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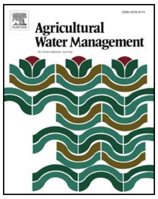

Deficit irrigation effects on yield and yield components of grain sorghum

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ABSTRACT

Development of sustainable and efficient irrigation strategies is a priority for producers faced with water shortages. A promising management strategy for improving water use efficiency (WUE) is managed deficit irrigation (MDI), which attempts to optimize yield and WUE by synchronizing crop water use with the crop's reproductive stages. In comparison, deficit irrigation (DI) is applied at a fraction of the full (FI) irrigation requirement. Soil water use and grain yield of grain sorghum [Sorghum bicolor (L.) Moench] were evaluated in the High Plains of Texas, USA under three irrigation strategies: FI, DI, and MDI from 2010 to 2012. Grain yields of FI sorghum averaged 3.7 Mg ha^{-1} greater ($p < 0.001$) than DI sorghum in all years. However, MDI yields averaged 1.6 Mg ha^{-1} more than DI yields, which was significant in 2010 and 2012 ($p \le 0.006$). The WUE of FI sorghum was significantly greater than MDI in 2012 ($p = 0.003$) and DI in 2010 and 2012 ($p \le 0.001$) demonstrating that limiting water did not reduce WUE in two of the three years. Results suggest that WUE's of grain sorghum are not compromised under MDI compared with FI in most cropping seasons. While FI provides the greatest opportunity to reduce production risks through increased yield, if irrigation water is limiting, MDI provides less risk than DI due to its ability to maintain yield and WUE. Yield was stabilized in all years by increasing seed panicle^{-1} under MDI, which was supportive of concentrating irrigation water between growing point differentiation and half bloom to maintain ovules.

1. Introduction

Grain sorghum is a drought tolerant crop that is suitable for rain-fed and deficit irrigation due to its physiological adaptability to short-term water stress (Assefa et al., 2010; Garrity et al., 1982a; Garrity et al., 1982b; Peacock, 1982). Although grain sorghum can withstand prolonged periods of water stress, such tolerance comes at the expense of reduced yield (Assefa et al., 2010; Peacock, 1982). Delineating crop reproductive responses under water-stressed field conditions is critical to the adoption of management strategies that optimize yield under deficit irrigation.

Historically, irrigation practices on the Texas High Plains have been related to irrigation well capacities during peak demand periods, but due to declining well capacities and water district restrictions, historical irrigation practices are no longer viable. Because irrigation helps mitigate production risks associated with often un-predicable in-season precipitation in semi-arid zones while improving crop quality and value (Wagner, 2012), research to understand crop responses to the amount and timing of irrigation is essential. In a review of previous research on the High Plains, Staggenborg et al. (2008) reported that July precipitation is most beneficial for sorghum grain yield, which coincides with the reproductive period of sorghum in this region. The authors specified that in a rain-fed cropping system, grain sorghum yields increased 0.1–0.2 Mg ha^{-1} for each cm precipitation received in July. Regardless of precipitation timing, water availability at critical growth stages is often of greater importance than annual precipitation (Larfarge et al., 2002).

In anticipation of widespread shortages of water for irrigation, Garrity et al. (1982a,b) predicted that irrigated agriculture was entering the "age of management" whereby water deficits could not be avoided, but should be anticipated and managed. As producers adopt conservation measures driven by limited water supplies and social pressures, irrigation management strategies that concentrate water during critical growth stages or employ supplemental irrigation rather than traditional fully irrigated practices could potentially stabilize crop production and an agriculturally driven economy for an extended period (Bordovsky et al., 2011).

