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Modeled El Niño-Southern Oscillation Effects on Grain Sorghum under Varying Irrigation Strategies and Cultural Practices

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Modeled El Niño-Southern Oscillation Effects on Grain Sorghum under Varying Irrigation Strategies and Cultural Practices

R.L. Baumhardt,* R.C. Schwartz, G.W Marek, and J.E. Moorhead

ABSTRACT

Equatorial sea surface temperatures vary systematically to cause the El Niño southern oscillation (ENSO) that produces predictable weather patterns in North America and may permit long-range climate predictions and eventual proactive summer crop irrigation management. The declining Ogallala Aquifer in the Southern High Plains and consequently limited well capacities challenge producers to adapt cropping practices for irrigation that doesn't meet crop water demand. Our objective was to evaluate sorghum [*Sorghum bicolor* (L.) Moench] yield response to ENSO climate-informed management of cultural practices and irrigation strategies on a Pullman soil (fine, mixed, superactive, thermic Torrertic Paleustoll). We used the simulation model SORKAM and long-term (1961–2000) weather records from Bushland, TX, classified by ENSO phase to calculate sorghum grain yields for all combinations of irrigation levels (0.0, 2.5, 3.75, or 5.0 mm d^{-1}), planting day of year (DOY = 135, 156, 176), and cultivar maturity (early, 95 d; medium, 105 d; late, 120 d). Using the September–November Oceanic Niño Index (ONI) to identify ENSO phase, La Niña years had 50 mm less precipitation and a corresponding 14.5% reduction in overall yield to 4550 kg ha^{-1} for sorghum planted at 16 plants m^{-2} population. Late maturing cultivars and late planting led to sorghum freeze injury and reduced yields regardless of ENSO phase. While yields consistently increased with irrigation, we conclude that concentrating water to irrigate an area partitioned 2:1 or 1:1 at 3.75- or 5.0-mm d^{-1} with complementary dryland produced >30% more grain, overall, than uniformly irrigating an area at 2.5 mm d^{-1}.

Core Ideas

- Maturing Oceanic Niño Index identified La Niña years with less rain and yield.
- Increased irrigation plus rain improved yield but water use efficiency plateaued.
- Irrigation of partitioned areas with dryland improved yield independent of El Niño southern oscillation phase.

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The semiarid climate of the US High Plains physiographic region that extends from Texas to South Dakota (Gutentag et al., 1984) receives an average of <500 mm precipitation annually, providing from 40 to 80% of the potential evapotranspiration (Follett et al., 2012) and necessitating irrigation to meet crop water demand. Because irrigation from the Ogallala (High Plains) Aquifer that began in the 1950s exceeds the practically negligible recharge south of Nebraska, the resulting spatially weighted water table decline since pre-development ranges from 3.8 m in Oklahoma to 12.5 m in Texas (Stewart, 2003; McGuire, 2017). About 90% of groundwater withdrawals in High Plains states was used for irrigation, but other competing groundwater allocations include municipal water (4–6%) and livestock, industrial, or mining uses (1–3%) that may vary locally (Wagner, 2012; Scanlon et al., 2017; Dieter et al., 2018). For example, 91% of groundwater use in the Permian Basin is for irrigation with 3% used for hydraulic fracturing oil wells (mining), but at a water-use/oil-recovery ratio of ~1.0 in the adjoining Delaware Basin (Scanlon et al., 2017) the recent discoveries initially producing up to 1530 m^3 oil daily (Darbonne, 2018) can expand competition for water. Increased competition for water resources in addition to the declining water table effects encourage innovative irrigation strategies.

A consequence of the declining groundwater table and aquifer saturated thickness is decreasing irrigation well capacity that may be insufficient to meet crop demand. This has been offset by improved irrigation scheduling based on evapotranspiration (ET) replacement (Howell, 2001), more efficient application methods such as subsurface drip or Low Energy Precision Application (Colaizzi et al., 2009), and managed deficit irrigation that defers water application to critical growth stages (Bell

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Abbreviations: DOY, day of year; ENSO, El Niño southern oscillation; ET, evopotranspiration; HI, harvest index; ONI, Oceanic Niño Index; PM, physiological maturity; WUE, water use efficiency (kg m-3).

et al., 2018). Irrigation would be recommended for managed deficit irrigation during growing point differentiation or the "boot" (panicle exertion) critical growth stages (Stichler et al., 1997; Vanderlip et al., 1998; Gerik et al., 2003). Baumhardt and Howell (2006) pointed out, however, that deficit irrigation is often applied uniformly during the growing season because of the practical limitation imposed by irrigation well capacity that precludes growth stage specific large irrigations. Planting date and cultivar maturity combine to determine growing season duration that increases yield proportionately when irrigation well capacity meets sorghum ET demand (Vanderlip et al., 1998). Under deficit irrigation at rates of ≤2.5 mm d^{-1}, grain sorghum water use efficiency and yield for the Southern High Plains was achieved with early planting of early-maturing cultivars (Baumhardt and Howell, 2006). Converting from uniform field deficit irrigation (water spreading) to partitioned field irrigation that concentrates water resources to better meet crop ET needs but includes a dryland area, increased simulated yield and water use efficiency (WUE) of both grain sorghum and cotton [*Gossypium hirsutum* (L.)] (Baumhardt et al., 2007; Nair et al., 2013; Baumhardt et al., 2015). Integration of growing season rain and irrigation for management strategies differing by planting date and cultivar may benefit from climate predictions.

Greater reliance on growing season precipitation represents a means to reduce irrigation water withdrawals and the subsequent depletion of the Ogallala Aquifer, but precipitation on the southern High Plains is erratic in both distribution and amount that varies from 89 to 580 mm per year (Baumhardt and Salinas-Garcia, 2006). A climate analysis by Mauget and Upchurch (1999) identified favorable fall and winter precipitation during the El Niño phase, warm (>0.5°C) sea surface temperature anomalies conditions, and below average precipitation during the cool (<–0.5°C) La Niña phase. They observed no change in summer precipitation during the El Niño phase, but the corresponding rains during La Niña phases decreased after June. Proactive wheat management was possible on the Southern High Plains for developing El Niño or La Niña phases that coincided with timely decisions regarding planting date and fertilizer management, (Mauget et al., 2009). Using ENSO phase for long-range climate predictions may permit proactive summer crop and irrigation management (Jones et al., 2000; Baumhardt et al., 2015).

