

Evapotranspiration of Deficit Irrigated Sorghum

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Abstract

Deficit irrigation commonly is used in regions with reduced or limited irrigation capacity to increase water use efficiency (WUE). This research measured sorghum (*Sorghum bicolor* L. Moench) water use (ET) and yield so WUE could be determined. Two precision weighing lysimeters were used to accurately measure sorghum ET from a fully irrigated field (FULL) and a deficit irrigated field (DI; ~50% irrigation) that was irrigated by a lateral-move sprinkler system at Bushland, TX in 1993. Sorghum ET decreased 10% from 621 mm to 560 mm with a 48% decline in irrigation. WUE for both grain and dry matter increased slightly with DI but seed mass, and harvest index were unaffected. Sorghum extracted soil water mainly above 1.2 m in the Pullman soil profile if well watered, but DI sorghum extracted soil water to 1.7 m. Sprinkler DI beginning with a nearly full soil water content profile permitted the crop to better exploit the soil profile water and minimize soil water deficit effects on crop yield in a year with typical summer rainfall for Bushland (~210 mm) such that yield was not reduced by DI.

Introduction

Deficit irrigation as characterized by English et al. (1990) has the fundamental goal to increase water use efficiency (WUE). Fereres and Soriano (2006) recently reviewed deficit irrigation and concluded that the level of irrigation supply should be 60-100% of full evapotranspiration (ET) needs in most cases to improve water productivity. They indicated "regulated deficit irrigation" (RDI) was successful in several cases, especially with fruit trees and vines, to not only increase water productivity but also farm profit. Deficit irrigation (DI) is widely used in the Southern High Plains and Columbia Basin in the U.S. with their limited irrigation capacities (Musick et al., 1988; English, 1990). High irrigation frequencies have been reported by Miller (1977) and Miller and Aarstad (1976) to improve DI results with sugarbeet on sandy soils, but Faci and Fereres (1980) and English and Nakamura (1989) reported little or no effect of irrigation frequency on DI with cereal crops, especially on finer texture soils. Farre and Faci (2006) reported greater WUE with sorghum (*Sorghum bicolor* L. Moench) compared with corn (*Zea mays* L.) with DI in Spain on a loam soil. Tolk and Howell (2003) reported mean WUE for sorghum of 1.46 kg m^{-3} at Bushland, TX on the Pullman clay loam soil, but they reported a greater WUE for the Amarillo sandy loam soil and smaller WUE for the Ulysses silt loam soil. They also reported differences in WUE in two seasons across four irrigation levels.

The purpose of this paper is to present and briefly discuss and describe the ET of deficit and more fully irrigated grain sorghum measured at Bushland, TX with precision weighing lysimeters (Marek et al., 1988; Howell et al., 1995a) and the resulting WUE (for both grain and biomass) computed from the ET and yield. The crops were produced in large fields that were sprinkler irrigated frequently (2-3 times per week if required) to maintain adequate soil water for the “well-watered” crop ET.

Procedures

This study was conducted at the USDA-ARS Laboratory at Bushland, TX (35º 11' N lat.; 102º 06' W long.; 1,170 m elev. above MSL) in 1993. Crop ET was measured with two weighing lysimeters (Marek et al., 1988) each located in the center of two 4.4-ha 210 m E-W by 210 m N-S fields. The soil at this site is classified as Pullman clay loam (fine, mixed, superactive thermic Torrertic Paleustoll) (Unger and Pringle, 1981; Taylor et al., 1963) which is described as slowly permeable because of a dense B22 horizon about 0.3 to 0.5 m below the surface. The two east lysimeter fields were used for this experiment. The plant available water holding capacity within the top 2.0 m of the profile is approximately 240 mm (Tolk and Howell, 2001) and ~200 mm to the 1.5-m depth. A calcareous layer at about the 1.4 m depth somewhat limits rooting and water extraction below this depth, depending on the crop. Variations of this soil series are common to more than 1.2 million ha of land in this region and about 1/3 of the sprinkler-irrigated area in the Texas High Plains (Musick et al., 1988). Weighing lysimeters offer one of the most accurate means to measure ET (Hatfield, 1990). Predominate wind direction is SW to SSW, and the unobstructed fetch (fallow fields or dryland cropped areas) in this direction exceeds 1 km. The field slope is less than 0.3 percent. More descriptive information on the facility is provided in Howell et al. (1995b), Howell et al. (1997), Howell et al. (2004), and Evett et al. (2000).