A promising management strategy for improving water use

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efficiencies is deficit irrigation, which attempts to optimize the use of irrigation water and precipitation (English, 1990). Traditionally, deficit irrigation entailed irrigation at a fraction of what the crop would use if water were not limited (Howell et al., 2007). However, a more intensified management approach considers the dynamics of crop water use throughout the growing season (Vadez et al., 2013). An optimally managed deficit irrigation strategy may also depend on the amount and depth distribution of water stored in the soil profile at the time of planting. Accordingly, two important components of managed deficit irrigation are (i) the attempt to minimize evaporative losses of water directly from the soil, which occurs during the early part of the cropping season when the fraction of soil covered by the crop is small, and (ii) to concentrate irrigation at stages of crop growth critical to determining potential yield. These two components must be considered together, not independently, as increases in yield may not always be achieved through maximization of water extraction by the plants. While water stress at any stage can reduce sorghum yield, water stress during the reproductive stage of sorghum is the most detrimental (Assefa et al., 2010). With grain sorghum, it has been well-documented (Van Oosterom and Hammer, 2008; Tolk et al., 2013; Prasad et al., 2008; Blum, 2005; Crauford and Peacock, 1993; Peacock, 1982; Eck and Musick, 1979) that water stress from growing point differentiation through anthesis suppresses grain yield due to reduced seed number.

Seed number is established shortly after growing point differentiation, the initial stage of reproductive development (Vanderlip and Reeves, 1972). Water stress during the boot stage minimizes head exertion from the flag leaf sheath, which restricts flowering and the success of pollination (Gerik et al., 2003). During anthesis, water stress may induce floral abortion and decrease seed number. In contrast, water stress from anthesis through the dough stage reduces grain mass (Ockerby et al., 2001; Maman et al., 2004). Understanding the effects of the magnitude of water use during these crop developmental phases on grain production is essential to evaluate and incorporate water conservation measures into irrigation practices.

The objectives of this study were to determine the effect of deficit irrigation strategies and resultant plant available water (*PAW*) on sorghum grain yield and associated yield components; specifically, harvest index (*HI*), panicles per unit land area, number of seeds per panicle, and seed mass. The effect of deficit irrigation strategies on grain WUE was also assessed.

2. Materials and methods

Research was conducted at the USDA-Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, Texas, USA (35°11′N, 102°5′W; 1170 m elevation) for three growing seasons from 2010 to 2012. Twelve experimental plots (15- by 109-m) in a randomized complete block design were established on a 180- by 109-m field on Pullman clay loam (Fine, mixed, superactive, thermic Torrertic Paleustoll) with < 1% slope. Soil water retention characteristics of the Pullman soil were determined using the pressure plate extractor method of Klute (1986) to determine the available water for each depth increment (Bell, 2014). A mid-season grain sorghum cultivar (DeKalb DKS44-20) was evaluated under four irrigation treatments: full irrigation (FI), deficit irrigation (DI), managed deficit irrigation (MDI), and non-irrigated (NI). Each treatment was replicated three times. Scheduling of FI was based on weekly measurements of the soil water depletion within the rooting zone (0–1.6 m). Soil water contents were determined using a neutron moisture gage (model 503DR, InstroTek, Inc., Raleigh, NC) from 0.1- to 2.3-m depth in 0.2-m increments at weekly intervals throughout the growing season at two locations in each of the 12 experimental plots. An additional four access tubes were located in MDI plots for a separate detailed sub-study of MDI that were used in the MDI water balance. The neutron moisture gage was previously field calibrated for the Pullman soil for the A, Bt and Btk horizons (Evett and Steiner, 1995) with 1.0% accuracy. The depth of irrigation water applied was 25–32 mm to the FI treatment when stored soil water fell below a set managed allowable depletion (MAD) defined as 50% of plant available water within the rooting zone at field capacity, which was calculated as the difference between depth averaged water contents at -33 kPa ($0.328\ \mathrm{m^3\,m^{-3}}$) and -1.5 MPa ($0.197\ \mathrm{m^3\,m^{-3}}$) measured in 0.2-m increments throughout the root zone (0–1.6 m). In this soil, the calculated plant available water within the rooting zone was 210 mm [($0.328\ \mathrm{m^3\,m^{-3}}$–$0.197\ \mathrm{m^3\,m^{-3}}$) × 1600 mm].