In a 1954–2011 field experiment, Baumhardt et al. (2016) reported mean sorghum growing season rain increased from 193 mm for La Niña years to 236 mm for Neutral and 262 mm for El Niño phase years, but differences in rain amount or the corresponding measured yield increases of 500 and 800 kg ha^{-1} were not significant. Preliminary (1961–2000) crop growth simulations using a 12 plant m^{-2} population and standardized field and cultivar conditions, revealed greater sorghum yield trends with grain yields for Neutral and El Niño phases that were significantly greater than for the La Niña phase. We therefore hypothesize that simulated sorghum yields using long-term weather as input will reveal ENSO phase specific deficit irrigation strategies that increase grain yields. Our objective was to evaluate sorghum grain yield response to ENSO climate informed management of varying cultural practices and irrigation allocation strategies. To achieve this we simulated sorghum response to planting date, cultivar maturity, and irrigation level for all ENSO phases during a 40 yr period then computed the weighted average yield for either spreading a fixed water resource to deficit irrigate a large area or concentrating irrigation on a smaller area combined with a complementary dryland area.

MATERIALS AND METHODS

Grain sorghum growth and yield was simulated according to the methods of Baumhardt et al. (2005) using the model SORKAM (Rosenthal et al., 1989) as updated to version 2000 (W.D. Rosenthal and R.L. Vanderlip, personal communication, 2000). Model required daily weather input of solar irradiance (MJ m^{-2}), maximum and minimum air temperature (°C), and precipitation (mm) was supplied from records at the USDA-ARS, Conservation and Production Research Laboratory, Bushland, TX (35°11′ N, 102°5′ W; 1170 m elevation) for growing seasons during 1961–2000. Soil fertility was necessarily assumed to be adequate for sorghum because SORKAM does not simulate nutrient effects on crop growth and yield. The simulations were performed for a 1.8-m deep Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) profile divided into nine layers having similar porosity and plant available water (Baumhardt et al., 2005). For comparison among alternative management practices as replicated by years, the soil profile was reset each year to a uniform water content of 160 mm, which was the long-term median soil water observed at planting for stubble-mulch tillage (Baumhardt et al., 2017). Maximum sorghum rooting depth was not restricted within the 1.8 m soil profile depth, which is consistent with observed rooting to depths >1.5 m for dryland sorghum grown on a Pullman soil at Bushland (Moroke et al., 2005). Soil water evaporation was calculated by the Priestley-Taylor method with an overall 1.45 scale factor, after Howell et al. (1989), using constants of 0.19 for albedo, 9.9 mm for U (stage 1) and 7.8 mm d^{-1} for C (stage 2) as reported by Steiner (1989) for the two stages of soil water evaporation. Runoff was calculated using the measured SCS curve number of 82 for sorghum reported by Hauser and Jones (1991).

Crop Simulations

Our simulations began 2 wk before the scenario planting date for all possible combinations of three cultivar maturity levels, three planting dates, and four water application levels. Scenario water levels ranged from dryland (rain only) to rain + irrigation totaling 2.5, 3.75, and 5.0 mm d^{-1} and were applied, independently of crop growth stage, in 10 d intervals using a 25, 37.5, or 50 mm maximum application depth. These irrigation levels represent a range of well pumping capacities approximating 3, 4.6, and 6.1 L min^{-1} ha^{-1}, which are consistent with progressively more productive irrigation wells in the region. We selected three generic cultivars that produce 15, 17, or 19 leaves to represent early-, medium-, and late-maturing cultivars requiring ~ 95, 105, and 120 d to reach maturity, which were planted 15 May (early), 5 June (normal), and 25 June (late) for evaluating a broad range of growing season durations on deficit irrigated sorghum performance. A population of 16 plants m^{-2} in single rows 0.76 m apart was selected as an intermediate plant density for transitioning from irrigated to dryland production. The resulting 36 simulation scenarios were evaluated for each of 40 yr of weather records for a total of 1440 simulations. The SORKAM simulations continued until the earlier date of crop physiological maturity or a killing frost, when grain yield and water use estimated from growing season rain, irrigation, and soil water were determined.

Inferring alternative cultural practice effects on grain sorghum growth, yield, and water use efficiency is critically dependent on the validity of SORKAM to simulate plant responses under variable growing conditions. In addition to numerous reports validating SORKAM (Rosenthal and Gerik, 1990; Heiniger et al., 1997; Xie et al., 2001), Baumhardt and Howell (2006) also validated SORKAM calculated grain sorghum yields for the Pullman soil at Bushland using location recorded weather and actual cropping conditions (e.g., planting date). Their simulated grain yields averaged ~4% more than observed yields ($r^2 = 0.70$, RMSE = 903.5 kg ha^{-1}) of the corresponding similarly planted late- and medium-maturity hybrids from a 1984–1998 wheat-sorghum-fallow rotation study (Jones and Popham, 1997). The corresponding water use averaged 470 mm and was not significantly different ($P = 0.10$) from the SORKAM simulated value of 507 mm according to a paired *t* test (Baumhardt and Howell, 2006). These successful yield and water use estimations indicated SORKAM adequately simulates these factors throughout a broad range of climate and growing conditions and no further validation was performed.

El Niño Southern Oscillation Classification

The efficacy of using ENSO phase as a tool for climate informed management was evaluated using the readily available monthly Oceanic Niño Index (ONI) of the Niño 3.4 region (5° N–5° S, 120°–170° W) published by the National Weather Service Climate Prediction Center (CPC, 2018). The ONI classifies ENSO phases based on deviations in observed equatorial sea surface temperature from reference temperatures of centered 30-yr periods that are updated every 5 yr to account for any temperature bias due to climate change. A maturing ENSO phase determined from the ONI 3-mo period from September through November was used as the basis of comparison. Warm El Niño phase conditions occur when the ONI exceeded 0.5°C, cold La Niña conditions are designated by ONI values less than −0.5°C and all exceptions to those conditions were ENSO phase Neutral. The resulting years for each ENSO phase listed by Baumhardt et al. (2016) for 1961–2000 comprised 14 yr for the Neutral phase and 13 yr each for the El Niño and La Niña phases.

Analyses

Sorghum growth, grain yield, water use (i.e., sum of precipitation, irrigation and change in soil water), and the WUE, calculated as the ratio of yield to water use, were evaluated for each of 36 simulation scenarios appearing each year. Climatic variability from the unique weather conditions, e.g., rainfall and temperature, specific to a simulated growing season (1961–2000) provided the source of random experimental error to test SORKAM projected crop growth response of each scenario. We compared ENSO phase, irrigation capacity, cultivar maturity, and planting date fixed effects on modeled sorghum performance according to a factorial arrangement of a completely randomized design using SAS glimmix ANOVA procedures (SAS Institute, 2014). We subsequently isolated simulated sorghum water use, growth, and yield performance by specific ENSO phase with years as a random effect to better compare cultivar maturity, planting dates, and irrigation fixed effects within each phase. Contrasts (estimated with the slice option in the mixed model LS-means statement) were used to evaluate simple within subject effects. Unless specified otherwise, all statistical analysis effects were declared significant at the 0.05 probability level.