The sorghum cultivar, DK-56[1/] (Dekalb, Monsanto Co., St. Louis, MO), was planted in the field on 27 May (DOY 147) in E-W rows 0.76 m apart with a six-row conventional farm planter. The six rows at each lysimeter [about 10 m total length] with four rows in the lysimeter were planted by hand with the same sorghum cultivar and later thinned to match the field plant population. The SE lysimeter was planted on May 27 (DOY 147), and the NE lysimeter was planted on 28 May (DOY 148). Irrigation (16 mm) was applied uniformly on 28 May (DOY 148) for seed germination and uniform emergence. The final mean emerged field plant stand was 22 plants m^{-2} in the two fields. Harvest plant density counts averaged 20-21 plants m^{-2} for both fields and lysimeters. The fields and lysimeters were fertilized on 8 May (DOY 159) at the rate of 11.2 g (N) m^{-2} with granular urea (45-0-0) and disked to incorporate. The lysimeter fields were cultivated and furrow diked (both to retain rain and irrigation amounts as well as match the 'free board" water retention by the lysimeter walls). The lysimeters were hand harvested on 5-6 Oct (DOYs 278-279), and the fields were combine harvested on the same dates.

<u>Lysimeter Measurements</u>

Lysimeter mass was determined using a Campbell Scientific CR-7X data logger to measure and record the lysimeter load cell (Interface SM-50) signal at 0.5-Hz (2 s) frequency. The load cell signal was averaged for 5 min and later reported as 30-min means (reported on the mid point of the 30 min, i.e. data were averaged from 0-30 minutes and reported at 15 min). The lysimeter mass resolution was 0.01 mm, and its accuracy exceeded 0.05 mm (Howell et al., 1995a). Daily ET was determined as the difference between lysimeter mass losses (from evaporation and transpiration) and lysimeter mass gains (from irrigation, precipitation, or dew) divided by the lysimeter area (9 m^2). A pump regulated to -10 kPa provided vacuum drainage, and the drainage effluent was held in two tanks suspended from the lysimeter (their mass was part of the total lysimeter mass) and independently weighed by load cells (drainage rate data are not reported here). ET for each 24-h period was divided by 1.02 to adjust the lysimeter area to the mid point between the two walls (10 mm air gap; 9.5 mm wall thickness; 9.18-m^2 area instead of 9.00-m^2 area). This correction would be applicable for full-cover crops, but it would not be necessary for bare soil conditions. Nevertheless, it was applied to all data uniformly.

<u>Irrigation Treatments</u>

The east lysimeter field was irrigated with a lateral-move sprinkler system with the north half (NE) being irrigated to meet the crop water use (FULL) and the south half (SE) being DI with approximately 50% of the FULL rate by using smaller nozzles. The FULL treatment was managed to meet the water demand of the crop. Irrigations were applied with a 10-span lateral-move sprinkler system (Lindsay Manufacturing, Omaha, NE) with an end-feed hose and aboveground, end guidance cable. The sprinkler system was aligned N-S, and irrigated E-W or W-E. The system

[1/] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by the USDA-Agricultural Research Service.

was equipped with gooseneck fittings and spray heads (Senninger Super Spray, Orlando, FL) with concaved spray plates on drops located about 1.5 m above the ground and 1.52 m apart. Each spray head was equipped with a 100-kPa pressure regulator and a 1-kg polyethylene drop weight. Irrigations were scheduled to meet the ET water use rate and were typically applied in one to two 25-mm applications per week. Irrigations were managed on the FULL treatment to minimize soil water deficits with the available irrigation capacity allowing 25-30 mm .for rainfall storage. The DI treatment allowed the soil water profile to gradually deplete.

