CROP WATER USE
IN LIMITED-IRRIGATION ENVIRONMENTS

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INTRODUCTION

The goal in High Plains agriculture is to use water most effectively in production systems to generate crop yield. To achieve this goal, we must use effective means to capture and store precipitation in the soil profile during noncrop periods, to capture and efficiently use precipitation received during the growing season, and to apply irrigation water in amounts and at times that are most efficient. The selection of appropriate crops – ones that match the expected water supply conditions of the production system – is also a requirement. This paper discusses options and practices that can lead to more effective use of water. These discussion points have application to both dryland and irrigated production systems.

YIELD vs. WATER RELATIONSHIPS

Crop yield vs. water relationships provide information that can be used in making decisions on the appropriateness of crops in production systems, through a consideration of the expected water supply conditions. Figure 1 illustrates the general relationships between seed yield and water amount (ET or water use). ET refers to evapotranspiration while water use refers to ET plus losses by runoff and internal drainage from the soil profile. Seed yield vs. ET is a linear relationship, although variability can and does exist. Seed yield vs. water use (ET + Runoff + Drainage) is typically a curvilinear relationship, with losses from runoff and drainage increasing with increasing water supply in the system. The seed yield vs. ET relationship is more transferable among geographic locations than is the seed yield vs. water use relationship that is more influenced by soil and landform characteristics that influence runoff and drainage.

Table 1 lists values of “Threshold ET”, “Maximum ET for a typical full-season variety”, “Slope of seed yield vs. ET”, and “Slope of long-term seed yield vs. ET” for five crops from research in western Kansas (Khan, 1996; Khan et al., 1996). “Threshold ET” is the ET necessary to move into the seed producing segment of the yield vs. ET relationship: at the “Threshold ET” value and below, seed yield is zero. “Maximum ET” is seasonal ET measured from emergence to physiological

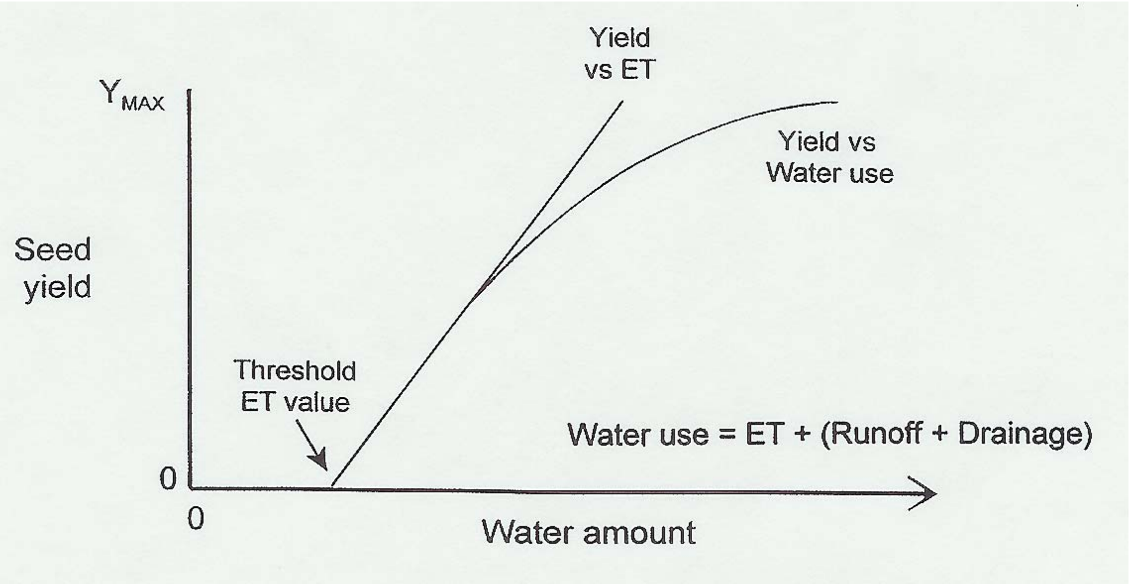

Fig. 1. General relationships between seed yield and water amount (ET or water use).

maturity and gives the upper value of ET expected for full-season varieties with good water conditions (no water stress). The "Slope of yield vs. ET" gives the seed yield increase per inch of ET in the seed producing segment of yield vs. ET. This is the expected yield increase due to water (ET) in a year with no out-of-the-ordinary yield reducing factor such as hail or frost damage. Because out-of-the-ordinary yield reducing events do occur, the "Slope of long-term yield vs. ET" is less than the yield vs. ET slope for an individual good year.

