Reprinted from *Agronomy Journal*
Vol. 86, No. 6

Water–Yield Relationships for Irrigated and Dryland Wheat in the U.S. Southern Plains

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ABSTRACT

A climate with high evaporative demand and limited precipitation restrict yields of winter wheat (*Triticum aestivum* L.) grown in the semiarid U.S. southern High Plains. Stress effects can be avoided or minimized by management practices that increase soil water storage at planting or by application of irrigation water. We analyzed a 178 crop-year database of irrigated and dryland wheat data from Bushland, TX, to develop relationships that define the grain yield and water-use efficiency (WUE) response to a wide range in seasonal evapotranspiration (ET) associated with water deficits and to evaluate yield response to stored soil water at planting. The ET–grain yield relationship was determined as linear, with a regression slope of 1.22 kg grain per m^3 ET above the ET threshold of 208 mm required to initiate grain yield. Maximum yields (>7.0 Mg ha^{-1}) required 650 to 800 mm seasonal ET. Maximum yields observed in the combined database were 2.8 and 8.2 Mg ha^{-1} for dryland and irrigated wheat, respectively. The linear regression response of grain yield to soil water stored at planting, 1.57 kg m^{-3}, was significantly higher than the yield response to seasonal ET. Largely similar WUE values occurred over a wide range of seasonal ET within irrigated and dryland data sets; however, WUE values for irrigated wheat averaged about double the values for dryland wheat. A curvilinear relationship determined between WUE and yield emphasizes the importance of obtaining high yields for efficient water use.

WINTER WHEAT is a major dryland (≈400 000 ha) and irrigated (≈250 000 ha) crop grown in the U.S. southern High Plains, second only to cotton. It is the largest irrigated crop grown on the clay soils (≈50% of the total irrigated area) and is often managed to provide both grain production and fall and winter grazing by cattle. Cattle are usually removed during early to mid-March, about the time of floral initiation. The crop has excellent drought tolerance, is deep rooted, and is widely grown under limited (deficit) irrigation. Because of declining groundwater storage and well yields from pumping the Ogallala aquifer, limited irrigation is widely practiced on crops that possess drought tolerance and are grown successfully without irrigation.

Long-term average annual precipitation in the southern High Plains ranges from 380 mm in the southwest to 580 mm in the northeast and averages 470 mm. Growing-season precipitation for wheat production averages 250 mm, or approximately one-third of the evapotranspiration (ET) requirements for wheat grown under adequate irrigation. Elevation in the winter wheat region of the southern High Plains ranges from 700 m in the east-southeast to 1300 m in the northwest. Irrigated yields are higher in areas having favorable groundwater supplies and cooler environments during spring development through grain filling. Seasonal precipitation is an important water resource for wheat grown under both dryland and limited-irrigation management.

The area has a relatively high-evaporative-demand climate, with seasonal ET mostly in the range of 700 to 800 mm for wheat that is adequately irrigated to prevent plant water stress (Musick and Porter, 1990). High yields from irrigated research plots at Bushland are mostly in the range of 6 to 8 Mg ha^{-1}, while dryland yields are mostly in the range of 1 to 2 Mg ha^{-1}. The excellent drought tolerance of adapted cultivars, the wide range in yields between irrigated and dryland production on mostly high water-storage clay and clay loam soils, and seasonal precipitation that averages 250 mm result in good potential for efficient management of limited irrigation.

Dryland wheat is grown following summer fallow on 15 to 20% of the dryland wheat area in the eastern part of the region, where annual precipitation is >500 mm. In the drier western part (400 to 450 mm annual precipitation), ≈40% of the dryland wheat is grown after summer fallow. The 400-mm annual precipitation isoline reasonably well defines the boundary between dryland wheat production and grassland areas to the west.

The yield relationship to seasonal ET for wheat has been reported as linear by Hunsaker and Bucks (1987), Steiner et al. (1985), and Musick and Porter (1990). Additionally, linear relationships have been reported for ET deficits during selected growth stages by Schneider et al. (1969) and during postanthesis grain filling by Aggarwal et al. (1986). Some investigators have reported curvilinear ET–yield relationships when the ET calculation probably included profile drainage (Sharratt et al., 1980) and when irrigation during early spring vegetative growth failed to increase grain yield (Shipley and Regier, 1972; Shawcroft, 1983). Other investigators have determined curvilinear ET–yield relationships, with yield response decreasing with increasing ET (Ehlig and LeMert, 1976; Musick et al., 1963).