Soil Water Measurements

Soil water contents were measured periodically using a neutron probe (model 503DR Hydroprobe. CPN International, Inc., Martinez, CA) at 0.2-m depth increments beginning with the 0.10-m depth using 60-s counts. Two access tubes were located in each lysimeter (read to 1.9 m depth) and four tubes were located in the field surrounding each lysimeter (read to 2.3-m depth). The probe was field calibrated for the Pullman soil using a method similar to that described by Evett and Steiner (1995).

Plant and Yield Sampling

Plant samples from three separate 1.5-m^2 areas were obtained periodically to measure crop development. These field samples were taken at sites about 10 to 20 m away from the lysimeters in areas of the field representative of the lysimeter vegetation. Leaf area index (LAI), crop height (CH), and aboveground dry matter (DM) were measured from three samples. Final yield was measured by harvesting the lysimeter grain and aboveground plant matter from each lysimeter (9 m^2), and dry matter and yield at harvest were measured from three adjacent 1.5-m^2 plant samples.

Water Use Efficiency

Water use efficiency (WUE) was computed based on Viets (1962) and Zwart, and Bastiaanssen (2004) [see also Farre and Faci (2006) and Tolk and Howell (2003)]. WUE_g (in kg m^{-3}) was the ratio of grain yield (dry) (GY_d; in g m^{-2}) to ET (in mm); WUE_{dm} (in kg m^{-3}) was the ratio of DM (in g m^{-2}) to ET (in mm); and harvest index (HI) was the dimensionless ratio of GY_d to DM.

Results

The crop emerged on 3 June (DOY 154). The rainfall received from crop planting until harvest was 211 mm typical for a normal summer rainfall season at Bushland, TX [~480-500 mm long-term annual mean]. Almost one-third of the growing season rain (70 mm) was received on 14 and 15 July (DOYs 195 and 196). The FULL irrigation treatment received 369 mm of season irrigation and the DI treatment received 171 mm of irrigation. Measured drainage was 46 mm for the FULL treatment and 29 mm for the DI treatment. Total net water applied (rain plus irrigation) was 586 mm for FULL and 388 mm for DI from planting and 563 mm for FULL and 365 for DI from the emergence date (Fig. 1).

Crop Evapotranspiration

The seasonal ET rates are shown in Figure 2 and the cumulative seasonal ET was shown in Figure 1 for comparison with the rainfall and applied water. Seasonal ET amounts were 621 and 560 mm for the FULL and DI treatments from emergence. The FULL ET (ET_{FULL}] was about 40 mm less than that reported by Tolk and Howell (2003) for their 100% ET treatment in 1998 and 85 mm more than their reported 100% ET in 1999. It was about 30 mm less than the T-1 treatment (100% ET) in 1995 for sorghum in Spain (Farre and Faci, 2006). The DI sorghum ET [ET_{DI}] was about 20 mm more than that reported by Tolk and Howell (2003) for their 50% ET treatment in 1998 and 100 mm more than their reported 100% ET in 1999. The Bushland ET_{DI} was about mid way between the T-1 ET (588 mm) and T-2 ET (544 mm) reported by Farre and Faci (2006) for 1995 in Spain from a line source experiment. The daily ET deficit ratio [$ET_{DI}\,ET_{FULL}^{-1}$; Fig. 1 and 2] was somewhat erratic during the early season due to the usually smaller ET rates, except following rain or irrigation when the deficit ET ratio was near 1.0. Following full crop development (Fig. 3; ~60 days after emergence) with still a minor decline in profile soil water (Fig. 4A), the deficit ET ratio gradually declined below 1.0 likely due to less soil water evaporation from the smaller irrigations until the soil water profile gradually depleted further (Fig. 4B), but it never was less than 0.75 after full cover until near crop maturity. Daily ET rates were about 7-8 mm d^{-1} with full cover [after