Table 1. Yield vs. ET relationship for crops of the central High Plains.

Crop	Max. ET for full-season variety	Threshold ET	Slope of yield vs. ET	Slope of long-term yield vs. ET *
Corn	25 in.	10.9 in.	16.9 bu/ac./in.	13.3 bu/ac./in.
Grain sorghum	21 in.	6.9 in.	12.2 bu/ac./in.	9.4 bu/ac./in.
Sunflower	22 in.	5.4 in.	218 lb/ac./in.	150 lb/ac./in.
Winter wheat	24 in.	10.0 in.	6.0 bu/ac./in.	4.6 bu/ac./in.
Soybean	24 in.	7.8 in.	4.6 bu/ac./in.	3.8 bu/ac./in.

* Long-term (multi-year) slope is less than full slope due to yield reducing factors such as hail, freeze damage, insects, diseases, etc.

The “Threshold ET” value is of critical importance in assessing if seed yield will likely be obtained in drier crop environments. Within the four summer row crops of Table 1, “Threshold ET” is 5.4 inches for sunflower, 6.9 inches for sorghum, 7.8 inches for soybean, and 10.9 inches for corn. If water supply available for crops is limited, the “Threshold ET” values illustrate why sunflower or sorghum would be preferred over corn. Also, the water stress sensitivity of growth stages of various cops is important in assessing their suitability for drier environments. The “Slope of yield vs. ET” is important in assessing the response of crops to irrigation that is converted into ET. Within the four summer row crops of Table 1, yield response per inch of ET is 218 lb/acre/inch for sunflower, 276 lb/acre/inch for soybean, 683 lb/acre/inch for sorghum, and 946 lb/acre/inch for corn. These values illustrate the greater yield responsiveness of corn to irrigation.

The relationships of Table 1 were developed from multiple data sources (treatments, years, and locations) and represent conditions consistent with full-season cropping in the central High Plains. The values of Table 1 can be altered by specific conditions of crops and growing seasons. Growing season ET of a specific year will be greater, or less, than the “Maximum ET” values of Table 1 if the year has greater, or less, potential ET than the average year. With water-stress conditions, if water application is beneficially timed, yield can be obtained even when actual ET is less than “Threshold ET.” And, if water application is poorly timed and water-stress conditions exist, yield may not be obtained even though actual ET is greater than “Threshold ET.” With water-stress conditions, if water application is beneficially timed, the yield benefit will be greater than the “Slope of yield vs. ET” of Table 1. And, if water application is poorly timed and water-stress conditions exist, the yield benefit will be less than the “Slope of yield vs. ET” of Table 1.

YIELD RESPONSE TO WATER STRESS

Yield sensitivity to water deficit during various growth periods (e.g., vegetative, flowering, grain formation, and ripening) varies among crops. In general, grain crops are more sensitive to water deficit during flowering and early seed formation than during vegetative and ripening (Doorenbos and Kassam, 1979). Soybean is an exception, being more sensitive to water stress during bean formation than during flowering or vegetative. If growth is under water-stress conditions, rain or irrigation at the most water-sensitive growth period will provide more yield increase per unit of water than if water is applied during other growth periods. Table 2 gives the relative yield response (decrease) per unit of ET deficit (water deficit) during growth periods of five crops. The values should be compared within a crop to get the relative weighting of water stress sensitivity of various growth periods for the individual crop. That is, within corn, an inch of ET deficit during flowering decreases grain yield 3.8 times as much as an inch of ET deficit during the vegetative stage (0.53/0.14 = 3.8). Within grain sorghum, an inch of ET deficit during flowering decreases grain yield 2.0 times as much as an inch of ET deficit during the vegetative stage (0.42/0.21 = 2.0). Along with sensitivity to water stress in corn being greatest during flowering, daily ET is greatest during flowering through the milky-fluid growth stage. These two factors working together produce the critical need for water in corn during flowering.

