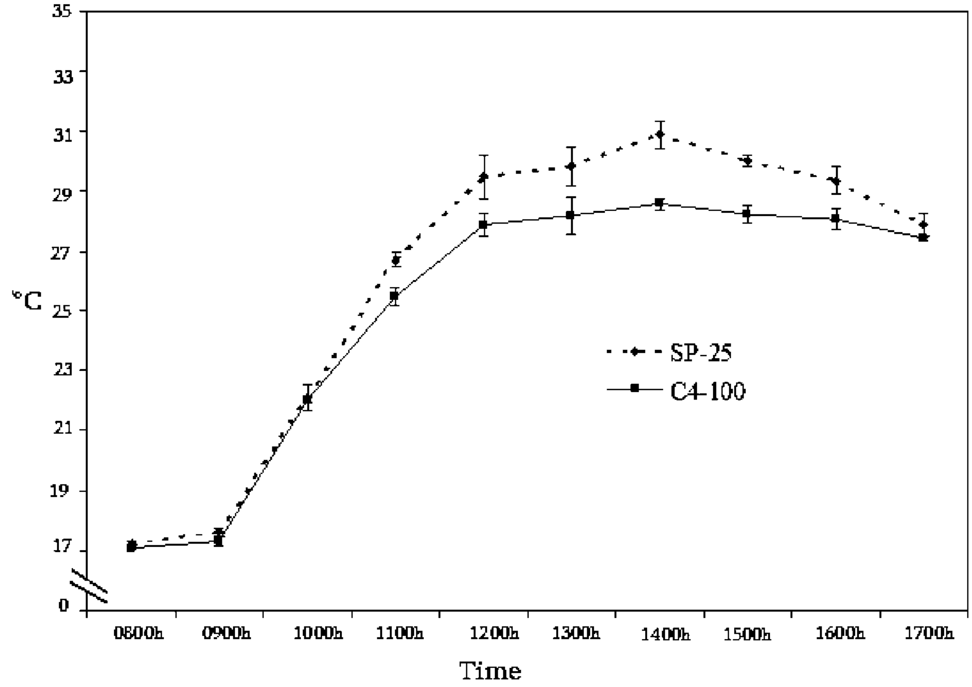

Fig. 3. Comparison of hourly grain sorghum leaf temperatures on 8 Aug. 2004 at Bushland, TX, for selected treatments in the middle position experiment of the stubble mulch area.

We assumed that all treatment plots within an experimental area contained equal amounts of soil water at time of seeding. The volumetric soil water contents varied with time of measurement as a result of plant use and seasonal precipitation (Tables 7 and 8). The soil water was depleted to a greater extent in experiments located on the upper and middle slope positions as compared to the bench. Soil water amounts on 29 July were less for the SP-25 treatment than for the other treatments that had no tillers or few tillers. These findings support the contention that tillers result in grain sorghum plants using large quantities of water early in the growing season, resulting in a severe lack of water during the critical growth stages. Although tillers can be beneficial in many situations, particularly when water is not limiting, they can cause severe water stress and reduced yields under dryland conditions when water is limited because the plants and tillers cannot be sustained. Hammer et al. (1987) reported that fertile tillers account for up to 60% of the total leaf area. Lafarge et al. (2002) showed that tillers contributed from as little as 5% of grain yield to as much as 80%, depending on plant population. Those studies agree with our findings that show tillers produced under limited water conditions increase leaf area during the vegetative growth stage that depletes the soil water and then the tillers contribute little or no grain to final yield.

2004 Tribune, KS, Experiments

The winter and early spring precipitation was extremely low. However, amounts during June, July, and August were among the highest ever recorded (Table 2). This led to very favorable growing conditions for dryland grain sorghum and resulted in grain yields similar to those for irrigated fields.

The number of tillers produced on the various treatments at Tribune in 2004 (Table 9) closely paralleled those found at Bushland in that year (Tables 5 and 6). The clump treatments produced fewer tillers than the uniformly spaced plant treatments.

Table 7. Total soil water (mm) in 180 cm soil profiles of selected treatments† at various times for the experiments on the stubble-mulched area at Bushland, TX, in 2004.

Position on bench terrace	29 July	18 Aug.	14 Sept.	4 Oct.
Upper				
SP-25 (13 cm from plant)	441b‡	422b	403b	459b
C4-100 (13 cm from clump)	515a	446b	415b	466b
C4-100 (38 cm from clump)	511a	480a	448a	483a
SP-25-TR	531a	478a	460a	480a
Middle				
SP-25 (13 cm from plant)	464b	440b	419b	475a
C4-100 (13 cm from clump)	542a	490a	448ab	484a
C4-100 (38 cm from clump)	533a	499a	460a	480a
SP-25-TR (13 cm from plant)	521a	511a	475a	494a
Bench				
SP-25 (13 cm from plant)	543a	502b	475a	495a
C4-100 (13 cm from clump)	558a	538a	486a	491a
C4-100 (38 cm from clump)	556a	539a	495a	491a
SP-25-TR (13 cm from plant)	558a	555a	501a	504a

† Treatments were SP-25 (plants every 25 cm), C4-100 (clumps of four plants every 100 cm), and SP-25-TR (plants every 25 cm with tillers removed by hand) in 75-cm rows.

‡ Numbers followed by the same letter within a column for a particular position are not significantly different according to a protected LSD mean separation ($P < 0.05$ level).