In this paper we emphasize evaluating water-use efficiency (WUE), defined as kilograms of grain yield per cubic meter of seasonal ET, over a wide range of water responses from dryland to fully irrigated. Water-use efficiency was extensively reviewed in a book edited by Taylor et al. (1983) and further reviewed by Stewart and Steiner (1990) with specific application to irrigated and dryland grain sorghum [*Sorghum bicolor* (L.) Moench] in the southern High Plains. This paper further expands this work for winter wheat, using available data from long-term irrigation and dryland studies at Bushland, TX.

Although irrigated wheat can be grown successfully over a relatively wide range of water deficits and grain yields, the use of irrigation to manage water deficits normally prevents a significant reduction in WUE. In dryland cropping systems, however, where water deficits cannot be controlled by irrigation, the severe deficits that occur in the southern High Plains can considerably lower WUE. Musick et al. (1984) reported that WUE of dryland wheat averaged about one-half the WUE of irrigated wheat grown over a wide range of water deficits. The present study,

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Published in Agron. J. 86:980–986 (1994).

Abbreviations: ASW, available soil water; ET, evapotranspiration; WUE, water-use efficiency.

using a much larger database and more comprehensive analysis, supports this difference in WUE of irrigated and dryland wheat.

Water-use efficiency values are sensitive to yield level and have substantially improved with the release of the high-yielding semidwarf cultivars. In the southern High Plains, WUE increased from 0.44 kg m^{-3} with 'Concho' grown in the late 1950s (Jensen and Sletten, 1965), to 0.54 kg m^{-3} with 'Tascosa' grown in the late 1960s (Schneider et al., 1969), to 0.94 kg m^{-3} with semidwarf cultivars grown during 1979 to 1982 (Musick et al., 1984). Tests at Bushland since 1982 indicate that WUE of irrigated semidwarf cultivars has not further increased significantly.

Irrigation tests with winter wheat in the Great Plains and the Pacific Northwest have indicated WUE values mostly in the range of 0.8 to 1.0 kg m^{-3} (Miller, 1977; Musick et al., 1984; Shawcroft, 1983). Because of a threshold ET offset for the first increment of grain yield, the WUE of an additional increment of ET is higher than the WUE value representing maximum ET for adequate irrigation to prevent plant water stress and associated maximum yield. For example, Steiner et al. (1985) determined by linear regression a response slope of 1.6 kg m^{-3}, compared with WUE of 1.3 kg m^{-3} for maximum yield. When WUE values for winter and spring wheat are compared, values are slightly to appreciably higher for spring wheat, probably because of substantially reduced ET from planting to floral initiation, a 5-to 6-mo period for winter wheat compared with a 5- to 6-wk period for spring wheat.

Dry matter accumulation during vegetative growth to floral initiation has a low correlation with grain yield. We have measured reduced grain yield from early planting of winter wheat and excessive fall vegetative growth when fall forage growth was not utilized by livestock grazing. Reported WUE values for spring wheat are frequently in the 1.0 to 1.2 kg m^{-3} range (Aggarwal et al., 1986; Cooper, 1980; Lal, 1985; Shimshi and Kafkafi, 1978). Some studies have resulted in higher values, such as 1.5 to 1.9 kg m^{-3} by Rao and Bhardwaj (1981) and 1.4 to 1.5 kg m^{-3} by Ehlig and LeMert (1976). Several studies have reported WUE values that are higher under deficit than under adequate irrigation, especially when irrigation is applied in relation to critical stages of plant development (Ehlig and LeMert, 1976; Schneider et al., 1969; Singh et al., 1979).

The importance of stored soil water at planting has received long-term recognition in dryland wheat studies in the western Great Plains and has been the primary reason for use of cropping systems involving summer fallow (Johnson, 1964; Johnson and Davis, 1972, 1980; Unger, 1972). In addition to its importance for dryland agriculture, beginning the season with a wet soil profile is important for successful management of limited irrigation in this area, which is associated with a declining groundwater resource and limited well yields. Because of data variability, the relationship between stored soil water at planting and wheat yield has been difficult to quantify using data from long-term cropping system studies at Bushland (Unger, 1972). Storage and depletion of available soil water (ASW) at planting in relation to yield are analyzed and discussed in this paper. The major objective is to develop and evaluate relationships among seasonal ET, grain yield, WUE, and ASW at planting using a wide range of data from irrigated and dryland studies conducted on the clay soils of the southern High Plains. Results are interpreted for efficient management and use of both precipitation and irrigation water resources for wheat production.