Table 2. Relative yield response per unit of ET (within a crop) to water deficit during selected growth periods.

	Growth period			
Crop	Vegetative	Flowering	Yield formation	Ripening
Corn	0.14	0.53	0.19	0.14
Grain sorghum	0.21	0.42	0.21	0.16
Sunflower	0.25	0.42	0.27	0.06
Winter wheat	0.19	0.51	0.25	0.05
Soybean	0.10	0.40	0.50	-----

The relative weighting of water stress sensitivity within a crop is illustrated in Table 2. Relative weightings of water sensitivity give insight into the growth periods of most critical water need for those five crops. Rainfall during the most sensitive growth periods will give the greatest yield benefit. Also, limited irrigation should be timed to avoid water stress at the most sensitive growth stages. That timing strategy will give the greatest yield benefit from a limited water resource. The timing of limited irrigation to give maximum seed yield benefit is given in Table 3.

Table 3. Timing of limited irrigation for maximum seed yield benefit.

Crop	Initiation of limited irrigation….	To avoid (lessen) water stress particularly during
Corn	Near (prior) or at tasseling	Silking
Grain sorghum	Head extension	Flowering
Sunflower	Head development	Disk flowering
Winter wheat	Head extension	Flowering
Soybean	Mid to late pod set	Early to mid bean fill

Of the five crops of Tables 1, 2, and 3, corn and soybean are the two most affected by water-critical growth periods. Corn yield is most negatively impacted by water stress from near-tasseling through silking, typically mid through late July. Soybean yield is most negatively impacted by water stress during bean fill, typically mid August to mid September. Therefore, if in a limited-irrigation production system and the water supply can not be depended on to avoid (or lessen) water stress in the critical times for corn and soybean, these two crops become much less attractive as crop choices. The suitability of crops for rainfed-only production systems in drier environments is influenced by "Threshold ET" (Table 1) and water stress sensitivity (Table 2). Crops with greater "Threshold ET", and with greater water stress sensitivity, are less appropriate for rainfed-only systems than crops with lower "Threshold ET" and lower water stress sensitivity. The suitability of crops for limited-irrigation production systems in drier environments is influenced by "Threshold ET", water stress sensitivity, crop response to added water ("Slope of yield vs. ET"), and dependability of the irrigation water supply.

PREPLANT IRRIGATION

Preplant irrigation is often an inefficient use of water in production systems where in-season irrigations are applied. In Texas, Musick et al. (1971) found that preplant irrigation did not increase grain sorghum yields appreciably when all treatments received the same two or three in-season irrigations. With irrigated corn in west-central Kansas, Stone et al. (1987) found no significant grain yield increase from preplant irrigation when there were multiple in-season irrigations. After an analysis of available soil water (ASW) data from corn fields receiving in-season irrigation in northwest Kansas, Rogers and Lamm (1994) stated "preseason irrigation of corn should not be a recommended practice for the region."

As producers attempt to stretch limited water supplies and the times of application to maintain systems that use limited-capacity wells, questions arise on the advisability of using preplant irrigation. In a review of preplant irrigation in the High Plains, Musick and Lamm (1990) concluded that "benefits of preplant irrigation are likely to be greatest when the soil profile is dry before planting" and "benefits are likely to be low when soil profiles are moderately wet at time of irrigation." The retention and storage of preplant irrigation in our deep silt loam soils are heavily dependent on water content of the soil profile during and after irrigation. As soil water content increases, water losses from evaporation, profile drainage, and surface runoff increase. A need exists for guidelines and illustrations of preplant irrigation efficiencies that will aid producers as they consider the practice to stretch limited well capacities and water supplies. From work in irrigated areas of the Canadian prairies, Hobbs and Krogman (1971) concluded that preseason irrigation was advisable (relatively efficient) when soil water was below 50% of maximum ASW. Dormant-season irrigation research in west-central Kansas found that water loss from the soil profile occurs at increasing levels as water content of the soil profile rises above 60% of maximum ASW (Stone et al., 1987). Rogers and Lamm (1994) stated that additional irrigation above the amount required to bring the profile to 50% of maximum ASW has a high probability of being lost or wasted.