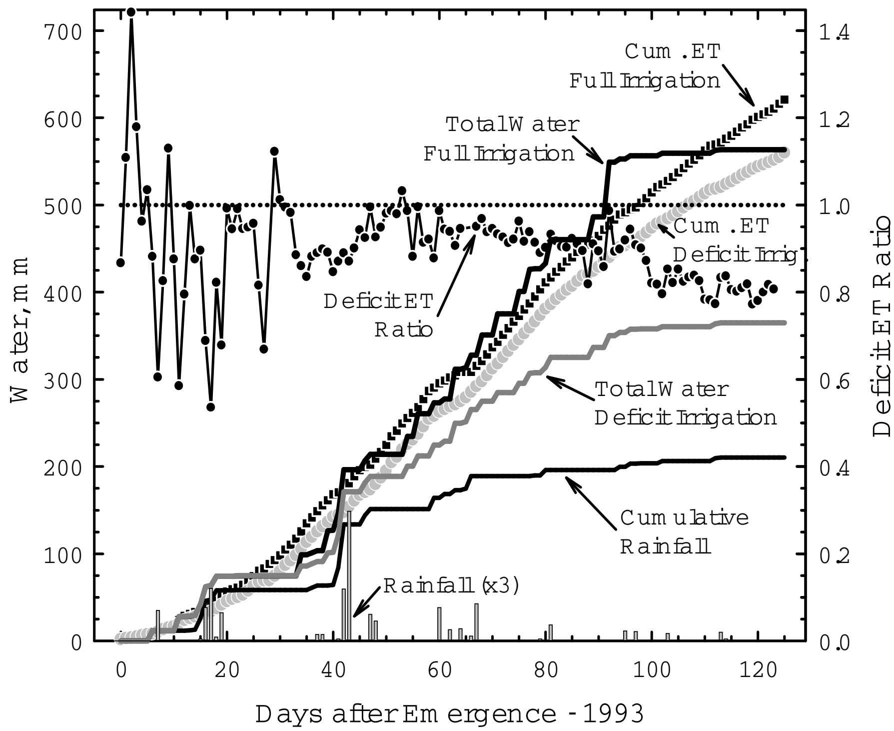

Figure 1. Water balance parameters for the 1993 sorghum growing season (note the rainfall bars were multiplied by 3 to be more visible on the scale). The deficit ET ratio was the daily ratio of ET_{DI} to ET_{FULL} [$ET_{DI}\,ET_{FULL}^{-1}$] (right axis scale).

the boot growth stage at ~60 days after emergence in (Fig. 3)] with a few days with ET rates of 8-10 mm d^{-1} (Fig. 2) likely due to stronger regional advection.

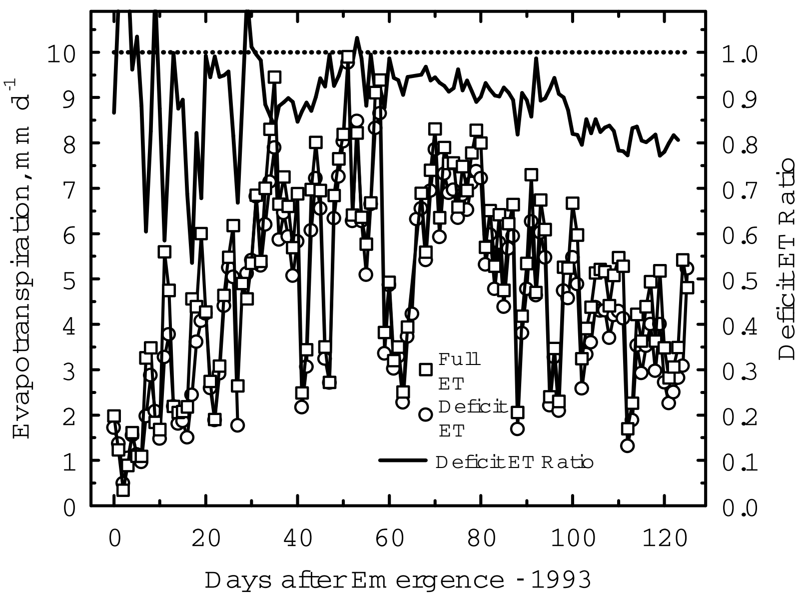

Figure 2. Daily ET rates and the daily deficit ET ratio [ET_{DI} ET_{FULL}^{-1}] (right axis scale).