MATERIALS AND METHODS

Irrigated Tests

The irrigated wheat database (105 treatment-years) was developed from 14 irrigated field tests conducted during 1978 through 1992 at the USDA Conservation and Production Research Laboratory, Bushland, TX. Most tests were designed to evaluate eight irrigation treatments including a treatment that did not receive irrigation after fall establishment (designated as dryland) and a treatment with irrigation to avoid plant water stress and produce near maximum yields. Limited-irrigation treatments mostly involved applying or deleting an irrigation during three spring development stages: tillering through jointing, boot stage through anthesis, and early to mid-grain filling. Some tests included treatments to evaluate effects of plant water stress during specific development stages. Irrigation was withheld to allow the development of stress and applied to terminate stress at the desired development stage. Experimental designs permitted evaluation of plant stress and water application effects during single and multiple periods.

Irrigation depths of 80 to 125 mm (mostly 100 mm) were applied by gated pipe to level border plots 8 m wide by 20 or 40 m long, using flood irrigation that resulted in uniform plot coverage. Plots were level and laser smoothed to zero slope before planting each crop, resulting in excellent irrigation uniformity from rapid flooding. Plots were bordered with earth berms. Thirteen irrigated tests were conducted after summer fallow (wheat-fallow system). Precipitation between crops was adequate for uniform profile wetting of the plot area. One test was annual cropping with preplant irrigation applied for profile wetting. Four tests received a small irrigation for seed zone wetting and timely stand establishment.

Five irrigated tests included cultivars as either main plot treatments randomized with irrigation main plot treatments or as subplot treatments within irrigation main plots. Cultivars differed in height, release date, or drought tolerance. All tests were randomized block design with three or four replications. All data presented are treatment means. The cultivars used for this database analysis were semidwarfs having relatively high yield potential under irrigation: Vona, TAM 101, TAM 105, TAM 107, TAM 108, and TAM 200. The cultivar TAM 105 was used in more than half the tests and represents about half of the database. The semidwarf cultivars used in irrigation tests have very good drought tolerance, yield ability, and environmental adaptation to the climate. Semidwarf cultivar grain yields compare favorably with the taller cultivars when grown under dryland conditions and exceed yields of the older tall cultivars by about 15 to 30% under irrigated conditions with the more intermediate yield increases obtained under limited irrigation.

Wheat planting dates ranged from 26 September to 12 October (average, 4 October). Planting rates ranged from 70 to 100 kg ha^{-1} and row spacing was mostly 0.25 m. Two tests had 0.3-m row spacing. Rates of applied N and P were adequate for high irrigated yields. Grain yields were determined from duplicate plot combine samples of $\approx$9 m^2 each. Grain moisture content was determined by oven drying and yields are reported as 125 g kg^{-1} moisture, wet basis. Tests were conducted on Pullman clay loam (slowly permeable fine, mixed, thermic Torrertic Paleustoll; described by Unger and Pringle, 1981). The 1.8-m profile has plant-available water storage capacity of 247 mm between field-measured lower limit and drained upper limit values.

Soil water contents were determined after planting or emergence, periodically during the season, and after harvest. Most tests involved gravimetric sampling of one core per plot by 0.3-m increments to 1.8 m. In some tests, we used neutron meter sampling for water content by 0.2-m increments to 2.4 m. Beginning and end of season soil water contents along with precipitation and applied irrigation, measured with pipeline propeller meters, were used in calculation of seasonal ET.

Dryland Tests

Dryland data were taken from experiments conducted during 1958 to 1991 at Bushland with winter wheat grown in a wheat-sorghum-fallow cropping system in graded-terrace fields of 2 to 3 ha. Dryland data for 1942 to 1957 were excluded for this analysis, since soil water contents were measured to only the 1.2-m depth, while depletion in some years probably occurred from below this depth. In the wheat-sorghum-fallow system, two crops are grown in a 3-yr sequence, with 11 mo between harvest and planting of each crop, primarily for precipitation storage as soil water to enhance dryland yields compared with continuous or annual cropping. In the wheat-sorghum-fallow graded-terrace field study, terrace channels collected storm runoff, which was measured for individual storms with H-flumes equipped with stage recorders. Seasonal runoff for the 34-yr record averaged 4.4% of precipitation. Procedures and results through 1972 were reported by Jones (1975). Other available dryland data from winter wheat having soil water contents measured to the 1.8-m depth included data from 1958 to 1972 for wheat-sorghum-fallow from conservation bench terrace watersheds (Jones, 1975) and field plot experimental data for continuous wheat and wheat-fallow cropping systems with different tillage treatments (data through 1969 reported by Johnson and Davis, 1972). The data used for this analysis represent the stubble-mulch (subtilled) tillage treatment that had the highest average yield. The continuous wheat and wheat-fallow plot areas were located on a nearby level site that experienced very little storm runoff.