To illustrate water loss from preplant irrigation in spring, we used the KS Water Budget software (Khan et al., 1996) to project soil water levels and corn grain yields (Table 4). Projections were for conventionally-tilled corn (as opposed to no-till) with annual precipitation of 17.5 inches. As a point of reference, Goodland, KS has long-term annual precipitation of 17.7 inches. We assumed four levels of ASW in the 6-foot soil profile on 15 March (column 1, Table 4): 10, 30, 50, and 70% of maximum ASW, which are 1.4, 4.2, 7.1, and 9.9 inches of water in the profile, respectively. We then projected ASW on 15 May and corn grain yield for the four initial levels of ASW with no irrigation, and 17.5 inches of precipitation (column 2, Table 4). Column 3 shows results where 1.0 inch of water was added to profile water on 15 April, and then no later irrigations. In each of columns 4, 5, and 6, an additional 1.0 inch of water was added to profile ASW on the indicated date. We did not estimate irrigation application efficiencies, but were estimating the retention efficiency of water added to stored soil water on the expressed dates. Where ASW was at 10% of maximum on 15 March, about 0.9 inches of each 1.0 inch added to storage in April was in storage on 15 May, and yield increase was 15 to 17 bu/acre per 1.0 inch of water added to storage in April. Where ASW was at 30% of maximum on 15 March, there was again about 0.9 inches of each 1.0 inch added to storage in April in storage on 15 May. Yield increase was 12 to 17 bu/acre per 1.0 inch of water added to storage in April, with the yield increase decreasing with increasing irrigation amount. Where ASW was at 50% of maximum on 15 March, the first 2 inches showed an increase in storage on 15 May of 0.9 inches per 1.0 inch added to storage. The fourth 1.0 inch of added water showed a gain on 15 May of only 0.6 inch. Grain yield showed a similar trend, with the first 2 inches showing yield increase of 13 and 11 bu/acre. The fourth 1.0 inch added to storage showed a yield increase of 5 bu/acre. Where ASW was at 70% of maximum on 15 March, water gains and yield benefits resulting from water additions were dropping rapidly. The third 1.0 inch addition to storage showed an improvement of only 0.4 inch of water and 2 bu/acre of yield. The fourth 1.0 inch addition showed improvements of only 0.2 inch of water and 1 bu/acre of yield.

The projections in Table 4 illustrate the precipitous decrease in benefits from spring preplant irrigation as ASW increases above about 60% of maximum. Rainfall conditions for a given year would influence the projected values and efficiencies of Table 4. Also, these projections do not consider the application efficiencies of preplant irrigation. The use of spring preplant irrigation on the deep silt loam soils does appear to be a relatively efficient use of water if the ASW level plus added water does not exceed 60% of maximum ASW, and if the water can be added to the soil profile with acceptable water application efficiencies.

Table 4. Illustration matrix for preplant irrigation[1]

Soil water	Net irrigation during spring (inches)[3]				
on 15 March[2]	0.0	1.0	2.0	3.0	4.0
10%	2.7 in.[4]	3.6 in.	4.5 in.	5.4 in.	6.3 in.
1.4 in.	0 bu/ac[5]	13 bu/ac	30 bu/ac	46 bu/ac	61 bu/ac
30%	5.1 in.	6.1 in.	7.0 in.	7.9 in.	8.8 in.
4.2 in.	40 bu/ac	57 bu/ac	73 bu/ac	87 bu/ac	99 bu/ac
50%	7.7 in.	8.6 in.	9.5 in.	10.3 in.	10.9 in.
7.1 in.	83 bu/ac	96 bu/ac	107 bu/ac	115 bu/ac	120 bu/ac
70%	10.0 in.	10.7 in.	11.2 in.	11.6 in.	11.8 in.
9.9 in.	112 bu/ac	118 bu/ac	122 bu/ac	124 bu/ac	125 bu/ac

[1] Annual precipitation of 17.5 inches. Conventionally-tilled corn. Four levels of available soil water (ASW) are assumed for 15 March.