Crop Development

Figure 3 shows the crop development in 1993. Neither crop height (CH) nor dry matter (DM) were different (based on the standard deviations of the sample observations) between the FULL and DI treatments. Leaf area index (LAI) was essentially the same for the FULL and DI fields until about 90 days after emergence when the soil water profile had greater depletion (Fig. 4B). LAI peaked near 5.0-5.2 m^2 m^{-2}, which was less than the sorghum maximum of the T-1 treatment LAI (100% ET; Farre and Faci, 2006) of 6.4 m^2 m^{-2} in Spain. Maximum DM was near 1,800-2,000 g m^{-2} which was similar to that reported by Farre and Faci (2006) [dry matter of 1,838 g m^{-2}] in Spain for their T-1 treatment (100 % ET).

Soil Water

Figure 4 shows the mean field soil water content profiles for the two fields. The lysimeter and field soil water profiles did not differ significantly, except the lysimeters only permitted measuring to the 1.9-m depth (data not given here). Most sorghum root extraction in the Pullman soil occurred above the 1.2-m depth for the FULL field and the DI field before boot (Fig. 4 A and B), but DI sorghum extracted some soil water to the 1.7-m depth in the Pullman soil after the boot stage well below the interface with the calcic horizon, showing that sorghum roots will penetrate the calcareous soil if water is available there and if overlying horizons become dry.

Water Use Efficiency

Table 1 summarizes the WUE and yield data. The DM, grain yield, harvest index, and seed mass were not statistically different on the two lysimeters between the FULL and DI treatments based on a t-Test. Seed mass averaged 25 mg $seed^{-1}$, and HI averaged 0.45. The HI was somewhat lower than that reported for the T-1 treatment (100% ET) by Farre and Faci (2006) of 0.49. Mastrorilli et al. (1995) reported well-watered sorghum seed mass of 26 mg $seed^{-1}$ in Italy. Grain yield of the FULL lysimeter (898 g m^{-2}) was slightly greater than the yield reported for the T-1 treatment (100% ET) by Farre and Faci (2006) of 854 g m^{-2} in Spain or the 100% ET treatment yield reported by Tolk and Howell (2003) for the Pullman soil at Bushland of 865 g m^{-2} in 1998 and 879 g m^{-2} in 1999. Mastrorilli et al. (1995) reported well watered sorghum yield of 634 g m^{-2} in Italy in 1991. Harvest DM of 2006 g m^{-2} at Bushland was greater than that reported for the T-1 treatment (100% ET) by Farre and Faci (2006) of 1,838 g m^{-2} in Spain. Mastrorilli et al. (1995) reported sorghum DM of 2,040 g m^{-2} in Italy for non-stressed sorghum.

Table 1. Summary of ET, yield, and WUE data for the treatments. Numbers in parenthesis are standard deviations of the individual row yields in a lysimeter.

Category	Treatments	
	FULL	DI
ET (mm)	621	560
Grain Yield (g m^{-2}) (dry)	898* (43)	919* (45)
Dry Matter (g m^{-2})	2,006* (77)	2,042* (91)
Seed Mass (mg $seed^{-1}$)	24.9* (1.00)	24.6* (0.50
HI	0.448* (0.018)	0.450* (0.005)
WUE_g (kg m^{-3})	1.45	1.64
WUE_{dm} (kg m^{-3})	3.23	3.65
* n.s. Difference by t Test for Differences between FULL and DI.		