RESULTS AND DISCUSSION

Growing Season Conditions

Precipitation for the 1961–2000 simulated growing seasons averaged 240 mm but was subsequently partitioned to reveal the effects of ENSO phase and crop management that includes planting date, cultivar maturity, and irrigation level. The 207 mm mean precipitation for the La Niña ENSO phase was a significant ($P < 0.01$) 20% reduction from the 260 mm average for the Neutral and El Niño phases. The growing season extending earlier planting date and later cultivar maturity were associated with significantly ($P < 0.01$) greater seasonal precipitation (Table 1) regardless of ENSO phase probably because potentially longer frost-free periods have been weakly correlated to ENSO indices (McCabe et al., 2015). Because water deficit stress can delay growth and extend the growing season the observed seasonal precipitation was significantly greater for dryland, 0.00 mm d^{-1} irrigation, than for any of the 2.50, 3.75, or 5.00 mm d^{-1} irrigation levels except for the El Niño phase.

The overall 40 yr simulated growing season time to anthesis ranged from 79 d for the La Niña phase to the significantly ($P < 0.01$) shorter 75-d average for El Niño and Neutral phases with all phases maturing about 40 d later. For dryland sorghum, our simulated anthesis and physiological maturity (PM) was delayed ($P < 0.01$ for both anthesis and PM) ~2 wk during the drier La Niña phase compared with Neutral and El Niño phases (Table 1). Although sorghum anthesis and PM for all ENSO phases were significantly ($P < 0.01$) later for dryland, these became progressively earlier for the 2.50 mm d^{-1} and 3.75- or 5.00-mm d^{-1} irrigation rates because delays in sorghum development due to water stress were reduced or prevented by the added water. As might be expected, progressively later maturing cultivars significantly ($P < 0.01$) extended the growing season duration for both anthesis and PM for each of the ENSO phases, but we simulated earlier PM for mid (June 5) planting dates for each ENSO phase. For all ENSO phases, an interaction between irrigation level and either the planting date or cultivar maturity delayed PM of sorghum with earlier planting dates or cultivar maturities and the lower dryland or 2.5 mm d^{-1} irrigation levels. The delay in grain sorghum development can shift the growing season of some irrigation combinations with planting date or cultivar maturity to later months that typically receive less precipitation and, consequently, cause greater reliance on irrigation and exposure to potential freeze injuries.

Anthesis typically occurred during mid-August to mid-September and, typically, was early enough in the growing season to avoid freeze events; however, anthesis freeze injuries did occur in 2.7% of the simulations or 38 events with two-thirds of those (25 events) during the drier La Niña phase ($P < 0.01$). By contrast, PM freeze injuries that represent a concern due to potential yield reduction were observed in 22% or 312 of the simulations and were, in the absence of a significant ENSO effect, evenly divided among the phases (Table 1). Within any ENSO phase, PM freeze injury for sorghum planted DOY-176 averaged 77% of these 312 events but were practically

Table 1. The ENSO phase specific mean time to reach anthesis and physiological maturity and the seasonal rain and irrigation at maturity for scenario planting date (PD), irrigation capacity (I), and cultivar maturity (C) main effects, with the corresponding ANOVA significance levels.†

	Seasonal rain			Days to anthesis			Days to maturity			Freeze by maturity		
	ENSO phase			ENSO phase			ENSO phase			ENSO phase		
Effect	La Niña	Neutral	El Niño	La Niña	Neutral	El Niño	La Niña	Neutral	El Niño	La Niña	Neutral	El Niño
Planting date, DOY		mm					d				Events	
135	223 a‡	291 a	287 a	86 a	81 a	80 a	121 a	118 a	117 a	13 b	10 b	5 b
156	204 b	251 b	261 b	77 b	72 b	72 b	116 b	114 b	114 b	19 b	13 b	11 b
176	193 c	233 c	235 c	74 b	71 b	70 b	120 a	119 a	117 a	75 a	91 a	75 a
Irrigation, mm d^{-1}												
0.0 (dryland)	229 a	269 a	264 a	99 a	85 a	80 a	132 a	123 a	119 a	54 a	46 a	31 a
2.5	204 b	257 b	260 a	76 b	74 b	74 b	118 b	116 b	115 b	21 b	24 b	20 b
3.75	196 b	252 b	259 a	70 c	70 c	71 c	113 c	114 b	114 b	16 b	22 b	19 b
5.0	199 b	255 b	262 a	70 c	70 c	71 c	114 c	115 b	115 b	16 b	22 b	21 b
Cultivar maturity												
Early	188 c	244 c	247 c	66 c	65 c	65 c	106 c	107 c	106 c	7 c	8 c	7 c
Medium	210 b	258 b	263 b	80 b	74 b	74 b	121 b	117 b	116 b	42 b	40 b	31 b
Late	222 a	273 a	274 a	91 a	84 a	82 a	131 a	126 a	125 a	58 a	66 a	53 a
Significance		P > F			P > F			P > F			P > F	
PD	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
I	< 0.01	0.02	0.73	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.01
PD × I	0.10	0.31	0.98	0.65	0.21	0.99	< 0.01	< 0.01	< .03	0.40	0.54	0.68
C	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
C × PD	0.09	0.44	0.25	0.94	0.89	0.97	0.19	0.01	0.05	< 0.01	< 0.01	< 0.01
C × I	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.31	0.22
C × I × PD	0.99	0.99	> 0.99	> 0.99	> 0.99	> 0.99	0.84	0.69	0.67	0.97	0.52	0.99

† ENSO, El Niño southern oscillation; DOY, day of year; PD, planting date; I, irrigation; C, cultivar.

‡ Effect means within columns followed by the same letter are not significantly different, *P* = 0.05.

exclusive to simulation scenarios with irrigations >0 mm d^{-1} that increased vegetative growth. Likewise, the DOY-176 late planting led to almost half of the 38 simulated anthesis freeze injuries, highlighting the greater risk due to late planting. Approximately half of the PM and all of the anthesis freeze injuries were simulated using the 0.00 mm d^{-1} irrigation level regardless of the ENSO phase because of growth delays related to water stress (Donatelli et al., 1992; Farré and María Faci, 2006; Bell et al., 2018). Medium and late maturing cultivars incurred progressively greater, 36% and 57%, PM freeze injury because of the cultivar specific delayed maturity (Table 1).

