Symposium Papers

Modeling Irrigation Management Strategies to Maximize Cotton Lint Yield and Water Use Efficiency

R. L. Baumhardt,* S. A. Staggenborg, P. H. Gowda, P. D. Colaizzi, and T. A. Howell

ABSTRACT

Increasing pumping costs and declining well capacities in the Southern High Plains compel producers to seek irrigation strategies to maximize yield and water use efficiency (WUE), which is the ratio of yield to evapotranspiration (ET). Cotton (*Gossypium hirsutum* L.) is suited to deficit irrigation using wells ranging from 0.29 to 0.93 L s^{-1} ha^{-1} capacity to supply limited, 2.5 mm d^{-1}, to complete, 8.1 mm d^{-1} ET replacement. Our objectives were to (i) evaluate irrigation capacity and duration effects on lint yield, and (ii) compare application strategies that maximize yield and WUE. The simulation model GOSSYM was used with 1959 to 2000 weather records from Bushland, TX, to calculate yields of cotton grown on a Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) with 50 or 100% initial available soil water. We compared all combinations of irrigation duration (4, 6, 8, and 10 wk) and capacity (for ET replacement of 2.5, 3.75, and 5.0 mm d^{-1} and dryland). Simulated lint yield decreased as irrigation decreased; however, yields for similar irrigation totals increased with increasing irrigation capacity. Simulated yields for cotton irrigated > 8 wk did not differ among irrigation capacities, but cotton irrigated at 5.0 mm d^{-1} maintained yield with earlier irrigation termination at 6 wk. Based on mean yields, we determined that spreading water to deficit irrigate a field with 2.5 mm d^{-1} yielded ~5% less lint than concentrating that water to irrigate smaller fields at 3.75 or 5.0 mm d^{-1} that were averaged with complementary (2:1 and 1:1) dryland areas.

The Ogallala Aquifer spans eight Great Plains states from Texas to South Dakota, and underlies ~27% of all U.S. agricultural land with ~30% of the total U.S. irrigation (Dennehy, 2000). Much of the aquifer has low recharge rates, and water pumped for irrigation, 95% of Texas High Plains water withdrawals, lowers the water table and decreases the well yield. Irrigation from the aquifer began in Texas during the 1940s and has resulted in estimated peak water table declines ranging up to 45 m with a spatially weighted mean decrease of 10.5 m since predevelopment conditions (McGuire, 2004). More recently, the 1980 to 2002 spatially weighted mean water levels show that the declining Ogallala Aquifer water table is common to other states, with both Kansas and Texas posting a 2.8-m decrease. Increasing irrigation costs due to higher fuel prices, combined with decreasing saturated thickness of the Ogallala Aquifer and related decreased irrigation well pumping capacity (Pittman et al., 2007) compel affected agricultural producers of the Southern High Plains to maximize yield while minimizing irrigation input.

R.L. Baumhardt, P.H. Gowda, P.D. Colaizzi, and T.A. Howell, USDA-Agricultural Research Service, Conservation and Production Research Laboratory, P.O. Drawer 10, Bushland TX 79012-0010; S.A. Staggenborg, Kansas State Univ., 2004 Throckmorton, Plant Sci. Ctr., Manhattan, KS 66506. Received 5 Aug. 2008. *Corresponding author (r.louis.baumhardt@ars.usda.gov).

Published in Agron. J. 101:460–468 (2009).
doi:10.2134/agronj2008.0041xs
Copyright © 2009 by the American Society of Agronomy, 677 South Segoe Road, Madison, WI 53711. All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher.

Water withdrawals from the Ogallala Aquifer for irrigation have been partially decreased through improved water application technologies like Low Energy Precision Application (LEPA) that have increased irrigation efficiency up to 95% (Howell, 2003). Also, improved irrigation scheduling practices increased crop WUE and yields where irrigation fully replaced ET (Howell, 2001). Where well capacity fails to fully meet crop water demand (i.e., deficit irrigation), management alternatives include limiting irrigation to critical growth periods (Musick and Sletten, 1966) or timely termination of irrigation to promote use of previously stored soil water. Alternatively, Baumhardt and Howell (2006) pointed out that deficit irrigation is often applied uniformly during the growing season because of the practical limitation imposed by irrigation well capacity that precludes large single irrigation applications during critical growth stages. Therefore, water deficit stress on a growing crop can span the entire growing season.

Suitability of deficit irrigation may vary with crop growth characteristic. For example, Wanjura and Upchurch (2000) reported a 60% corn (*Zea mays* L.) yield increase when comparing limited and full irrigation in contrast to only a 17% increase for similarly treated cotton. That is, the harvestable portion of a determinate crop like corn or wheat (*Triticum aestivum* L.) decreases more when water deficit stress conditions affect critical growth stages than an indeterminate crop like cotton that aborts or produces fewer fruiting forms (Doorenbos and Kassam, 1979). In this way, the indeterminate cotton crop may use water more efficiently by distributing produced assimilate to fewer harvestable fruit. This response suggests that uniformly spreading water to deficit irrigate a large area of cotton at a rate approaching 33% of the peak seasonal water demand would produce less lint than if the same amount of

Abbreviations: ET, evapotranspiration; WUE, water use efficiency.

water was concentrated to deficit irrigate smaller areas at 50 to 66% of peak demand and averaged with the complementary dryland area.

Optimum deficit irrigation of cotton must balance application capacity and duration with available soil water and rainfall amount and timeliness. At Bushland, TX, erratic growing season precipitation that varies in frequency and amount from 89 to 580 mm per year limit reliability of short duration field experiments that evaluate irrigation management strategies for maximizing long-term yields. Computer crop growth simulation models, together with long-term weather records provide an opportunity to expand the basis for comparing cotton irrigation strategies despite annual climatic variability. Staggenborg et al. (1996) found that GOSSYM, a cotton simulation model, accurately estimated crop water use on the Texas High Plains.

Our first objective was to determine the irrigation capacity, irrigation duration, and initial soil water content combination that would maximize lint yield of deficit-irrigated cotton. To achieve this, we simulated cotton lint yield and water use for every combination during each year of the 1959–2000 weather record at Bushland, TX. Our second objective was to compare the overall cotton lint yield response to a fixed water resource applied using various deficit irrigation strategies. To achieve this, we computed the weighted average lint yield for (i) a uniform spreading of the fixed water resource over the entire field, and (ii) a concentration of the fixed water resource over a portion of the field with complementary dryland areas.