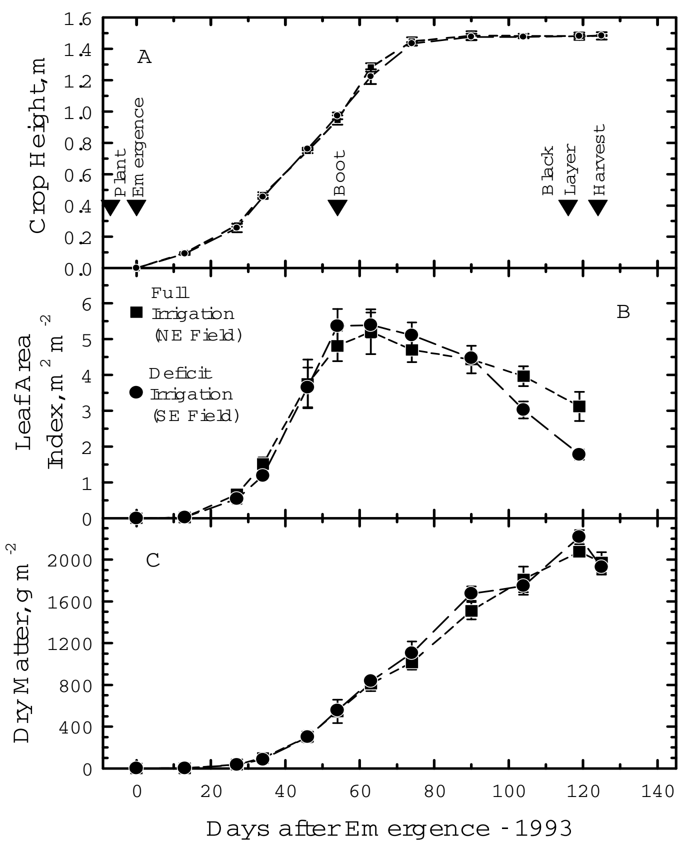

Figure 3. Crop development. Top (A) is crop height; middle (B) is leaf area index; and bottom (C) is dry matter.

WUE_{dm} at Bushland was 3.23 kg m^{-3} for FULL and 3.65 kg m^{-3} for DI. Farre and Faci (2006) did not report WUE_{dm}, but their data for the T-1 treatment (100% ET) were used to compute WUE_{dm} as 3.12 kg m^{-3}. Mastrorilli et al. (1995) reported WUE_{dm} of 4.85 kg m^{-3}. WUE_g was 1.45 kg m^{-3} for the FULL lysimeter and 1.64 kg m^{-3} for the DI lysimeter. Tolk and Howell (2003) reported WUE_g that varied from 1.31 kg m^{-3} in 1998 to 1.64 kg m^{-3} in 1999 for WUE_g of 1.46 kg m^{-3} for their T-1 treatment (100 % ET). WUE_g was reported as 1.51 kg m^{-3} for non-stressed sorghum in Italy (Mastrorilli et al.,1995). WUE_g increased at 50% ET in both years on the