Crop Water Use

The overall combined seasonal rain and irrigation means ranged from 368 mm for the La Niña to the significantly ($P < 0.01$) larger 390 mm for Neutral and 383 mm for El Niño phases. Within each ENSO phase we show, by irrigation level, all possible combinations of cultivar maturity and planting date in Fig. 1. The extended growing season due to later maturing cultivars and earlier planting dates also increased cumulative rain as shown by the shaded column fractions. Because dryland, no irrigation, conditions also extended the growing season, rainfall increased 30 mm over the 200 mm average of all other irrigation levels for the La Niña phase. By contrast, rainfall for the extended dryland growing season of Neutral and El Niño phase years increased ranged from 10 mm to 0 mm over the corresponding 255 and 260 mm rainfall for irrigated simulation scenarios. For the drier La Niña phase, the increasing irrigation rates added water, averaged over planting date and cultivar maturity, in the amount of 95 mm at the lowest 2.50 mm d^{-1} irrigation level, increasing to 208 mm for 3.75 mm d^{-1} and 342 mm for 5.00 mm d^{-1}. Likewise, the irrigation applied during the wetter Neutral phase decreased to 69 mm for 2.50 mm d^{-1}, 164 mm for 3.75 mm d^{-1}, and 293 mm for 5.00 mm d^{-1} and, for the El Niño phase, to slightly lower irrigation amounts of 53 mm, 152 mm, and 283 mm for the corresponding irrigation levels. Seasonal rain plus irrigation for the 2.50 mm d^{-1} irrigation level averaged 312 ± 12 mm across all ENSO phases, increasing to 410 ± 6 mm for 3.75 mm d^{-1} and 545 ± 2 mm for 5.00 mm d^{-1} irrigation levels, demonstrating that target supplemental irrigation levels were effectively managed independent of the ENSO phase.

Seasonal crop water use varied by ENSO phase, averaging 500 mm for La Niña compared with larger ($P < 0.01$) 520 mm for Neutral and 530 mm for El Niño phases due, in part, to their receiving 50 mm more rain than La Niña. As previously noted for rainfall, those factors that limit growing season duration such as late planting or early maturing cultivars, subsequently, reduced crop water use within any ENSO phase (Fig. 2). For example, water use for later DOY-176 planted sorghum decreased often by >65 mm to 468–493 mm from the 525–553 mm observed for DOY 135 planted sorghum depending on the ENSO phase. The progressively longer growing season for medium and late maturing cultivars similarly increased water use by 30 to 45 mm compared with the early maturing cultivar that used 474 mm during La Niña phase or an average of 500 mm for the Neutral and El Niño phases. It is not surprising that water use increased progressively as the irrigation levels increased from 0.00 mm d^{-1}, dryland, to the rain plus supplemental irrigation of up to the 5.00 mm d^{-1} level (Fig. 2). That is, mean water use for the highest irrigation rate ranged from 601 to 610 mm across all ENSO phases or similar to that reported for Pullman soil by Tolk and Howell (2001), while dryland

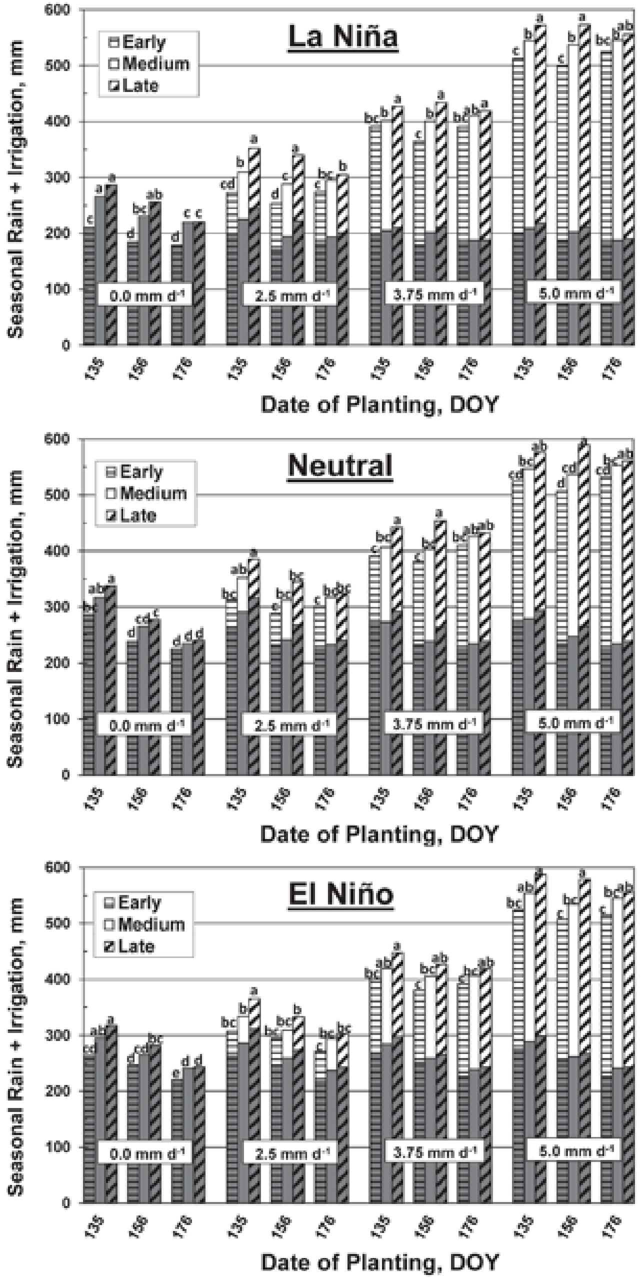

Fig. 1. Combined seasonal rain (shaded fraction of columns) and irrigation for early, medium, and late maturing sorghum cultivars planted on day of year (DOY) 135, 156, and 176 for dryland and deficit irrigation of up to 2.5, 3.75, and 5.0 mm d^{-1} during all El Niño southern oscillation phases. Columns from common irrigation levels with the same letter are not significantly different, *P* = 0.05.