MATERIALS AND METHODS

We used the cotton growth simulation model GOSSYM (Baker et al., 1983) v. 4 that was previously validated under Southern High Plains conditions (Staggenborg et al., 1996; Baumhardt, 2002) to calculate cotton lint yields and water use at the USDA–Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, TX (35°11′ N, 102°5′ W; and 1170 m MSL). Simulations were performed for a 1.8-m deep Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) profile divided into two horizons (0.0–0.3 and 0.3–1.8 m) with similar soil bulk density, texture, and hydrologic properties based on field measurements (Baumhardt et al., 1995) or the values supplied for that soil type with the model. The initial soil profile water content was uniformly reset for all simulations to either an optimum 100% of field capacity water storage scenario (~400 mm plant-available soil water) or a 50% field capacity scenario (~200 mm plant-available soil water) that is consistent with soil water storage after disk tillage fallow of limited wheat residue (Unger and Parker, 1975). Typical N mineralization for a Pullman soil during fallow provides ~45 kg N ha^{-1} in the profile (Eck and Jones, 1992) that we supplemented with an additional 200 kg N ha^{-1} in the model inputs; thus, providing ample N to meet cotton demand for a yield potential of ~1500 kg ha^{-1} (Hake et al., 1991). The total N of 245 kg in this study is similar to the 258 kg ha^{-1} total soil profile N reported by Staggenborg et al. (1996), and consistent with the well-fertilized treatment levels used during 2000 by Chua et al. (2003). All other soil fertility elements were considered adequate for cotton because GOSSYM does not determine the effects of other nutrients on crop growth. Maximum rooting depth was unrestricted within the 1.8 m soil profile depth, but developing dry dense layers could restrict rooting. In these simulations, runoff of irrigation or rain was not permitted in order to duplicate the effects of furrow dikes (tied ridges) used as part of LEPA irrigation to prevent runoff (Schneider and Howell, 2000; Howell, 2001).

Crop Simulations

The response of a stripper type cotton cultivar with an indeterminate growth habit similar to All-Tex Atlas (Levelland, TX),[1] supplied variety file ST1 (Staggenborg et al., 1996), was simulated in rows 0.76 m apart with 13 plants m^{-2} using actual long-term (1959–2000) daily records of solar irradiance (MJ m^{-2}), maximum and minimum air temperature (°C), precipitation (mm), and wind run (km) as input (Baumhardt et al., 2007). All simulations began on DOY 131 or 2 wk before our selected DOY 145 emergence date, which follows 10 d after the recommended 15 May planting date for Bushland. Simulations continued until physiological maturity (100% open bolls) or a killing freeze, when lint yield and estimated water use or growing season ET were determined.

Cotton growth, lint yield, and water use were calculated for dryland conditions (rain only) under the two initial soil profile water content levels as a basis for evaluating irrigation effectiveness. Similarly, rain plus the two initial soil water treatments were supplemented with three deficit irrigation capacities of 2.5, 3.75, and 5.0 mm d^{-1} applied, independently of crop growth stage, on a 7-d interval that totaled 17.5, 26.8, and 35 mm (respectively). These irrigation levels represent a range of well pumping capacities of ~0.29, 0.43, and 0.58 L s^{-1} ha^{-1}, which provide application depths consistent with declining (weak) to adequate irrigation well capacities. Irrigation applications began ~37 d after emergence at first square, flower bud initiation, because irrigation begun at this time resulted in the greatest lint yield during a 12-yr study elsewhere on the Southern High Plains (Wanjura et al., 2001). Irrigation applications were continued for durations of 4, 6, 8, and 10 wk. All possible combinations of initial soil water content (2 levels) by irrigation capacity (3 levels) and duration (4 levels) plus dryland, totaling 26 treatments, were evaluated for each of 42 yr of weather records, resulting in a total of 1092 simulations.

Analyses

Cotton growth, lint yield, ET, and the WUE, calculated as the ratio of lint yield to total ET, were determined from simulations for each of the 26 treatment combinations or experimental units. For soil and weather input conditions unique to a specific year, GOSSYM simulates unique cotton growth responses for that experimental unit. We used the measured climatic variability including rainfall and temperature of 42 actual growing seasons (1959–2000) as the source of random experimental error to test variable

[1] The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Table 1. Initial soil water and irrigation duration and capacity effects on mean lint yield and related statistical distribution parameters [median, standard error (SE), skewness] for the 42-yr simulations (n = 42).

		Irrigation capacity, mm d^{-1}											
		2.5	3.75	5.0	2.5	3.75	5.0	2.5	3.75	5.0	2.5	3.75	5.0
Parameter	Dryland	4-wk irrigation duration			6-wk irrigation duration			8-wk irrigation duration			10-wk irrigation duration		
	kg ha^{-1}												
					50% initial soil water content profile								
Mean	222	392	539	664	436	603	719	455	626	736	461	634	732
Median	137	382	535	645	449	597	691	481	624	750	519	637	737
SE	39.8	46.1	40.1	34.4	46.9	38.8	33.4	48.3	39.3	33.2	49.1	39.4	32.6
Skewness†	1.52	0.44	0.39	0.30	0.33	0.54	0.52	0.35	0.56	0.31	0.37	0.50	0.18
					100% initial soil water content profile								
Mean	724	820	869	883	847	899	895	863	913	893	872	912	890
Median	718	801	809	820	812	833	831	828	839	831	831	844	833
SE	33.5	35.2	39.2	42.0	38.3	43.8	44.1	40.0	45.9	44.5	41.0	46.7	45.3
Skewness	0.19	−0.11	−0.07	0.06	−0.05	0.11	0.16	−0.06	0.18	0.26	−0.02	0.30	0.44

† Positive skewness implies that the calculated lint yield distribution is shifted toward values less than the mean and negative skewness implies that the calculated lint yields are distributed toward values greater than the mean.

crop response to treatment combinations. For each of the 26 treatments, we plotted the declining ranked yield from the 42 simulations as a function of the probability of a yield being exceeded (exceedence probability) according to Barfield et al. (1981) and calculated simple univariate statistics (mean, median, skewness, and SE). Variability in cotton growth, lint yield, and ET due to erratic precipitation during the 42 growing seasons resulted in heteroscedastic experimental error between initial soil water content treatments with differences of 5 to 35% for dependent parameters. We, therefore, used SAS general linear model ANOVA procedures (SAS Institute, 1988) to compare the effects of irrigation capacity and duration within common initial soil water content levels according to a factorial arrangement of a completely randomized design replicated by years.