Gravimetric soil water contents were taken by 0.3-m increments to the 1.8-m depth at planting and after harvest and were used along with precipitation and storm runoff to calculate seasonal ET. Grain yields were determined by field combine harvest of entire plot or field areas. No fertilizer was applied to dryland tests because water strongly limited grain yield. Dryland fields and field plots were located ≈ 1 km from irrigated plot areas on Pullman clay loam. The dryland database for 1958 through 1991 is representative of long-term climate means and variability.

Dryland wheat was planted at 35 to 50 kg ha^{-1} seeding rates in row spacings of 0.3 to 0.34 m. Planting dates were mostly late September or early October (average, 1 October) and occurred mostly following rains, with seed placement into moist soil. In a few seasons, delayed emergence and/or prevailing dry surface soil conditions during fall and winter limited tillering, nodal crown root development, and rooting depth.

RESULTS AND DISCUSSION

Seasonal ET-Yield Relationship

The relationship between seasonal ET and grain yield is presented in Fig. 1. For the irrigated tests, seasonal ET ranged from 310 to 800 mm and grain yield ranged from 2.0 to 8.2 Mg ha^{-1}. ET for the treatment designated to provide adequate irrigation ranged from 665 to 800 mm and averaged 733 mm. Grain yields ranged from 5.4 to 8.2 Mg ha^{-1} and averaged 6.1 Mg ha^{-1}. With the exception of four treatment-years, dryland yields ranged from zero to 2.0 Mg ha^{-1}. The dryland data combined with the irrigated data represent the full range of zero to 8.2 Mg ha^{-1} yields for determining the seasonal ET-grain yield relationship. The linear regression relationship was statistically significant ($R^2 = 0.74$) with a slope of 1.22 kg of grain yield per cubic meter of seasonal ET above the yield threshold of 206 mm of ET.

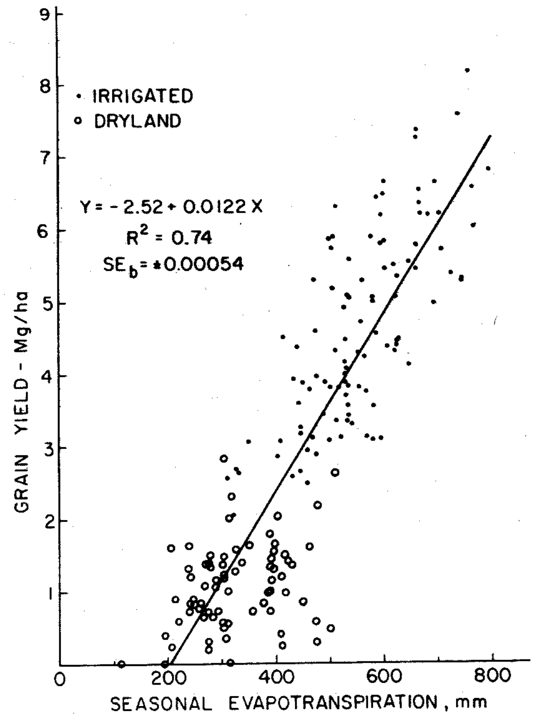

Fig. 1. Relationship of grain yield to seasonal evapotranspiration.

The 206-mm ET threshold for the first grain yield increment was 0.28 of the 733 mm average ET for adequately irrigated treatments. This value compares favorably with a grain yield threshold of 0.30 ET_{max} reported by Howell (1990) for irrigated wheat based on data from Bushland during 1956 to 1959 (Jensen and Sletten, 1965). A grain yield-ET threshold of 0.20 was calculated for spring wheat by Musick and Porter (1990), using data from Sharratt et al. (1980). Spring wheat has a much shorter vegetative growth period from emergence to floral initiation, reducing the relative ET fraction during this period and thus reducing the threshold ET value for grain yield.