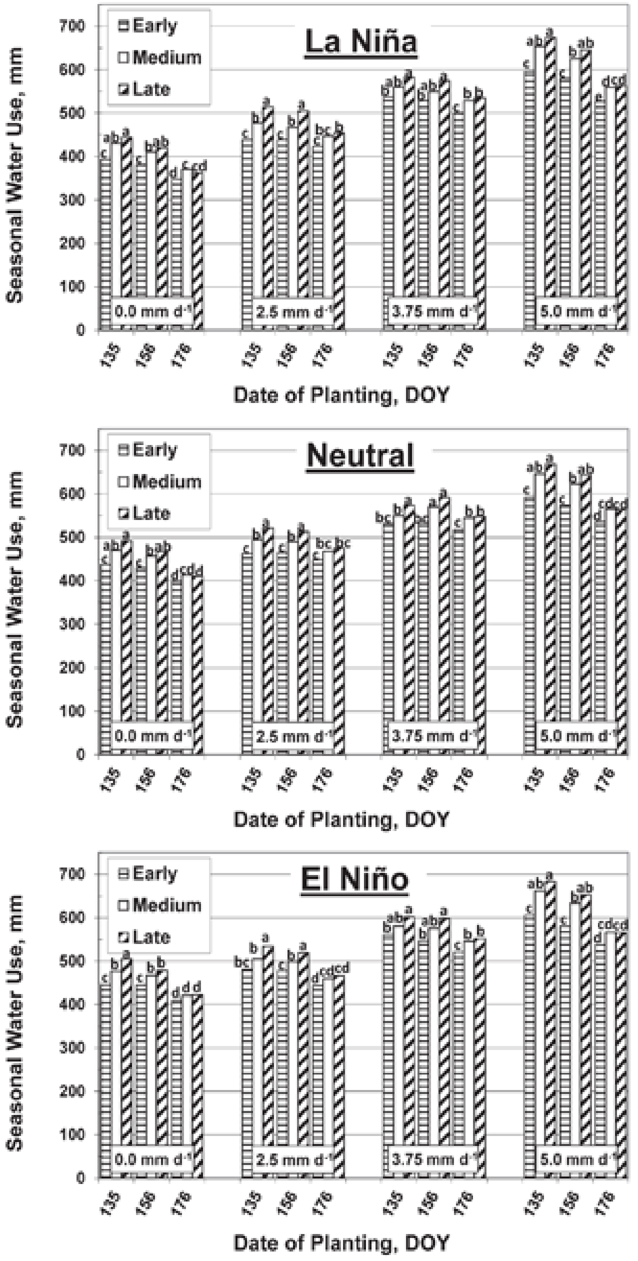

Fig. 2. Simulated (1961–2000) sorghum water use of early, medium, and late maturing cultivars planted on day of year (DOY) 135, 156, and 176 for dryland (rain only) and rain + deficit irrigation supplying up to 2.5, 3.75, and 5.0 mm d^{-1} during all El Niño southern oscillation phases. Columns from common irrigation levels with the same letter are not significantly different, *P* = 0.05.

sorghum water use decreased by ~210 mm to 395 mm during the La Niña phase and averaged 445 mm for the wetter Neutral and El Niño phases. Mean seasonal water use for the 2.50 mm d^{-1} irrigation rate averaged ~480 mm across all ENSO phases, ranging from a low of 463 mm for the La Niña to a high of 487 mm for El Niño phases. Likewise, increasing irrigation to 3.75 mm d^{-1} rate elevated mean seasonal water use to 550 mm, ranging from a low of 544 mm for the La Niña ENSO phase up to 565 mm for the El Niño.

Seasonal water use increasingly relied on precipitation during wetter ENSO phases, ranging from 41% for the La Niña phase to 50% for the Neutral and El Niño phases. Regardless of ENSO phase, rain supplied ~60% of dryland crop water use with the balance, 40%, from soil water. As irrigation levels progressively increased from 2.50 mm d^{-1} up to 5.00 mm d^{-1}, rain contributed proportionally less to crop water use, decreasing from 44 to 33% during the drier La Niña phase and from 53 to 43% during wetter Neutral and El Niño phases. Consequently, the fraction of crop water use supplied by the progressively higher irrigation levels increased from 21 to 60% for the La Niña phase compared with similar increases from 14 to 49% for Neutral and 11 to 46% for El Niño phases. As irrigation rates increased, the simulated crop water use supplied by the soil

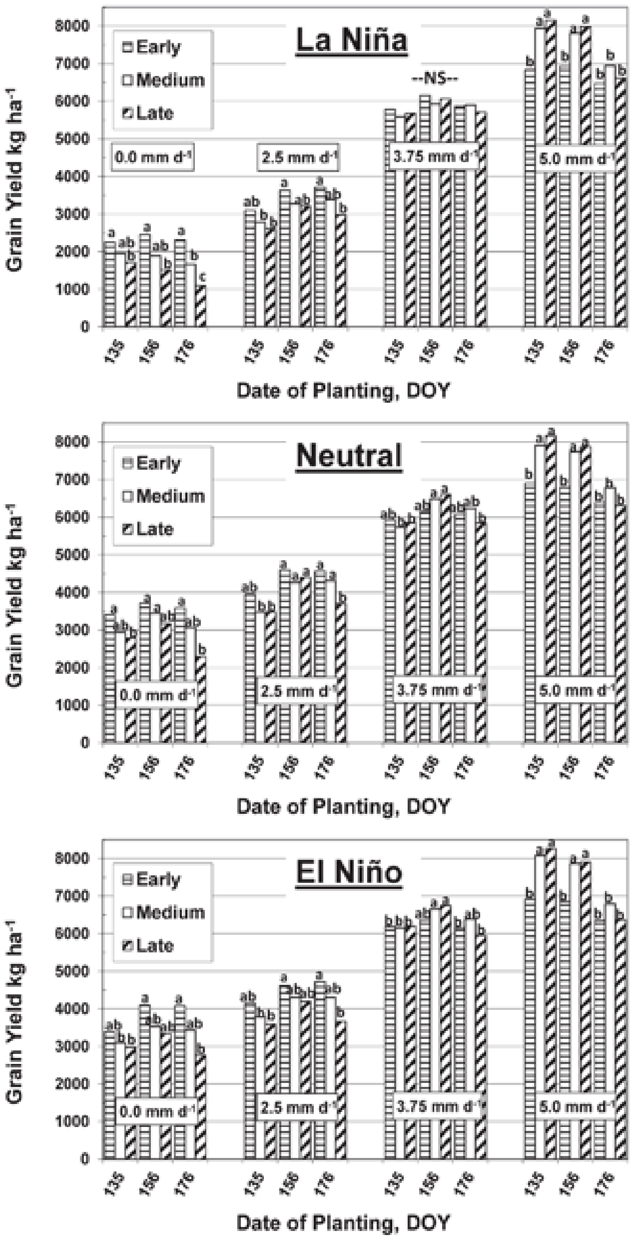

Fig. 3. Simulated (1961–2000) sorghum grain yield of early, medium, and late maturing cultivars planted on 15 May, 5 June, and 25 June (day of year [DOY] 135, 156, and 176) for dryland (rain only) and rain + deficit irrigation supplying up to 2.5, 3.75, and 5.0 mm d^{-1} during all El Niño southern oscillation phases. Columns from common irrigation levels with the same letter are not significantly different, $P = 0.05$.

decreased from 35% for 2.50 mm d^{-1} to 26% for 3.75 mm d^{-1} and 10% for 5.00 mm d^{-1} regardless of ENSO phase.