[2] Available soil water as percentage of maximum, and in inches, for the 6-ft profile on 15 March.

[3] If applied, 1st 1.0 in. of irrigation on 15 April, 2nd 1.0 in. on 8 April, 3rd 1.0 in. on 1 April, and 4th 1.0 in. on 25 March.

[4] Inches of available soil water in the 6-ft profile on 15 May.

[5] Corn grain yield in bushels per acre.

PRECIPITATION STORAGE DURING NONCROP TIMES

The improved ability of no-till systems, compared with conventional, stubble-mulch (sweep) tillage, to capture and retain precipitation during fallow and to have more water stored in the soil profile for the next crop has been quantified in a number of dryland studies in the High Plains (Table 5). Key factors that lead to improved capture and storage of precipitation in noncrop periods are reduced levels of tillage, increased amounts of residue, and keeping the residue as upright as possible. Water loss from evaporation resulting from a single tillage event can be about 1/2 inch (Good and Smika, 1978). The water loss amount is influenced by depth of tillage, extent of disturbance, crop residue remaining on the surface after tillage, soil water amount at the time of tillage, and weather conditions after tillage. The gain in stored soil water during fallow is increased by increasing the amount of residue (mulch) (Greb et al., 1967). Storage of precipitation during fallow is also increased by having the residue in an upright position (Smika, 1983). During winter, standing residue can trap blowing snow and keep this water source on the field. Standing residue also benefits precipitation storage by decreasing evaporation losses, as compared with flat residue. Of the atmospheric conditions of air temperature, vapor pressure deficit, solar radiation, and wind speed, “Soil water losses were best correlated with wind movement” (Smika, 1983). Standing residue decreases wind speed at the soil surface, thereby reducing the evaporation of water. The decreasing of wind speeds at the soil surface by standing residue is also why standing residue is so effective at reducing soil erosion by wind.

Table 5. Additional water gain during fallow with no-till compared with conventional-till of various rotations and locations in the High Plains.

		Additional stored water in soil profile with no-till compared with conventional-till at planting of:[+]				
Years	Location	Wheat in WW	Wheat in WF	Wheat in WSF	Sorghum in WSF	Reference
		---------------- inches ----------------				
1963-66	North Platte, NE		3.4	1.5		Smika & Wicks, 1968
1975-87	Akron, CO		1.7			Smika, 1990
1993-01	Akron, CO		2.8			Nielsen et al., 2002
1987-90	Garden City, KS	0.7	1.5	1.5	1.6	Norwood, 1992
1984-93	Bushland, TX	1.1	0.6		0.9	Jones & Popham, 1997

[+] WW = continuous wheat, WF = wheat-fallow, and WS = wheat-sorghum-fallow.

The principles of less tillage, more residue, and upright residue can lead to additional water stored in the soil profile as with the systems of Table 5. Variability exists in precipitation storage data from field studies, however, 1.5 to 2 inches of additional water stored at planting as a result of no-till techniques compared with conventional till is a reasonable expectation in typical cropping systems of the central High Plains. It is reasonable to project that reduced tillage-increased residue principles will result in more stored water at planting in limited irrigation systems, as is the case in dryland cropping systems.

EFFICIENCY OF WATER SUPPLY USE DURING GROWING SEASONS

The relation between growing season water supply (ASW at emergence and in-season precipitation), and grain yield of sorghum and wheat is presented in Fig. 2 and 3, respectively. The data sets are from 30 years of research near Tribune, KS. Data are from dryland cropping systems, and some from preplant irrigation: with no data having in-season irrigations. Grain yields increased at mean rates of 6.7 bu/acre (sorghum) and 3.78 bu/acre (wheat) per inch of water supply. These values are less than the long-term slopes of 9.2 bu/acre (sorghum) and 4.5 bu/acre (wheat) of yield increase per inch of ET from Table 2. Water supply has lower slope than ET because some of the water supply would be lost as runoff and evaporation from precipitation events, and some would remain in the soil profile as water stored at crop maturity.