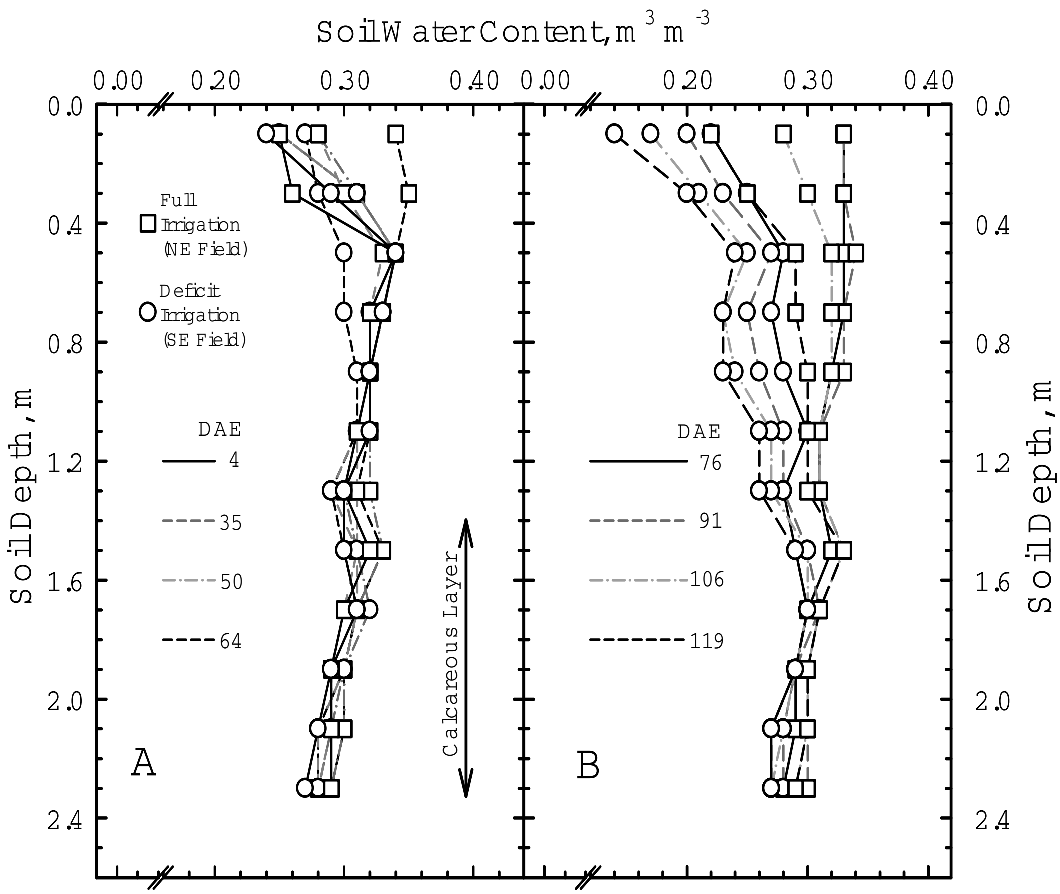

Figure 4. Soil water content profiles (mean of four neutron tube sites) in each treatment field for emergence to boot (A) and boot to maturity (B).

Pullman soil as reported by Tolk and Howell (2003) but decreased with greater ET deficits in Spain (Farre and Faci, 2006).

Conclusions

Deficit irrigation of sorghum at Bushland in a year with typical summer rainfall did not reduce yield but increased water use efficiency. Sorghum is widely known as a drought tolerant crop (Krieg and Lascano, 1990; Farre and Faci, 2006; Tolk and Howell, 20003; Mastrorilli et al., 1995; etc.) so planned water deficits (Lamm et al., 1994) can be an effective irrigation management strategy to reduce irrigation applications, especially with lower capacity center pivot sprinkler systems. DI does impose greater risk of reduced yields from water deficits when rainfall deficits are greater than occurred here or when irrigation capacity is reduced more than 50% of that required for non-stressed production largely in agreement with the conclusion of Fereres and Soriano (2006).

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References

English, M.J. (1990). "Deficit irrigation: Observations in the Columbia Basin." *J. of Irrig. and Drain. Engr. (ASCE)* 116(3):413-426.

English, M.J., and Nakamura, B.C. (1989). "Effects of deficit irrigation and irrigation frequency on wheat yields." *J. of ASCE Irrig. and Drain.Div.* 115(IR2):172-184.

English, M.J., Musick, J.T., and Murty, V.V.N. (1990). "Deficit irrigation." pp. 631-663. In: G.J. Hoffman, T.A. Howell, and K.H. Solomon (eds.) *Management of Farm Irrigation Systems*, ASAE Mono., Am. Soc Agric. and Biol. Engr., St. Joseph, MI.

Evett, S.R., Howell, T.A., Todd, R.W., Schneider, A.D., and Tolk, J.A. (2000). "Alfalfa reference ET measurement and prediction." pp. 266-272. In: R.G. Evans, B.L. Benham, and T.P. Trooien (eds.) Proceedings of the 4th Decennial National Irrigation Symposium, Nov. 14-16, Phoenix, AZ, Am. Soc. Agric. and Biol. Engr., St. Joseph, MI.

Faci, J.M., and E. Fereres, E. (1980). "Responses of grain sorghum to variable water supply under two irrigation frequencies." *Irrig. Sci.* 1:149 – 159.

Farre, I., and Faci, J.M. (2006). "Comparative response of maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench) to deficit irrigation in a Mediterranean environment." *Agric. Water Mgmt.* 83:135-143.

Fereres, E. and Soriano, M.A. (2006). "Deficit irrigation for reducing agricultural water use." *J. Exp. Botany* JXB Advance Access published on November 6, 2006, DOI 10.1093/jxb/erl165.