RESULTS AND DISCUSSION

Lint Yield

Irrigation Capacity and Duration

Without irrigation (dryland), GOSSYM simulated lint yields for a dry 50% initial soil water content scenario ranged from 0 to 1130 kg ha^{-1} during the years 1959 to 2000 and averaged 222 kg ha^{-1} with an SE approaching 20% of the mean (Table 1). The calculated dryland lint yield declined rapidly as the exceedence probability increased from 0 to 50% (Fig. 1) because of infrequent high yields that skewed the mean yield well above the median 137 kg ha^{-1} lint yield. This reflects the yield response to erratic growing season precipitation amount (ranging from 149–657 mm) that is characteristic of the semiarid weather on the Southern High Plains. For the 50% initial soil water content scenario, dryland lint yields exceeded ~540 kg ha^{-1} (1 bale) in only 15% of the simulated crop years while crop failures

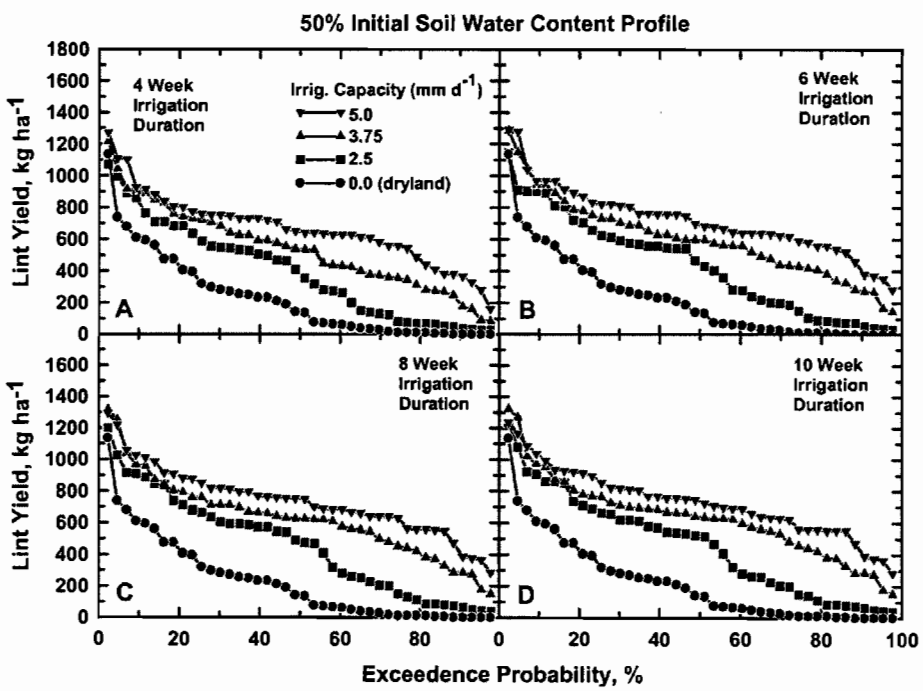

Fig. 1. Exceedence probability for simulated lint yields of cotton grown with 50% initial soil water content profiles and four treatment irrigation capacities (0.0 or dryland, 2.5, 3.75, or 5.0 mm d^{-1}) and four irrigation durations: (A) 4 wk, (B) 6 wk, (C) 8 wk, or (D) 10 wk.

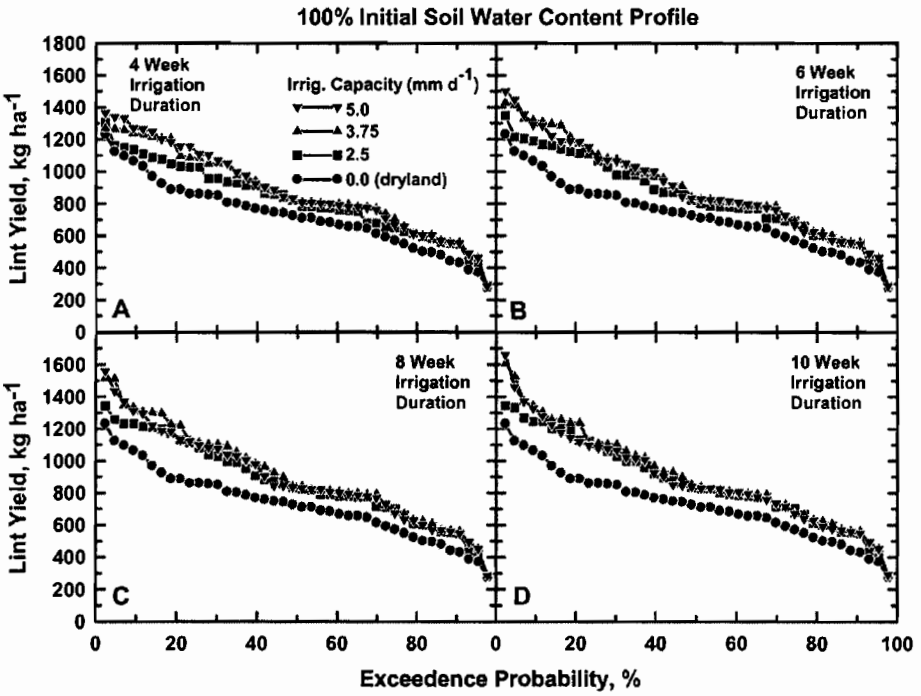

Fig. 2. Exceedence probability for simulated lint yields of cotton grown with 100% initial soil water content profiles and four treatment irrigation capacities (0.0 or dryland, 2.5, 3.75, or 5.0 mm d^{-1}) and four irrigation durations: (A) 4 wk, (B) 6 wk, (C) 8 wk, or (D) 10 wk.

producing lint yields of <11 kg ha^{-1} appeared in 25% of the years. Although soil with a 100% profile water content imposes practical management limitations, increasing the initial soil water content to this maximum increased dryland lint yields, which ranged from 274 to 1230 kg ha^{-1} for this same period and averaged 724 kg ha^{-1} with an SE of ~ 5% of the mean (Table 1). The exceedence probability for calculated dryland lint yields > 540 kg ha^{-1} were 80% with the 100% profile water content (Fig. 2) and would be preferred by risk averse producers. These lint yields show the importance of favorable initial stored soil water to buffer against water deficit stress during establishment and early growth of cotton.