Table 8. Total soil water (mm) in 180 cm soil profiles of selected treatments† at various times for the experiments on the no-tilled area at Bushland, TX, in 2004.

Position on bench terrace	29 July	18 Aug.	14 Sept.	4 Oct.
Upper				
SP-25 (13 cm from plant)	474b‡	429c	408c	487b
C4-100 (13 cm from clump)	532a	453bc	421bc	500ab
C4-100 (38 cm from clump)	530a	486a	453a	501ab
SP-25-TR (13 cm from plant)	534a	478ab	446ab	511ab
Middle				
SP-25 (13 cm from plant)	498b	447b	422b	499a
C4-100 (13 cm from clump)	558a	497a	453a	492a
C4-100 (38 cm from clump)	541a	506a	465a	493a
SP-25-TR (13 cm from plant)	552a	518a	480a	486a
Bench				
SP-25 (13 cm from plant)	548b	518b	481a	498a
C4-100 (13 cm from clump)	559a	545ab	492a	513ab
C4-100 (38 cm from clump)	541a	506ab	465a	493b
SP-25-TR	552a	518a	480a	486a

† Treatments were SP-25 (plants every 25 cm), C4-100 (clumps of four plants every 100 cm), and SP-25-TR (plants every 25 cm with tillers removed by hand) in 75-cm rows.

‡ Numbers followed by the same letter within a column for a particular position are not significantly different according to a protected LSD mean separation ($P < 0.05$ level).

Clumps did not show any yield advantage in this study, and this was not surprising considering the extremely high yield level (Table 9). The C4-100 treatment decreased yield, but the reduction was only 10 to 15%. The C4-100 treatment produced the lowest number of tillers and the relatively low plant population coupled with low tiller formation likely did not produce an adequate number of panicles for maximum yield. The SP-25-TR treatment reduced yields by 25 to 30%, likely due to the low number of panicles that were produced. Observations made during harvest suggested that yields were limited by lack of panicles because they were so large that stalk breakage was common. The fact that

Table 9. Mean values of measurements for grain sorghum as affected by five planting geometries in 75-cm rows in experiments at Tribune, KS, in 2004.†

Planting geometry‡	Tillers plant^{-1} 28 DAP§	Grain	Harvest index values	Aboveground biomass
	no plant^{-1}	kg ha^{-1}		kg ha^{-1}
Stubble-mulched area				
SP-25	2.3a¶	6206b	0.43a	12 660a
C3-75	1.0b	6090b	0.47a	11 366b
C4-100	1.1b	5691c	0.48a	10 400b
SP-38	3.1a	6472a	0.43a	13 202a
SP-25-TR	removed	4410d	0.48a	8 059c
No-tilled area				
SP-25	2.3a	6408b	0.45a	12 491ab
C3-75	1.2b	6426b	0.48a	11 743bc
C4-100	1.0b	6054c	0.48a	11 064c
SP-38	3.1a	6662a	0.44a	13 280a
SP-25-TR	removed	4707d	0.48a	8 605d

† Separate but identical experiments were conducted on stubble-mulched and no-tilled areas.

‡ Planting geometries were SP-25 (plants every 25 cm), C3-75 (clumps of three plants every 75 cm), C4-100 (clumps of four plants every 100 cm), SP-38 (plants every 38 cm), and SP-25-TR (plants every 25 cm with tillers removed by hand) in 75-cm rows.

§ Days after planting (DAP).

¶ Means in columns for a tillage area followed by the same letter are not significantly different according to a protected LSD mean separation ($P < 0.5$ level); each tillage area represents a separate experiment and cannot be compared statistically.

clumps depressed sorghum grain yields only about 10% under very favorable growing conditions is important because it indicates minimal downside risk with the use of clumps under dryland conditions even when seasonal precipitation is greater than normal.

Harvest index values were not different at the $P < 0.05$ level, but it is noteworthy that the values for the SP-25 and SP-38 treatments were always lower. These treatments had many more tillers than the other treatments and suggest some stress. Prihar and Stewart (1990) reported that the harvest index for grain sorghum has a genetic potential of about 0.53 when produced under little or no stress, and that the harvest index value decreases with increasing stress. The clump treatments, C3-75 and C4-100, and the SP-25-NT treatment that had all tillers removed, had harvest index values approaching the genetic potential of grain sorghum grown with little or no stress, even though they yielded less. This further supports our contention that the lower yields for these treatments were because of insufficient number of panicles.

CONCLUSIONS

In the southern Great Plains, dryland grain sorghum is commonly seeded during the wettest period of the year when plant available water is abundant in the soil profile. Our results indicate that growing plants in clumps compared to uniformly spaced plants reduces the number of tillers and vegetative growth. This preserves soil water until reproductive and grain-filling growth stages, which increases grain yield. There are marked differences in plant architecture of uniformly spaced plants compared to clumped plants. Uniformly spaced plants produce more tillers and the leaves on both the main stalk and tillers grow outward, exposing essentially all of the leaf area to sunlight and wind. In contrast, clumped plants grow upward with the leaves partially shading one another and reducing the effect of wind, thereby reducing water use. The benefit of clumps decreased as grain yields increased, and there was even a slight decrease when yields exceeded 6000 kg ha^{-1}. However, dryland grain sorghum yields seldom reach this level in semiarid regions so growing grain sorghum in clumps appears to be a useful strategy with little downside risk.

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