Grain Yield and Water Use Efficiency

Water made available to a crop from the soil, rain, or irrigation generally determines the resulting yields in a semiarid climate with minimal runoff or drainage losses. A 50 mm increase in mean growing season precipitation for Neutral and El Niño phases compared with the La Niña phase in our simulations occurred despite maturing ENSO phase effects being less pronounced during the boreal summer. The resulting overall simulated sorghum grain yield averaged across irrigation, planting date, and cultivar maturity levels differed by ENSO phase, which ranged from the significantly ($P < 0.01$) lower of 4550 kg ha^{-1} for La Niña to 5140 kg ha^{-1} for Neutral and 5290 kg ha^{-1} for El Niño phases. This reflects greater precipitation during the Neutral and El Niño phases. Grain sorghum yield increased with increasing irrigation levels, but varied with ENSO phase (Fig. 3). For example, increasing the irrigation level from 0.00 to 2.50 mm d^{-1} improved La Niña dryland grain yields of 1870 kg ha^{-1} by about 1300 kg ha^{-1} to 3190 kg ha^{-1} compared with more modest increases from 3160 kg ha^{-1} to 4080 kg ha^{-1} for the Neutral and from 3410 kg ha^{-1} to 4150 kg ha^{-1} for the El Niño phases (Table 2). At the 3.75 mm d^{-1} irrigation level, ENSO phase effects to increase grain yield diminished to < 450 kg ha^{-1} over the La Niña 5850 kg ha^{-1} low, ranging up to 6100 kg ha^{-1} for Neutral and 6310 kg ha^{-1} for El Niño phases. The ENSO phase had essentially no effect on simulated grain yield at the 5.00 mm d^{-1} irrigation rate and averaged 7260 ± 45 kg ha^{-1} across all phases.

Despite typically greater grain yield during wetter Neutral and El Niño phase years, the mean grain yield of late planted, DOY-176, sorghum was significantly ($P = 0.05$) lower than for the DOY-156 planting regardless of ENSO phase (Fig. 3) that we attributed, in part, to reduced growing season duration due to freeze events. An interaction of irrigation with planting date resulted from a shift in the consistently lowest yielding combination of DOY-176 planted sorghum irrigated with 5.00 mm d^{-1} to early, DOY-135, planted sorghum irrigated at lower rates of 2.50 mm d^{-1} and 3.75 mm d^{-1}. Although sorghum grain yield did not vary significantly ($P > 0.05$) with cultivar maturity in contrast to findings in Nebraska by Garrity et al. (1982), our consistently higher yields of early cultivars with 0.00 or 2.50 mm d^{-1} irrigation levels were similarly reversed by an interaction of higher-yielding late maturing cultivars that took advantage of the 5.00 mm d^{-1} irrigation (Fig. 3).

Plant use of the stored soil water, precipitation, and applied irrigation determines water use efficiency (WUE) and generally follows crop yield. Our calculated WUE for the La Niña phase of 0.85 kg m^{-3} was significantly ($P < 0.01$) lower than the 0.96 ± 0.01 kg m^{-3} average of Neutral and El Niño phases that reflected their corresponding greater simulated yields since the range in total water use differed by only 6% (Fig. 4). Our calculated WUE followed the greater grain yields resulting from increasing irrigation levels that averaged a peak 1.20 ± 0.01 kg m^{-3} across all ENSO phases for the 5.00 mm d^{-1} irrigation that provided almost half of the water used by the crop. For sorghum receiving 3.75 mm d^{-1} irrigation, the La Niña phase WUE of 1.07 kg m^{-3} was numerically lower than the average WUE of 1.11 ± 0.01 kg m^{-3} for the Neutral and El Niño phases and significantly ($P = 0.05$) lower than WUE of the 5.00 mm d^{-1} irrigation regardless of ENSO phase. Water use efficiency for sorghum receiving 2.50 mm d^{-1} irrigation increased from a low of 0.68 kg m^{-3} for La Niña up to 0.83 kg m^{-3} for the Neutral and 0.84 kg m^{-3} for the El Niño phases, indicating the greater impact of the additional precipitation on grain yield. The WUE of the 2.50 mm d^{-1} irrigation level was significantly different from the corresponding WUE at 3.75 mm d^{-1} for all ENSO phases. Dryland WUE for the drier La Niña phase averaged 0.43 kg m^{-3} compared with 0.66 kg m^{-3} and 0.73 kg m^{-3} for the Neutral and El Niño phases, respectively, and was unexpectedly less than long-term field estimates around 0.90 kg m^{-3} for sorghum (Jones and Popham, 1997; Baumhardt et al., 2017).

Table 2. The 40-yr and El Niño southern oscillation-phase specific mean simulated yield of uniform application of irrigation capacities and the weighted-average yield for split-pivot application strategy combinations resulting in a fixed total irrigation capacity. The uniform irrigation strategy base yield of 3810 kg ha^{-1} was from a fixed capacity deficit irrigation of 2.5 mm d^{-1}.

Application strategy	Irrigation capacity	Simulated yield	Weighted average yield	Yield fraction, phase specific uniform strategy	Yield fraction, overall base uniform strategy
	mm d^{-1}	kg ha^{-1}		%	
Overall					
Uniform	2.50	3810	3810	100	100
2:1	3.75	6090	5000	131	131
	Dryland	2810			
1:1	5.00	7260	5040	132	132
	Dryland	2810			
La Niña					
Uniform	2.50	3190	3190	100	84
2:1	3.75	5850	4530	142	119
	Dryland	1870			
1:1	5.00	7300	4590	144	120
	Dryland	1870			
Neutral					
Uniform	2.50	4080	4080	100	107
2:1	3.75	6100	5120	125	135
	Dryland	3160			
1:1	5.00	7210	5190	127	136
	Dryland	3160			
El Niño					
Uniform	2.50	4150	4150	100	109
2:1	3.75	6310	5350	129	140
	Dryland	3410			
1:1	5.00	7270	5340	129	140
	Dryland	3410			

The simulated sorghum WUE averaged across ENSO phase and irrigation level for planting dates DOY-135 at 0.87 kg m^{-3} was significantly ($P = 0.05$) lower than the 0.95 and 0.94 kg m^{-3} for DOY-156 or DOY-176, although the WUE within each ENSO phase repeated that planting date ranking (Fig. 4). Progressively later maturing cultivars produced incrementally lower WUE values that were significantly ($P = 0.05$) different for each ENSO phase. That is, La Niña phase WUE early, medium, and late maturing cultivars averaged 0.93 kg m^{-3}, 0.84 kg m^{-3}, and 0.78 kg m^{-3}, respectively, while the corresponding Neutral and El Niño phase WUE values averaged 1.02 ± 0.01 kg m^{-3}, 0.96 ± 0.01 kg m^{-3}, and 0.89 ± 0.01 kg m^{-3}. The significant ($P < 0.01$) interaction between cultivar maturity and irrigation level was manifested by a decreasing difference in WUE shown in Fig. 4 for progressively later maturing cultivars as the irrigation level increased from 0.00 to 3.75 mm d^{-1} and dissipated with 5.00 mm d^{-1} irrigation. This was attributed to early maturing cultivars sacrificing yield potential by limiting the crop canopy and accumulated biomass to expedite grain production in contrast with later maturing cultivars that emphasize biomass accumulation to exploit resources including water available from irrigation and rain during longer growing seasons to maximize grain yield.