Alternatively, deficit irrigation can be used to prevent dryland crop failures due to the limited 50% initial soil water conditions for an increased overall average simulated lint yield of ~580 kg ha^{-1}. Specifically, the 42-yr mean simulated yields of cotton that were deficit irrigated with applications totaling from 70 to 350 mm depending on the irrigation capacity and duration combination ranged from 392 to 736 kg ha^{-1} for the 50% initial soil water content (Table 1). During the same 1959 to 2000 period, simulated lint yields of cotton grown with 100% initial soil water content and identical irrigation applications ranged from 820 to 913 kg ha^{-1} that averaged 880 kg ha^{-1} overall. Our results show that benefits of higher irrigation capacity to significantly increase lint yields of cotton grown with initial soil water content of 50% (Table 2) were negated when the initial soil water was increased to 100%. The corresponding simulated lint yield variability resulted in SE that ranged from 4 to 12% of the mean for the 50% initial soil water content compared with a less variable SE range of 4 to 5% for the 100% initial soil water content (Table 1). With the lower 50% initial soil water content, overall mean (averaged across duration) simulated yields of cotton irrigated at the 2.5 mm d^{-1} capacity increased by 214 kg ha^{-1} over dryland to 436 kg ha^{-1} as crop water deficit stress was relieved for greater fruiting and fruit retention. Nevertheless, plotted lint yields for exceedence probabilities >50% decrease abruptly from ~455 kg ha^{-1} (Fig. 1) because of the large number of low yields. The risk averse producer will likely find this yield distribution undesirable compared with the more gradual yield decrease for increasing exceedence probabilities observed with the 3.75 and 5.0 mm d^{-1} irrigation capacity. Also, increasing irrigation to the 3.75 mm d^{-1} capacity for the 50% initial soil water content resulted in an additional 37% increase in the overall mean lint yield to 600 kg ha^{-1}, but at the maximum 5.00 mm d^{-1} irrigation capacity the lint yield averaged across duration treatments further increased by 113 to 713 kg ha^{-1}.

For the 100% initial soil water content, the mean simulated lint yield increased from 724 kg ha^{-1} for dryland to an overall average lint yield of 851 kg ha^{-1} with the 2.5 mm d^{-1} irrigation capacity or ~60% of the yield benefit observed for the drier

Table 2. Analysis of variance for irrigation capacity and duration treatment effects by initial soil water level on simulated lint yield, evapotranspiration (ET), and the corresponding water use efficiency (WUE). The ANOVA results designate the significance of treatment effects.

		50% initial soil water			100% initial soil water		
Effect	df	Lint yield	ET	WUE	Lint yield	ET	WUE
Capacity (C)	2	**	**	**	ns†	**	ns
Duration (D)	3	*	**	ns	ns	**	ns
C × D	6	ns	ns	ns	ns	ns	ns

* Significant at $P = 0.05$.

* Significant at $P = 0.01$.

† ns, not significant.

initial soil water condition. The simulations show that crop water needs supplied by 100% initial soil water diminished lint yield response to the progressively greater irrigation capacity treatments. That is, cotton lint yields averaged across irrigation duration increased ~6%, 47 kg ha^{-1}, to 898 kg ha^{-1} when irrigation capacity increased from 2.5 mm d^{-1} to 3.75 mm d^{-1} and remained unchanged by the greater 5.00 mm d^{-1} irrigation capacity. Calculated lint yields for the 2.5, 3.75, and 5.0 mm d^{-1} irrigation capacities were similar except for the infrequent yields above ~1200 kg ha^{-1}, or an exceedence probability < 20% (Fig. 2), that may reflect cotton yield responses under unusually favorable growing conditions. The resulting effect of increasing irrigation capacity on yield was not significant (Table 2) with 100% initial soil water content.

Lint yield increased with increasing irrigation for both 50% and 100% initial soil water contents; however, incremental crop yield increases declined at the highest irrigation capacity. Our results show that simulated lint yields increased with either favorable 100% initial soil water, or irrigation at 3.75 and 5.00 mm d^{-1} application capacities when the initial soil water was 50%. We attributed this to more extensive early season vegetative growth that increased the crop capacity for greater fruit formation and retention as observed by Turner et al. (1986) and Orgaz et al. (1992). Also, greater yield potential resulted when favorable soil water or early season irrigation prevented water deficit stress during fruitset and lint development of the early season crop.

Irrigation duration effects on simulated lint yields were determined among irrigation capacity levels and both initial soil water conditions. For the 50% initial soil water content, progressively longer irrigation durations consistently increased simulated lint yields found at exceedence probability > 50% (Fig. 1). The progressively longer duration irrigations also closed the differences in yields between the 3.75 and 5.0 mm d^{-1} capacity below 80% exceedence probability level. The corresponding cotton lint yields averaged across irrigation capacity increased significantly (Table 2) from 531 kg ha^{-1} for 4 wk duration to 586 kg ha^{-1} for 6 wk duration. Overall average lint yields for the 8 and 10 wk duration were 606 and 609 kg ha^{-1} (respectively) and differed significantly ($P < 0.05$) from the

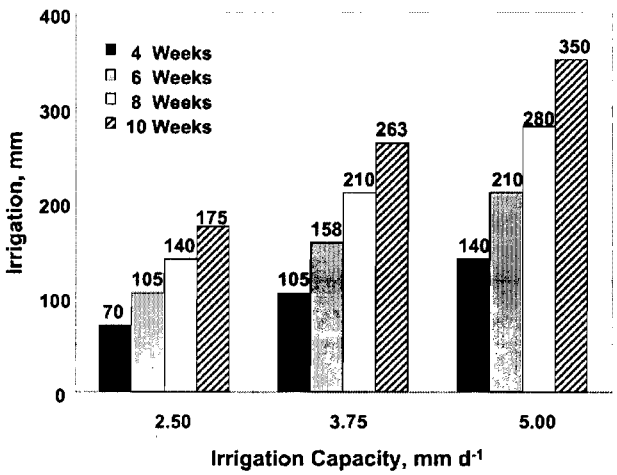

Fig. 3. Applied irrigation depths that were calculated from treatment capacities of 2.5, 3.75, and 5.0 mm d^{-1} and durations of 4, 6, 8, and 10 wk.

4-wk duration treatment. For the 50% initial soil water content, termination of irrigation at 4 to 6 wk reduced simulated yields compared with longer irrigation periods because of subsequent water deficit stress that could promote fruit abscission (McMichael and Hesketh, 1982; Guinn and Mauney, 1984b) of later bolls. No significant differences in simulated cotton lint yields irrigated for of 8 to 10 wk indicate that the growing season crop water demands were largely met by 8 wk.

In contrast, simulated lint yields of cotton grown with 100% initial soil water content ranged from 857 kg ha^{-1} when irrigated 4 wk to a not significantly different (Table 2) 891 kg ha^{-1} when irrigated 10 wk. Our results also show that simulated lint yields were largely unaffected by increasing irrigation duration except for exceedence probability < 20% (Fig. 2) resulting from unusually favorable growing season length and temperatures. Progressively longer irrigation applications necessarily increase the amount of water available for crop growth, but later irrigation applications may not translate into increased lint yield, in part, because short growing seasons on the Texas High Plains can limit boll maturation. For example, fewer than 50% of bolls initiated after August 20 fully mature during the growing season at Lubbock, TX, (Wanjura and Newton, 1981) or ~7 wk after first square in our test at Bushland, which is located 200 km further north.