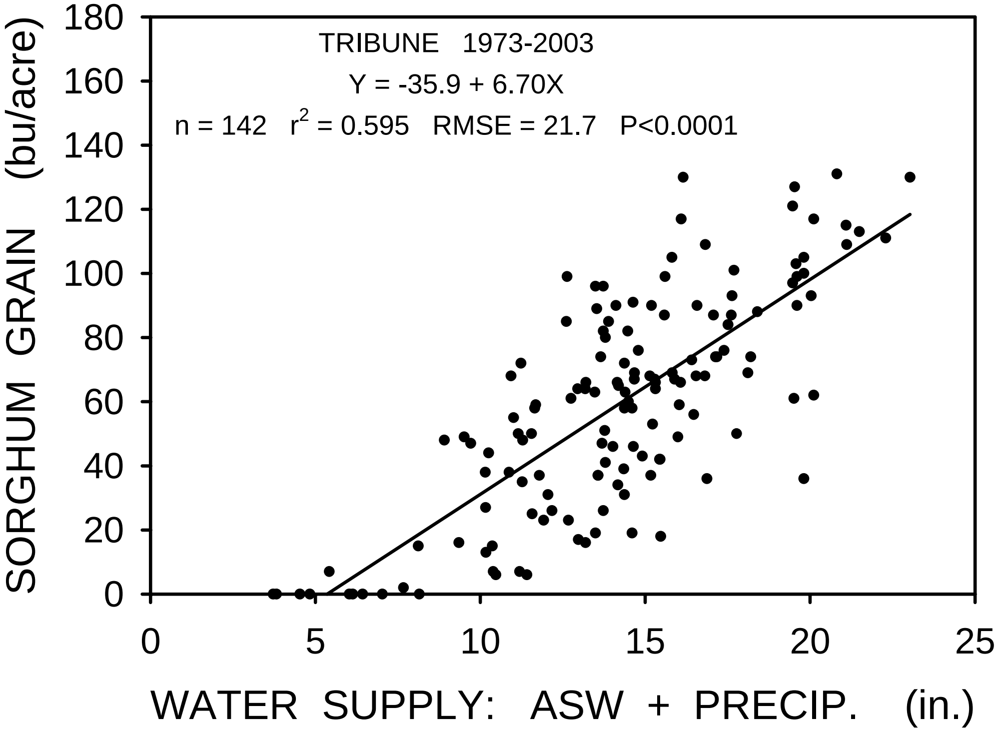

Fig. 2. Grain sorghum yield associated with water supply (available soil water plus within-season precipitation).