Linear regression relationships of grain yield as a function of seasonal ET were determined for irrigated grain sorghum data (Stewart et al., 1983) and for combined irrigated and dryland sorghum data (Stewart and Steiner, 1990). Grain sorghum also has a relatively short growth period of ≈ 30 d from emergence to floral initiation. Threshold sorghum yield values based on Bushland data were 142 mm ET for irrigated sorghum and 127 mm ET for combined irrigated and dryland data, much lower than for wheat. The relative ET threshold for grain sorghum yield of 0.20 of adequate irrigation was similar to spring wheat, but significantly lower than the 0.28 obtained for winter wheat grown at Bushland. The sorghum linear regression slope of 1.55 kg grain yield per cubic meter of seasonal ET above the yield threshold was 27% higher than the 1.22 kg m^{-3} value obtained for winter wheat. Both grain sorghum and winter wheat are well adapted dryland crops for the southern High Plains and both possess very good drought tolerance. The difference in the ET-yield regression slope between the two crops is similar to differences in harvest index.

Because of major seasonal variability, linear regression analysis of dryland yield and ET data for wheat did not result in a significant relationship. The highly significant linear relationship for the irrigated data only was not significantly different from the relationship for the combined irrigated and dryland data. Thus, the relationship developed using the combined data sets is useful in establishing a significant linear relationship that includes the dryland data and has general application to both irrigated and dryland production management. The winter wheat regression slope of 1.22 kg m^{-3} is about double the 0.64 kg m^{-3} reported for dryland wheat by Johnson and Davis (1980) based on 8 yr of data from a wheat-fallow study at Bushland, but is lower than the 1.58 kg m^{-3} reported for summer fallow wheat grown in the northwestern USA, a production area having a substantially lower evaporative demand climate (Leggett et al., 1974).

The seasonal ET of 700 to 800 mm for adequately irrigated winter wheat in the southern High Plains is similar to seasonal ET data reported by Cooper (1980) in Australia, and by Pinter et al. (1990) for adequately irrigated spring wheat grown in Arizona. In areas having lower seasonal ET, the yield threshold is also lower. Leggett et al. (1974) reported 100 mm as the ET for the yield threshold of winter wheat grown in the northwestern USA, similar to the 110 mm reported by Massee and Siddoway (1969) for spring wheat grown in southeastern Idaho.

Seasonal ET-WUE Relationship

The relationship of WUE to seasonal ET is presented in Fig. 2. Linear regression analysis performed separately on the irrigated and dryland data sets indicated regression slope values that are not significantly different from zero. The mean WUE values for the irrigated data set averaged 0.82 kg m^{-3}, or about double the dryland mean of 0.34 kg m^{-3}. The dryland mean value averaged 0.36 kg m^{-3} for the 34 yr of graded-terrace wheat data from a wheat-sorghum-fallow cropping system. For the corresponding time period of the irrigated tests, WUE values for dryland wheat averaged 0.41 kg m^{-3}, or half the average 0.82 kg m^{-3} from irrigated tests. Since the major difference in the combined data sets were associated with differences between dryland and irrigated test conditions, a functional response equation as representing combined data sets may not be valid and is not presented.

The absence of a significant trend in WUE values within irrigated and dryland data groups suggests that similar WUE values can occur over a relatively wide range of seasonal

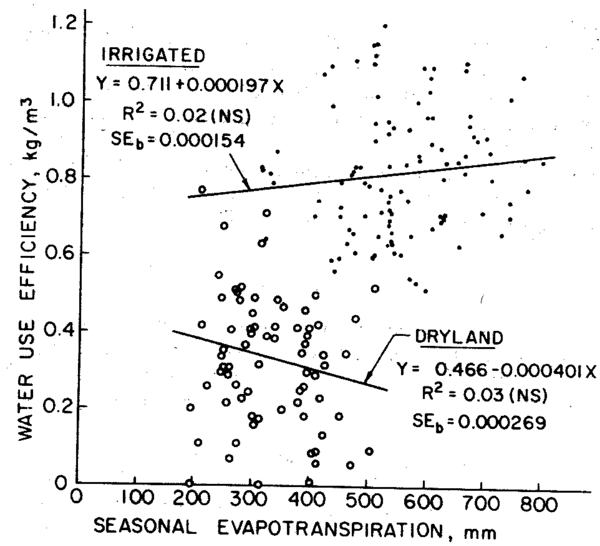

Fig. 2. Relationship of water-use efficiency to seasonal evapotranspiration.