Irrigation Depth

Increasing irrigation depth generally results in greater vegetative growth, flowering, fruit retention, and lint yield (Guinn and Mauney, 1984a, Morrow and Krieg, 1990; Colaizzi et al., 2004). However, the effects of both irrigation capacity and duration treatments may be confounded in this expected crop response. To clarify the independent contribution of these effects, we related lint yield to cumulative irrigation depths calculated for all irrigation capacity and duration treatment combinations. The three irrigation capacity treatments produced unique cumulative irrigation depth arrays that ranged from 70 mm for the 4 wk duration by 2.5 mm d^{-1} to 350 mm for the 5 mm d^{-1} by 10 wk duration (Fig. 3). These three irrigation capacity arrays included common application depths of 105, 140, and 210 mm that permitted direct comparisons of yield between irrigation capacity levels.

Mean simulated lint yields for the 100% initial soil water level ranged from ~820 kg ha^{-1} with 70 mm irrigation over 4 wk to a maximum of ~900 kg ha^{-1} for irrigation depths of 210 to 263 mm, and declined to ~890 kg ha^{-1} with the 10 wk full irrigation depth of 350 mm (Fig. 4). The plotted lint yields for the 100% initial soil water did not differ due to irrigation capacity or duration as inferred by ANOVA results (Table 2).

For the 50% initial soil water level, the mean simulated lint yields ranged from 392 kg ha^{-1} with 70 mm irrigation to a maximum of ~730 kg ha^{-1} with 350 mm of irrigation. At this lower initial soil water, simulated yields generally increased with increasing irrigation depth due to either greater application duration or increased capacity (Fig. 4). Those plotted lint yields increased along three distinct arrays that shifted significantly ($P < 0.01$) higher as the irrigation capacity increased. For example, the simulated lint yield of cotton receiving 105 mm of irrigation increased ~25% from 435 to 538 kg ha^{-1} when the application capacity increased 50% from 2.50 to 3.75 mm

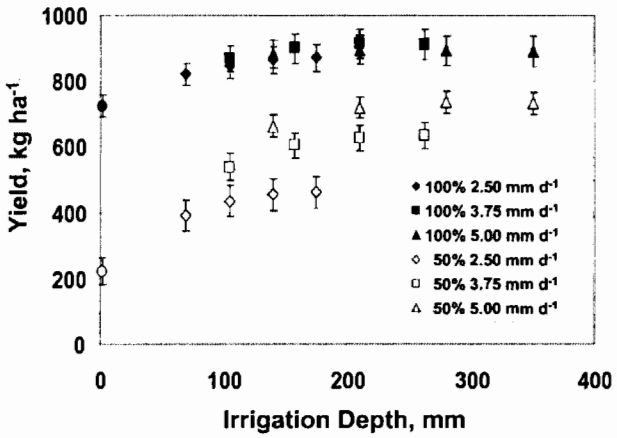

Fig. 4. Mean simulated yield (1959–2000) of cotton grown with initial soil water content profiles of 50% (open symbols) and 100% (shaded symbols) field capacity as a function of irrigation depth for dryland (circle) and irrigation capacities of 2.5 (diamond), 3.75 (square), and 5.0 mm d^{-1} (triangle). Error bars represent the SE.

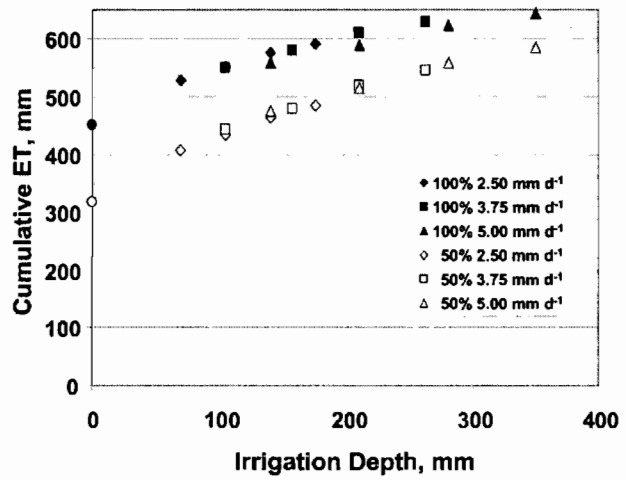

Fig. 5. Mean simulated cumulative evapotranspiration (1959–2000) of cotton grown with initial soil water content profiles of 50% (open symbols) and 100% (shaded symbols) field capacity as a function of irrigation depth for dryland (circle) and irrigation capacities of 2.5 (diamond), 3.75 (square), and 5.0 mm d^{-1} (triangle). Error bars that show the SE were generally masked by symbol size and are not visible.

d^{-1} (respectively). This effect was repeated for the 140 mm irrigation total when increasing irrigation capacity from 2.50 to 5.00 mm d^{-1} consequently increased yield 46% from 455 to 664 kg ha^{-1}. The yield benefit of greater irrigation capacity diminished with increasing irrigation depth as shown for the 210 mm depth when lint yield increased from 626 kg ha^{-1} to 719 kg ha^{-1} by increasing the application capacity from 3.75 to 5.00 mm d^{-1}.

In these yield comparisons, common irrigation depths were achieved at lower irrigation capacities by extending application 2 to 4 wk, which also increased the potential for soil water evaporation. The simulated differences in evaporation averaged ~1.0 mm d^{-1} between comparisons, but the resulting 13 to 28 mm greater evaporation due to the longer irrigation period probably would not account for the full yield advantage of the higher irrigation capacity treatments. Alternatively, higher capacity irrigation with 50% initial soil water could provide water to prevent early growing season water deficit stress during critical flowering and fruit set, which promoted greater lint yield. These results show that increasing irrigation duration did not increase mean yield to the same degree as increasing application capacity.

Cotton Evapotranspiration and Water Use Efficiency

The ET for dryland cotton is limited by the seasonal precipitation plus the initial soil water in the profile. The dryland cotton ET, during the 42-yr simulation period, increased with increasing initial soil water and averaged 320 and 450 mm for the 50 and 100% initial soil water profiles, respectively. Simulated cotton ET averaged across all irrigation capacity and duration treatments similarly increased with increasing initial soil water from 490 mm for the 50% soil water content to 584 mm for the 100% initial soil water content. Greater irrigation capacity and duration treatments that increased the applied irrigation depth, significantly increased simulated cotton ET for both 50 and 100% initial soil water content profiles (Table 2). The calculated cotton ET increased with increasing irrigation depth (Fig. 5). The simulated ET ranged to a maximum of 585 mm for the 50% initial soil water content profile and 640 mm for the 100% initial soil water content profile, but for common irrigation depths ET did not vary significantly with irrigation capacity for either the 50 or 100% initial water content treatments. This is in contrast to simulated cotton yields observed on the 50% initial soil water profile, which increased with increasing irrigation capacity.