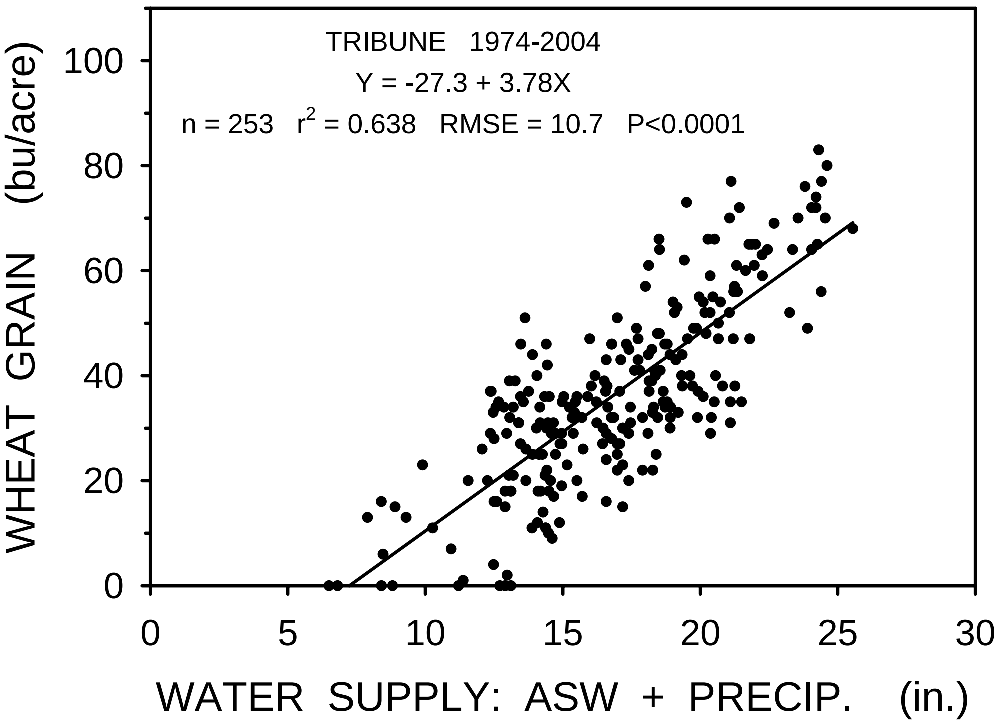

Fig. 3. Winter wheat yield associated with water supply (available soil water plus within-season precipitation).

We then separated out the data of Fig. 2 and 3 that was from conventional (sweep) tillage and no tillage dryland systems. The sorghum conventional till data are in Section A of Fig. 4 and the no-till data in Section B. With conventional till, the sorghum yield vs. water supply slope was 5.22 bu/acre/inch and with no till the slope was 7.45 bu/acre/inch. The wheat conventional till data are in Section A of Fig. 5 and the no-till data in Section B. With winter wheat, the grain yield vs. water supply slope was 3.24 bu/acre/inch with conventional (sweep) till and 5.20 bu/acre/inch with no till. The data of Fig. 4 and 5 indicate that residue and no till management provide for greater water use efficiency during the growing season compared with the conventional till systems. This improvement is from decreased evaporation and maintaining of infiltration capacities with residue.