The ratio of grain to biomass or the harvest index, HI, may clarify differences in the WUE that improves as the amount of grain produced per unit of water used increases. Factors interfering with normal maturing of grain typically depress HI, which was observed for the growing season limiting DOY-176 planting date, HI of 0.39, that was significantly ($P = 0.05$) less than the 0.42 mean HI for both DOY-135 and DOY-156 plantings (Fig. 5.). The HI consistently decreased with progressively later maturing cultivars, averaging 0.45 across ENSO phases for early cultivars compared with significantly ($P = 0.05$) different values of 0.41 and 0.36 for the medium and late maturing cultivars. Those cultivar maturity effects, however, were most striking at the dryland and 2.50 mm d^{-1} irrigation levels because water availability limited panicle, seed number, and seed mass development (data not shown). Water deficit stress that limits crop development and subsequent production of harvestable grain contributed to the significantly lower HI of 0.39 for La Niña compared with 0.42 for the wetter Neutral and El Niño phases. Our simulated HI generally increased as irrigation increased sufficiently to offset critical crop water demand regardless of ENSO phase, averaging 0.34 for dryland, 0.41 for 2.50 mm d^{-1}, 0.45 for 3.75 mm d^{-1}, and 0.44 for 5.00 mm d^{-1} levels. In fact, the mean HI of the 3.75- and 5.00-mm d^{-1} irrigation levels within all three ENSO phase combinations was 0.44, suggesting limited water stress for the higher irrigation levels.

Irrigation Strategies and Management Considerations

We compared sorghum grain yields for three irrigation strategies that spread a fixed water resource over an area that was (i) uniformly deficit irrigated at 2.50 mm d^{-1}, or concentrates that water on a partitioned area irrigated at rates of (ii) 3.75 mm d^{-1} and dryland in a 2:1 ratio, or (iii) 5.00 mm d^{-1} and dryland in a 1:1 ratio. Grain sorghum yields averaged across planting date and cultivar maturity for dryland and 2.50-, 3.75-, and 5.00-mm

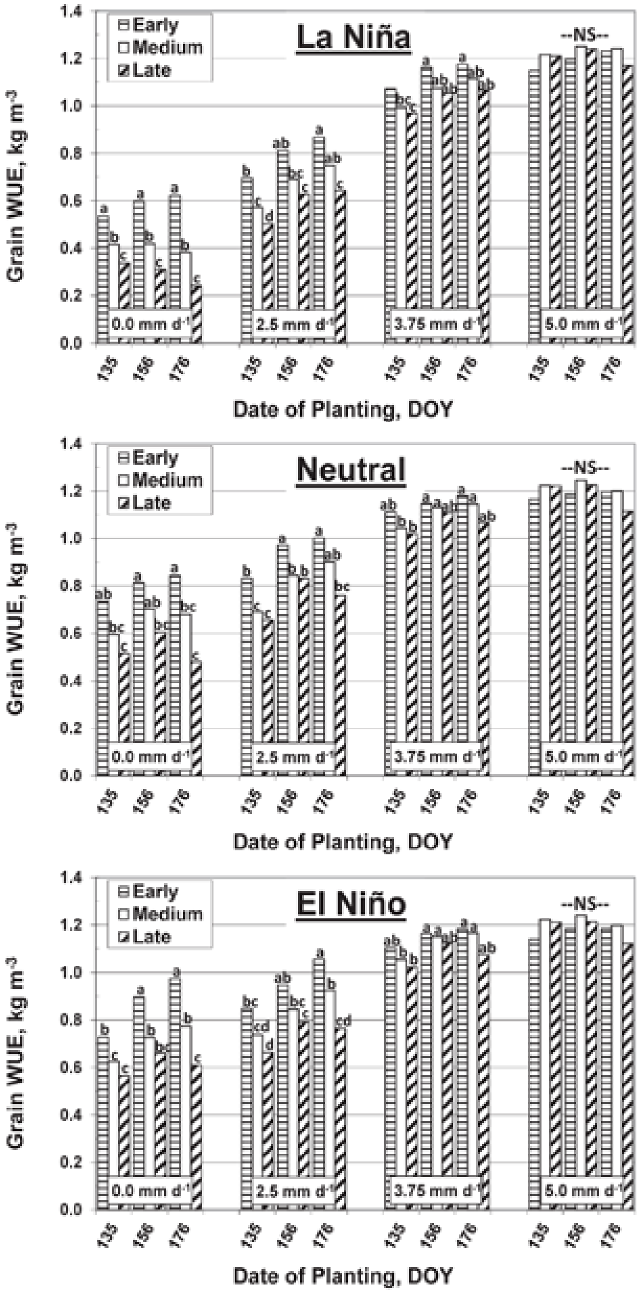

Fig. 4. Calculated grain sorghum water use efficiency (WUE) of early, medium, and late maturing cultivars planted on day of year (DOY) 135, 156, and 176 for dryland (rain only) and rain + deficit irrigation supplying up to 2.5, 3.75, and 5.0 mm d^{-1} during all El Niño southern oscillation phases. Columns from common irrigation levels with the same letter are not significantly different, $P = 0.05$.

d^{-1} irrigation levels are listed for the overall 40-yr simulation and by ENSO phase specific years with the weighted averages for irrigation strategies using uniform or the 2:1 or 1:1 partitioning in Table 2. The overall simulated mean grain sorghum yield of the 2.50 mm d^{-1} uniformly irrigated area averaged 3810 kg ha^{-1}, which we used as the 100% yield base for comparison. Weighted yield averages for areas partitioned into a 2:1 or 1:1 ratio of irrigation to dryland increased ~30% over the base yield to 5000- or 5040-kg ha^{-1} and mirrored the partitioned irrigation yield advantage reported by Baumhardt et al. (2007).