We compared the effects of initial soil water content and irrigation capacity and duration on the ratio of simulated lint yield (kg ha^{-1}) to the corresponding water use (m^3 ha^{-1}), that is, the WUE (kg m^{-3}). Cotton lint yields and water use simulated for the 100% initial soil water condition resulted in generally greater WUE of 0.152 kg m^{-3} compared with overall mean WUE of 0.110 kg m^{-3} for the 50% initial soil water content. Cotton WUE with the favorable 100% initial soil water content decreased from a maximum of 0.161 kg m^{-3} without irrigation down to the minimum of 0.137 kg m^{-3} for 350 mm irrigation (Fig. 6). The declining WUE of cotton on the 100% initial soil water was because lint yields did not increase in proportion to increasing irrigation depth although the percentage of unopened bolls increased (data not shown). Except for the 350 mm irrigation depth, WUE for 100% soil water profile case exceeded the WUE for any irrigation capacity by duration combination when the initial soil water content was 50%. Calculated WUE increased from 0.057 kg m^{-3} for dryland to a peak WUE of ~0.14 kg m^{-3} under the drier 50% initial soil water conditions. We attributed this to increasing early fruiting and fruit retention promoted by irrigation that relieved early growing season water deficit stress.

Model-calculated WUE for the 100% initial soil water profiles produced three irrigation capacity WUE arrays that declined with increasing irrigation duration, which were not statistically different (Table 2). The WUE arrays averaged an identical 0.153 kg m^{-3} for the 2.5 mm d^{-1} and 3.75 mm d^{-1} irrigation capacities, and 0.148 kg m^{-3} for the 5.0 mm d^{-1} capacity. In contrast, the calculated WUE for the 50% initial soil water profiles produced three distinct arrays (Fig. 6) that

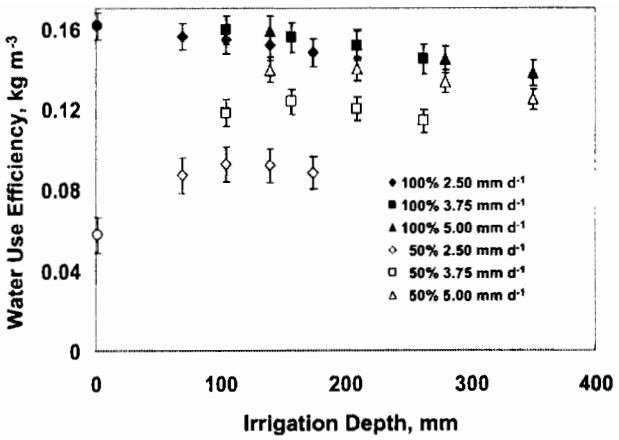

Fig. 6. Calculated water use efficiency of cotton grown with initial soil water content profiles of 50% (open symbols) and 100% (shaded symbols) field capacity as a function of irrigation depth for dryland (circle) and irrigation capacities of 2.5 (diamond), 3.75 (square), and 5.0 mm d^{-1} (triangle). Error bars represent the SE.

increased significantly as irrigation capacity increased, averaging 0.09 kg m^{-3} when irrigated at 2.5 mm d^{-1} capacity, 0.119 kg m^{-3} at 3.75 mm d^{-1} capacity, and 0.134 kg m^{-3} for the highest irrigation capacity of 5.0 mm d^{-1}. The WUE within each irrigation capacity array tended to peak at the 6-wk irrigation duration and decrease with greater application durations for the 50% initial soil water condition.

These results illustrate that greater initial soil water, irrigation capacity, and application duration increased simulated ET. However, irrigation practices for maximizing WUE varied with the initial soil water content and application capacity. Available water in soil profiles at 100% field capacity supplied sufficient water for production of early fruit and diminished the irrigation effect to increase lint yield in proportion to the application depth. Because soil water contents of 50% field capacity could not prevent developing plant water deficit stress, both increased irrigation capacity and duration of 6 to 8 wk reduced water deficit stress for increased fruiting and yield. As

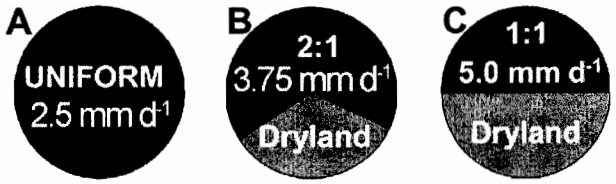

Fig. 7. Irrigated application strategies evaluated using mean simulated (1959–2000) lint yields corresponding to (A) uniform 2.5 mm d^{-1} irrigation strategy for the total area, (B) 2:1 irrigation strategy with 3.75 mm d^{-1} irrigation on two-thirds of the area and dryland cropping of the balance, and (C) 1:1 irrigation strategy with half receiving 5.0 mm d^{-1} and dryland cropping of the balance.

a result, irrigation management strategies should consider the contribution of available soil profile water at planting.

Irrigation Management Strategies

We applied these simulation results to address a practical management question on maximizing irrigated cotton lint yield either by spreading water resources over a large area using deficit irrigation or by concentrating water resources on a smaller adequately irrigated area that is averaged with the complementary dryland area. That is, we compared the three irrigation scenarios shown in Fig. 7, including spreading water uniformly to irrigate an area at 2.5 mm d^{-1}, applying water at 3.75 mm d^{-1} to two thirds of that area and not irrigating the balance (2:1), and applying water at 5.0 mm d^{-1} to half of that area and not irrigating the balance (1:1). The composite lint yields for each scenario were calculated using a weighted average of simulated cotton yields for both 50 or 100% initial soil water content profiles and irrigation applications durations of 4 or 8 wk. These durations represent the minimum irrigation period tested and the longest duration application that generally increased yield.