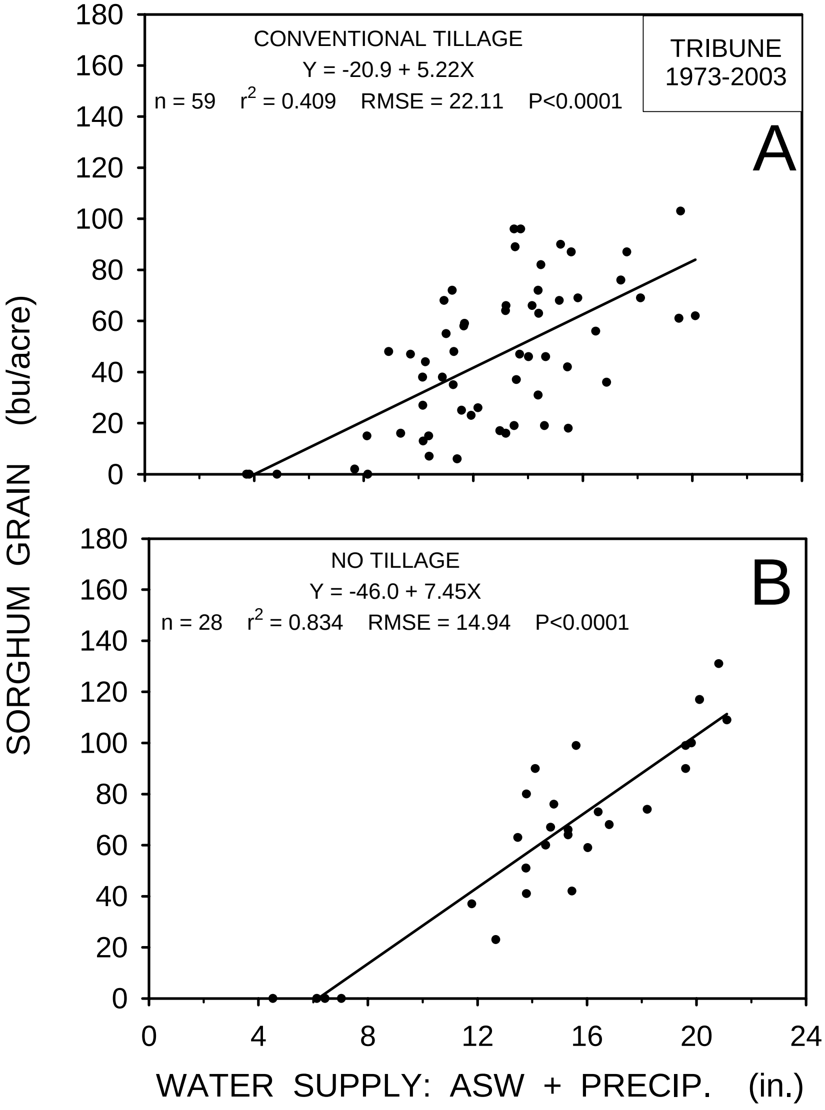

Fig. 4. Grain sorghum yield associated with water supply (available soil water plus within-season precipitation) for the dryland conventional tillage (section A) and dryland no tillage (section B) treatment groups.

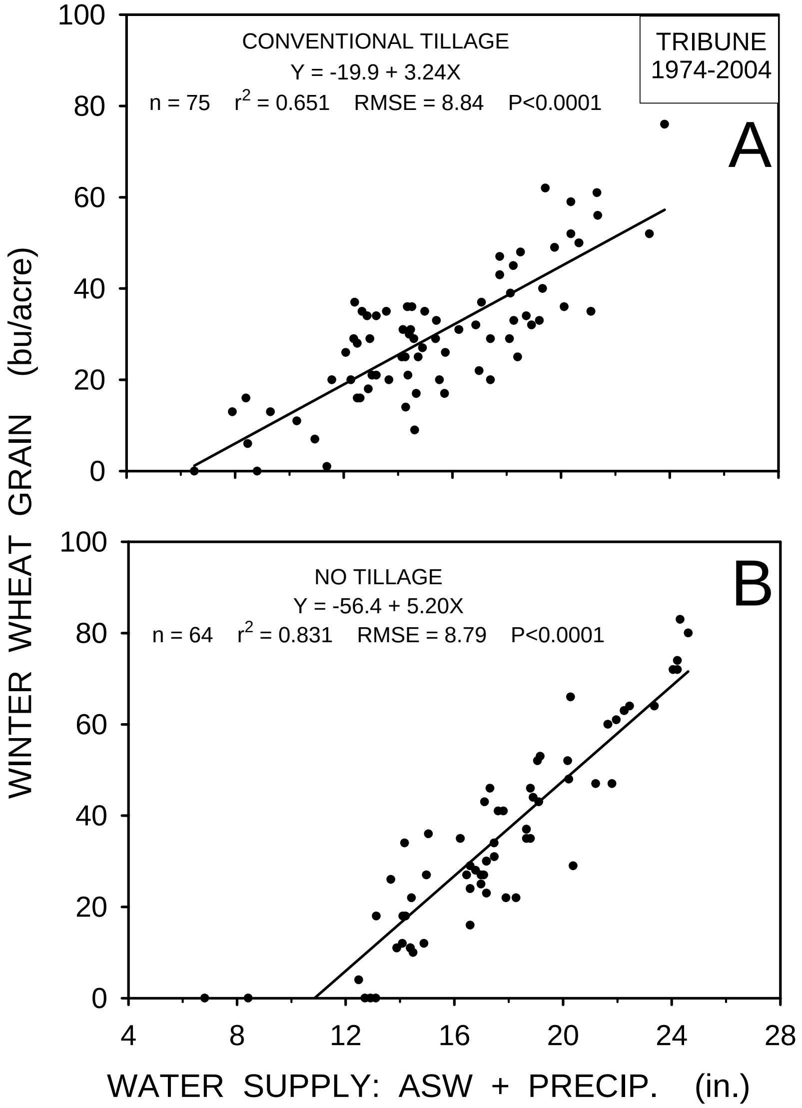

Fig. 5. Winter wheat yield associated with water supply (available soil water plus within-season precipitation) for the dryland conventional tillage (section A) and dryland no tillage (section B) treatment groups.

The improved yield response to water supply in no till compared with conventional till was in both sorghum (Fig. 4) and wheat (Fig. 5). It is reasonable to project the tillage-residue influence to limited irrigation environments, with the thought that increased residue would provide for more efficient use of in-season water supplies, as we have demonstrated with dryland cropping systems.

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