Deficit irrigation was scheduled at 50% of FI and applied at application depths similar to the FI treatment but less frequently. Managed deficit scheduling was based on a fraction of the cumulative amount of FI and varied with growth stage. During the vegetative growth stage, one or two irrigations were omitted from MDI compared with DI, such that applications amounts for MDI were less than 50% of the FI treatment for that stage. From growing point differentiation to half-bloom (approximately 35–70 days after planting for the specified sorghum variety at this site), irrigations for MDI were scheduled at 75% of FI. From half-bloom to physiological maturity, irrigations for MDI were scheduled at 50% of FI. As with DI, MDI irrigation depths were also applied at similar application depths of the FI treatment but less frequently.

Irrigation was applied with a three-span, lateral-move sprinkler system (Model 6000, Valmont Irrigation, Valley, NE). Drop hoses spaced 1.5-m apart were equipped with No. 15 low drift nozzles ($0.32\ \mathrm{L\,s^{-1}}$ regulated at 68.9 kPa) (Senninger Irrigation, Inc., Clermont, FL) at 0.5-m above ground surface, convex-medium grooved spray pads.

Prior to initiation of experimental plots in 2010, the research field was deep-tilled using a para-plow in the fall of 2009 to disrupt a plow pan that had formed under previous management. Research plots were deep chiseled each fall, following harvest, using a chisel-chopper drag plow (BJM Sales and Service, Hereford, TX). Plots were tilled twice each spring for weed control and seedbed preparation at a depth of approximately 0.13 m using a three-blade 4.5-m sweep plow with one 1.5-m wide center blade and two exterior 1.8-m wide blades.

Experimental plots were sampled and analyzed for fertility requirements in April of each experimental year for a grain-yield goal of $11\ \mathrm{Mg\,ha^{-1}}$ under irrigation and $4\ \mathrm{Mg\,ha^{-1}}$ under non-irrigated treatments. For all experimental years, mean nitrogen and phosphorus recommendations were 180–$193\ \mathrm{kg\,ha^{-1}}$ N and 29–$42\ \mathrm{kg\,ha^{-1}}$ P_2O_5, respectively for irrigated treatments. Each May, ammonium polyphosphate (10-34-0) and urea-ammonium-nitrate (32-0-0) were blended and knifed-in ($62\ \mathrm{kg\,ha^{-1}}$ N and $29\ \mathrm{kg\,ha^{-1}}$ P_2O_5) across all irrigated plots as a pre-plant fertilizer to meet the irrigated crop total phosphorus and partial nitrogen requirements. Remaining nitrogen requirements were satisfied through injection and application of 32-0-0 with irrigation water at the 10-leaf stage through the sprinkler system. Fertilizer requirements of the NI crop ($40\ \mathrm{kg\,ha^{-1}}$ N and $23\ \mathrm{kg\,ha^{-1}}$ P_2O_5) were knifed-in as a pre-plant fertilizer treatment. The sorghum was planted on 0.76-m row spacing using a Max-Emerge vacuum planter (John Deere, East Moline, IL) at a seeding density of $161{,}000\ \mathrm{ha^{-1}}$ in 2010 and 2011 and $173{,}100\ \mathrm{ha^{-1}}$ in 2012. Bicep II Magnum (Atrazine plus S-metolachlor; Syngenta Crop Protection, LLC) was sprayed as a pre-emergent to control in-season weeds.

Micrometerological variables were monitored using a datalogger (model CR23X, Campbell Scientific, Inc., Logan, UT) and environmental instrumentation located centrally within the experimental field. Measurements were recorded at 0.25-h intervals and included ambient air temperature and relative humidity (model HMP45C Temperature and Humidity Probe, Vaisala Inc., Helsinki, Finland), wind velocity (model 014A wind sensor, MET-ONE Instruments, Inc, Grants Pass, OR), and total global irradiance (model LI-200SA pyranometer, Li-Cor Biosciences, Lincoln, NE) all at 2 m above the surface. Precipitation was measured using a tipping bucket rain gage (TE525 M, Texas Electronics, Dallas, TX) and incoming and reflected short and longwave radiation in 2010 and 2012 (models CM14 albedometer and CGR3 pyrgeometer, Kipp and Zonen, Delft, Netherlands), and net radiation (model Q*7.1