The calculated composite cotton yield for 100% initial soil water and 140 mm irrigation water applied uniformly at 2.5 mm d^{-1} irrigation capacity for 8 wk averaged 863 kg ha^{-1} (Table 3). This yield was used as the basis of comparison with other application strategies and the 100% initial soil water profile. For the 2:1 irrigation strategy, we calculated a 2% lower weighted average yield of 850 kg ha^{-1} using 724 kg ha^{-1} for the dryland one-third and 913 kg ha^{-1} for the remaining area irrigated at 3.75 mm d^{-1} capacity. Similarly, the 1:1 irrigation strategy reduced the composite yield ~6% to 808 kg ha^{-1} by averaging dryland lint yield with 893 kg ha^{-1} simulated for cotton irrigated at a capacity of 5.0 mm d^{-1}. The declining weighted average lint yields simulated with 100% initial soil water were consistent with the decreasing cotton WUE observed for greater irrigation capacity and duration combinations. We also considered irrigation strategy effects on lint yields when net irrigation was reduced to 70 mm by decreasing the application duration to 4 wk. With irrigations reduced by half, the uniform 2.5 mm d^{-1} irrigation capacity produced simulated cotton lint yields of 820 kg ha^{-1} or ~95% of the base

Table 3. Irrigation application strategy effects on the weighted average lint yield for initial soil water contents of 50 and 100% of field capacity. The yield fraction was calculated using uniform irrigation at 2.5 mm d^{-1} capacity applied for an 8-wk duration as the basis of comparison.

		4-wk duration			8-wk duration		
Application strategy	Irrigation capacity	Lint yield	Weighted average yield	Fraction of base yield	Lint yield	Weighted average yield	Fraction of base yield
	mm d^{-1}	kg ha^{-1}		%	kg ha^{-1}		%
				100% initial soil water			
Uniform	2.5	820	820	95	863	863	100
2:1	3.75	869	820	95	913	850	98
	dryland	724			724		
1:1	5.0	883	803	93	893	808	94
	dryland	724			724		
				50% initial soil water			
Uniform	2.5	392	392	86	455	455	100
2:1	3.75	539	433	95	626	491	108
	dryland	222			222		
1:1	5.0	664	443	97	736	479	105
	dryland	222			222		

yield. Simulated cotton lint yields of 869 and 883 kg ha^{-1} for the 3.75 or 5.0 mm d^{-1} irrigation capacity levels, respectively, tended to be greater than yields for the uniform 2.5 mm d^{-1} irrigation capacity level; but, the resulting weighted average yields of 820 and 803 kg ha^{-1} for the 2:1 and 1:1 irrigation strategies differed little. The 100% initial soil water content met much of the cotton water demand for producing earlier bolls and, consequently, diminished crop response to irrigation.

Also in Table 3, we show the effects of the 2:1 and 1:1 irrigation strategies on simulated lint yield of cotton grown with 50% initial soil water that typically required irrigation to avoid water deficit stress. The 455 kg ha^{-1} yield for cotton uniformly irrigated at 2.5 mm d^{-1} capacity for 8 wk was substituted as the basis of comparison with other irrigation application strategies. For the 2:1 irrigation strategy, an 8% larger weighted average yield of 491 kg ha^{-1} was calculated using 222 kg ha^{-1} for the dryland one-third and 626 kg ha^{-1} for the remaining area irrigated at 3.75 mm d^{-1}. The 1:1 irrigation strategy also increased the composite yield ~5% to 479 kg ha^{-1} by averaging dryland lint yield with 736 kg ha^{-1} simulated for cotton irrigated 8 wk at the 5.0 mm d^{-1} capacity. The lower 137 kg ha^{-1} median dryland lint yield, used for risk averse assessment of irrigation strategy alternatives, decreased the simulated weighted average yields for the 2:1 and 1:1 irrigation strategies to 463 and 436 kg ha^{-1} (respectively). That is, the resulting lint yield differences from the uniform 2.5 mm d^{-1} irrigation level were ~ 4% smaller. When using the larger mean simulated dryland cotton lint yield, however, our data show that for a constant net irrigation application of 140 mm and limited initial soil water, the composite mean lint yields increased when water resources were concentrated to irrigate at a greater application capacity.

When the net irrigation application was decreased to 70 mm by reducing irrigation duration to 4 wk, the corresponding simulated lint yield decreased ~14% to 392 kg ha^{-1} for the uniform 2.5 mm d^{-1} irrigation capacity. The composite yield of the 2:1 irrigation strategy increased ~10% over the uniform irrigation at the 2.5 mm d^{-1} capacity to 433 kg ha^{-1} based on the weighted average of 222 kg ha^{-1} for the dryland one-third and 539 kg ha^{-1} for the remaining area irrigated at 3.75 mm d^{-1}. Similarly, averaging lint yields of 664 kg ha^{-1} for the 5.0 mm d^{-1} irrigation capacity with dryland produced a composite yield for the 1:1 irrigation strategy that increased ~13% to 443 kg ha^{-1}. The weighted average yields were also recalculated using the 137 kg ha^{-1} 42 yr median simulated dryland yield to assess irrigation strategies under risk averse conditions. Those composite yields decreased to 405 and 400 kg ha^{-1} for the 2:1 and 1:1 irrigation strategies (respectively), resulting in a small (<3%) increase compared with 2.5 mm d^{-1} uniformly irrigated treatment. These data confirm that using 2:1 and 1:1 irrigation strategies to apply 70 mm of irrigation water increased the weighted average lint yields to ~95 and 97% (respectively) of the base 453 kg ha^{-1} yield. Again, concentrating water resources to increase application capacity of irrigated areas increased the weighted average simulated lint yields.

SUMMARY AND CONCLUSIONS

The effects of initial soil water content, irrigation capacity, and application duration were evaluated using GOSSYM v. 4 simulated cotton lint yield and WUE. Our results showed that irrigation capacity and duration had a greater influence on lint yield at low initial soil water content (50% of field capacity) than at optimum initial soil water conditions (100% of field capacity at planting). With 100% initial soil water, increasing the irrigation depth resulted in greater lint yield and ET; however, the WUE tended to decline because of diminishing marginal increases in lint yield with greater irrigation. In contrast, simulated lint yields increased with increasing irrigation depth along independent application capacity arrays for the 50% initial soil water content condition. That is, increasing irrigation capacity from 2.5 mm d^{-1} to 3.75 or 5.0 mm d^{-1} significantly ($P < 0.01$) increased lint yield and consequently, WUE. These simulated trends were consistent with experimental lint yields at Bushland determined for increasing irrigation capacities (Colaizzi et al., 2004).

Based on these results, we compared lint yields of cotton irrigated uniformly at 2.5 mm d^{-1} with a spatially weighted-average yield for combination dryland and irrigated fields. For the 50% initial soil water content profile condition, spreading water to uniformly deficit irrigate a field with 2.5 mm d^{-1} produced ~5% less lint than concentrating the same water resources to irrigate a field at 3.75 or 5.0 mm d^{-1} and average that with the complementary dryland crop, where the irrigated-to-dryland field proportions were 2:1 or 1:1, respectively. We conclude that, as irrigation water resources decline, cotton yield and WUE can be maintained or increased by converting from uniform deficit irrigation (water spreading) to irrigation that concentrates water on a portion of the field with a complementary dryland area.