Hatfield, J.L. (1990). "Methods of estimating evapotranspiration." pp. 435-474. In: B.A. Stewart and D.R. Nielsen (eds.) *Irrigation of Agricultural Crops*, Agron. Mono. No 30, Am. Soc. Agron., Madison, WI.

Howell, T.A., Evett, S.R., Tolk, J.A., and Schneider, A.D. (2004). "Evapotranspiration of full-, deficit-irrigated, and dryland cotton on the Northern Texas High Plains." *J. Irrig. and Drain. Engr. (ASCE)* 130(4):277-285.

Howell, T.A., Schneider, A.D., Dusek, D.A., Marek, T.H., and Steiner, J.L. (1995a). "Calibration and scale performance of Bushland weighing lysimeters." *Trans. ASAE* 38(4):1019-1024.

Howell, T. A., Steiner, J.L., Schneider, A.D., Evett, S.R., and Tolk, J.A. (1997). "Seasonal and maximum daily evapotranspiration of irrigated winter wheat, sorghum, and corn - Southern High Plains." *Trans. ASAE* 40(3)623-634.

Howell, T.A., Steiner, J.L., Schneider, A.D., and Evett, S.R. (1995b). "Evapotranspiration of irrigated winter wheat — Southern High Plains." *Trans. ASAE* 38(3):745-759.

Howell, T.A., Tolk, J.A., Schneider, A.D., and Evett, S.R. (1998). Evapotranspiration, yield, and water use efficiency of corn hybrids differing in maturity." *Agron. J.* 90(1):3-9.

Krieg, D.R., and Lascano, R.J. (1990). "Sorghum." pp. 719–740. In: Stewart, B.A.,Nielsen, D.R. (eds.), *Irrigation of Agricultural Crops*. Am. Soc. of Agron., Madison, WI.

Lamm, F.R., Rogers, D.H., and Manges, H.L. (1994). "Irrigation scheduling with planned soil water depletion." *Trans. ASAE* 37:1491–1497.

Marek, T.H., Schneider, A.D., Howell, T.A., and Ebeling, L.L. (1988). "Design and construction of large weighing monolithic lysimeters." *Trans. ASAE* 31(2):477-484.

Miller, D.E. (1977). "Deficit high-frequency irrigation of sugarbeets, wheat, and beans." pp. 269-282. In: Proc. Specialty Conference on Water Irrigation and Management for Drainage, ASCE, Reno, NV, 20-22 July 1977.

Miller, D.E., and Aarstad, J.S. (1976). "Yields and sugar content of sugar beets as affected by deficit high-frequency irrigation." *Agron. J.* 68:231-234.

Mastrorilli, M., Katerji, N., and Rana, G. (1995). "Water efficiency and stress on grain sorghum at different reproductive stages." Agric. Water Mgmt. 28:23–24.

Musick, J.T., Pringle, F.B., and Walker, J.D. (1988). "Sprinkler and furrow irrigation trends -Texas High Plains." *Appl. Engr. Agric*. 4(1):46-52.

Taylor, H.M., Van Doren, C.E., Godfrey, C.L., and Coover, J.R. (1963). "Soils of the southwestern Great Plains field station." Misc. Publ.- MP-669, Texas Agric. Exp. Stat., College Station.

Tolk, J.A., and Howell, T.A. (2001). "Measured and simulated evapotranspiration of grain sorghum grown with full and limited irrigation in three high plains soils." *Trans. ASAE* 44(6)1553-1558.

Tolk, J.A., and Howell, T.A. (2003). "Water use efficiencies of grain sorghum grown in three USA southern Great Plains soils." *Agric. Water Mgmt.* 59:97–111.

Unger, P.W., and Pringle, F.B. (1981). "Pullman soil: Distribution, importance, variability, and management." Bull. 13 - 1372, Texas Agric. Exp. Stat., College Station.

Viets, F.G. (1962). "Fertilizers and the efficient use of water." *Adv. Agron.* 14:223-264.

Zwart, S.J., Bastiaanssen, W.G.M. (2004). "Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize." *Agric. Water Mgmt.* 69:115–133.