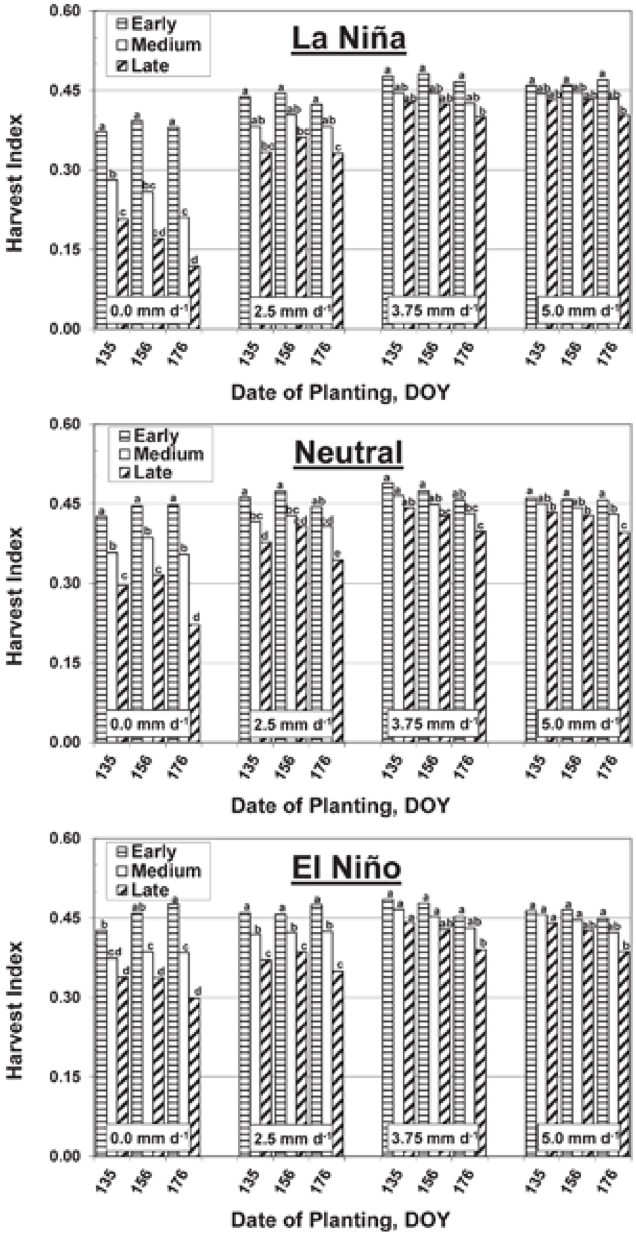

Fig. 5. Calculated grain sorghum harvest index (HI) of early, medium, and late maturing cultivars planted on day of year (DOY) 135, 156, and 176 for dryland (rain only) and rain + deficit irrigation supplying up to 2.5, 3.75, and 5.0 mm d^{-1} during all El Niño southern oscillation phases. Columns from common irrigation levels with the same letter are not significantly different, $P = 0.05$.

The lower simulated average grain yields specific to the drier La Niña years were approximately 620 kg ha^{-1} less than the overall mean of the uniform 2.50 mm d^{-1} irrigation or 3190 kg ha^{-1}, which was 84% of the overall base yield (Table 2). Likewise, mean La Niña yields from areas with partitioned irrigated to dryland ratios of 2:1 or 1:1 were 4530- or 4590-kg ha^{-1} that averaged 43% more than with uniform irrigation, but represent a modest 20% increase over the 3810 kg ha^{-1} base yield. Increased rain for Neutral and El Niño phase years contributed to greater uniformly irrigated yields, averaging 4080 kg ha^{-1} and 4150 kg ha^{-1} or about 8% more than the base yield. Simulated 2:1 or 1:1 partitioned yields during Neutral phase years ranged from 5120 to 5190 kg ha^{-1}, respectively, or 26%

more than with uniform irrigation, but 36% more than the base yield. Similarly, the 2:1 and 1:1 partitioned average yield of 5345 ± 5 kg ha^{-1} for El Niño years exceeded the phase specific uniform irrigation by 29 or 40% greater than the base. Although grain yields increased during wetter Neutral and El Niño phase years compared with those of La Niña, we identified no differences for yield optimization between either partitioning strategies regardless of the ENSO phase.

In lieu of irrigation to promote timely crop establishment, delayed planting of dryland crops due to unsuitable soil water conditions is an eventuality that often delays physiological maturity and increases production risk due to freeze injury. Sorghum freeze injury was simulated for 22% of all possible planting date, irrigation, and cultivar maturity combinations evaluated during the 40 test years. While all compared planting dates were subject to freeze injury prior to physiological maturity, freeze injuries were more frequent, 17% overall, for the late, DOY-176, planting date regardless of ENSO phase and should be avoided. The late maturing cultivar sustained freeze injury during 12% of all simulations compared with 8 and 2% for medium and early maturity cultivars and represent a risk reducing option under deficit irrigation. Dryland production often extended the growing season and sustained more frequent freeze injury, 9% overall during the 40 yr evaluated. For regions with need of cattle forage, sorghum freeze injury may be reduced by “haying out” the crop with an earlier harvest near anthesis and reduced affected crops to 2.6% of our simulations that were exclusively dryland.

SUMMARY AND CONCLUSIONS

Our results showed a significant ($P < 0.01$) 50 mm increase in mean growing season rain during Neutral and El Niño phases over the La Niña phase during the 1961–2000 simulated growing seasons. This paralleled a trend described by Baumhardt et al. (2016) even though ENSO phase effects are less pronounced during the boreal summer. Dryland, 0.00 mm d^{-1} irrigation, and late maturing cultivar scenarios extended the growing season that in addition to late, DOY-176, planting resulted in more frequent freeze injury regardless of ENSO phase. Simulated grain yield increased significantly ($P < 0.01$) in response to greater rain during Neutral and El Niño than for La Niña phases and because of progressively higher irrigation levels that increased seasonal water use. The corresponding WUE also improved as irrigation level increased, but the drier La Niña phase generally depressed WUE. Although precipitation during the wetter Neutral and El Niño ENSO phases contributed up to 50% of seasonal water use, we observed that for increasing irrigation levels the seasonal water use supplied by rain decreased to 33% for the La Niña and 43% on average for Neutral and El Niño phases. The increasing irrigation levels, likewise, reduced the soil water contribution to crop water use from 41% for dryland to 10% for full irrigation regardless of ENSO phase.

Management practices that conserve irrigation water by utilizing more precipitation stored as soil water or received during the growing season can potentially extend the useful life of the Ogallala aquifer. We conclude that, uniformly irrigating an area at 2.5 mm d^{-1} with a fixed water resource yielded less grain than concentrating that water resource to irrigate an area partitioned 2:1 at 3.75 mm d^{-1} and dryland or 1:1 at 5.0 mm d^{-1} and dryland because of more efficient water use. In lieu of any significant cumulative yield difference between either partitioning strategy regardless of the ENSO phase, the optimal partitioning strategy would depend on the site-specific production constraints and economics.

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