REFERENCES

Baker, D.N., J.R. Lambert, and J.M. McKinion. 1983. GOSSYM: A simulator of cotton crop growth and yield. South Carolina Agric. Exp. Stn. Bull. 1089. Clemson Univ., Clemson, SC.

Barfield, B.J., R.C. Warner, and C.T. Haan. 1981. Applied Hydrology and sedimentology for disturbed areas. Oklahoma Technical Press, Stillwater.

Baumhardt, R.L. 2002. Assessing limited growing season production risk to dryland cotton using GOSSYM crop growth simulation. *In* Annual meetings abstracts [CD-ROM]. ASA, CSSA, and SSSA, Madison, WI.

Baumhardt, R.L., and T.A. Howell. 2006. Seeding practices, cultivar maturity, and irrigation effects on simulated grain sorghum yield. Agron. J. 98:462–470.

Baumhardt, R.L., R.J. Lascano, and D.R. Krieg. 1995. The physical and hydraulic properties of a Pullman and Amarillo soil on the Texas South Plains. Tech. Rep. 95-1. Texas Agric. Exp. Stn., Lubbock.

Baumhardt, R.L., J.A. Tolk, T.A. Howell, and W.D. Rosenthal. 2007. Sorghum management practices suited to varying irrigation strategies: A simulation analysis. Agron. J. 99:665–672.

Chua, T.T., K.F. Bronson, J.D. Booker, J.W. Keeling, A.R. Mosier, J.P. Bordovsky, C.J. Green, and E. Segarra. 2003. In-season nitrogen status sensing in irrigated cotton: I. Yields and nitrogen-15 recovery. Soil Sci. Soc. Am. J. 67:1428–1438.

Colaizzi, P.D., S.R. Evett, and T.A. Howell. 2004. Irrigation methods and capacities for cotton in the Northern High Plains. p. 154–163. *In* K.A. Rainwater and T.M. Zobeck (ed.) High Plains Groundwater Resources: Challenges and Opportunities, Conf. Proc., Lubbock, TX. 7–9 Dec. 2004, Water Resources Center, Texas Tech Univ., Lubbock, TX.

Dennehy, K.F. 2000, High Plains regional ground-water study: USGS Fact Sheet FS-091-00. Available at http://co.water.usgs.gov/nawqa/hpgw/factsheets/DENNEHYFS1.html [accessed 25 Apr. 2008; updated 19 Feb. 2009; verified 19 Feb. 2009], U.S. Geological Survey, Lincoln, NE.

Doorenbos, J., and A.H. Kassam. 1979. Yield response to water. Irrigation and Drainage Paper 33. FAO, Rome.

Eck, H.V., and O.R. Jones. 1992. Soil nitrogen status as affected by tillage, crops, and crop sequences. Agron. J. 84:660–668.

Guinn, G., and J.R. Mauney. 1984a. Fruiting of cotton. I. Effects of moisture status on flowering. Agron. J. 76:90–94.

Guinn, G., and J.R. Mauney. 1984b. Fruiting of cotton. II. Effects of plant moisture status and active boll load on boll retention. Agron. J. 76:94–98.

Hake, K., K. Cassman, and W. Ebelhar. 1991. Cotton nutrition-N, P and K. Cotton Physiol. Today 2:1–3.

Howell, T.A. 2001. Enhancing water use efficiency in irrigated agriculture. Agron. J. 93:281–289.

Howell, T.A. 2003. Irrigation efficiency. p. 467–472. *In* B.A. Stewart and T.A. Howell (ed.) Encyclopedia of water science. Marcel Dekker, New York.

McGuire, V.L. 2004. Water-level changes in the High Plains Aquifer, predevelopment to 2002, 1980 to 2002, and 2001 to 2002. USGS Fact Sheet FS-2004–3026. Available at http://pubs.usgs.gov/fs/2004/3026/[modified 18 Aug. 2005; accessed 25 Apr. 2008; verified 19 Feb. 2009], U.S. Geological Survey, Denver, CO.

McMichael, B.L., and J.D. Hesketh. 1982. Field investigations of the response of cotton to water deficits. Field Crops Res. 5:319–333.

Morrow, M.R., and D.R. Krieg. 1990. Cotton management strategies for a short growing season environment: Water-nitrogen considerations. Agron. J. 82:52–56.

Musick, J.T., and W.H. Sletten. 1966. Grain sorghum irrigation-water management on Richfield and Pullman soils. Trans. ASAE 9:369–371, 373.

Orgaz, R., L. Maetos, and E. Fereres. 1992. Season length and cultivar determine the optimum evapotranspiration deficit in cotton. Agron. J. 84:700–706.

Pittman, E.G., J. Hunt, J.E. Herring, W.W. Meadows, T.W. Labatt, and D.V. Guerra. 2007. Water for Texas. Vol. II. Doc. No. GP-8–1. Texas Water Development Board, Austin.

SAS Institute. 1988. SAS/STAT user's guide. Release 6.03 ed. SAS Inst., Cary, NC.

Schneider, A.D., and T.A. Howell. 2000. Surface runoff due to LEPA and spray irrigation of a slowly permeable soil. Trans. ASAE 43:1089–1095.

Staggenborg, S.A., R.J. Lascano, and D.R. Krieg. 1996. Determining cotton water use in a semiarid climate with the GOSSYM cotton simulation model. Agron. J. 88:740–745.

Turner, N.C., A.B. Hearn, J.E. Begg, and G.A. Constable. 1986. Cotton (*Gossypium Hirsutum* L.): Physiological and morphological responses to water deficits and their relationship to yield. Field Crops Res. 14:153–170.

Unger, P.W., and J.J. Parker. 1975. No-till dryland grain sorghum after irrigated wheat with intervening fallow. Prog. Rep. No. 3330. p. 43–54. *In* A.F. Wiese (ed.) Sorghum research in the Northern High Plains of Texas—1974. Consolidated Prog. Rep 3329-3338. Texas Agric. Exp. Stn., College Station.

Wanjura, D.F., and O.H. Newton. 1981. Modeling cotton lint development. Trans. ASAE 24:496–499.

Wanjura, D.F., and D.R. Upchurch. 2000. Canopy temperature characteristics of corn and cotton water status. Trans. ASAE 43:867–875.

Wanjura, D.F., D.R. Upchurch, J.R. Mahan, and J.J. Burke. 2001. Cotton yield and applied water relationships under drip irrigation. Agric. Water Manage. 55:217–237.