ET. The variability in amount and distribution of seasonal precipitation is a significant source of variability. In addition, timing of limited irrigation contributed to variability within the irrigated database and the lack of significance in regression trends. For example, when 19 treatment-years of irrigated wheat data were compared for yield response to timing of irrigation, water applied during the boot to anthesis stages averaged twice the yield response of water applied during tillering through jointing, while having a similar effect on increasing seasonal ET. A significant aspect illustrated in Fig. 2 is that limited irrigation can be used to substantially increase the WUE of combined irrigation and precipitation, thus increasing the efficient use of total water resources for winter wheat production.

WUE-Grain Yield Relationship

The relationship of WUE to grain yield is presented in Fig. 3. The threshold ET requirement for the first yield increment causes the relationship to be curvilinear. Since zero grain yield results in zero WUE, the curvilinear relationship presented in Fig. 3 passes through the origin.

The relationship illustrates the importance of attaining relatively high yield for attaining high WUE. A highly significant relationship exists between yield and WUE within the dryland data set with linear regression indicating a WUE increase of 0.272 kg m^{-3} per tonne increase in grain yield (R^2 = 0.80). For the combined dryland and irrigated data sets, the curvilinear trend within the irrigated data yield range indicated a relatively strong diminishing return response within the high yield range. The association of high WUE values with high yields has important implications for both dryland and irrigation management for attaining efficient use of water resources in the semiarid climatic environment of the southern High Plains. It emphasizes the importance of limiting duration and severity of plant water stress and attaining relative high yields when limited-irrigation management is practiced.

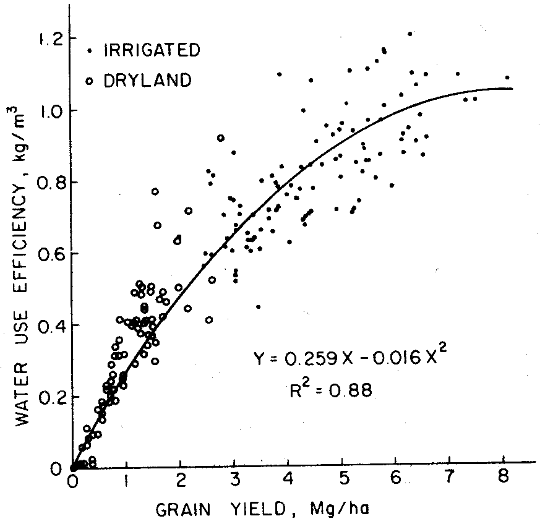

Fig. 3. Relationship of water-use efficiency to grain yield.

Profile Available Soil Water Depletion

Precipitation distribution in the southern High Plains tends to concentrate rainfall late in the winter wheat growing season. Precipitation declines in the fall, is relatively low during the winter, increases during the spring, and peaks in late May and early June during grain filling of wheat. The lag in increasing spring precipitation relative to plant water requirements normally results in the development of major plant stress in dryland wheat during the stress-sensitive stages of boot through anthesis. The availability of soil water during this stress-sensitive period and continuing into early grain filling is very important for maintaining dryland yield potential and the plant's ability to efficiently use late-season precipitation. It is also important for limited-irrigation management to moderate plant water stress and maintain ability to respond to critical-stage water application.

Illustrative time sequence curves of average ASW contents to the 2.1-m depth, based on neutron meter data measured weekly during spring growth, are presented in Fig. 4 for four dryland seasons that produced above-normal yields and four that produced below-normal yields. Data were taken from a nearby plot area by Johnson and Davis (1980). Also shown in Fig. 4 is above- and below-average cumulative precipitation and yield seasons. For the above-average seasons when yields averaged 2.31 Mg ha^{-1}, fall precipitation increased soil water contents after planting and the ASW contents at beginning of spring growth were similar to soil water storage at planting. The 4-yr average 135 mm of profile depletion between 1 March and 1 June contributed substantially to high dryland yields. These seasons contrasted with the below-average seasons, when less ASW was stored at planting, 38 mm of profile depletion occurred by 1 March, and only 30 mm additional depletion occurred during March, April, and May. Limited rooting during the predominantly dry falls and winters limited the depth of rooting during spring growth. Soil water depletion depth was limited to 0.9 m, leaving 72 mm ASW stored in the 2.1-m profile after harvest, primarily in the lower profile. The deeper root system during above-average yield seasons depleted ASW to only 25 mm

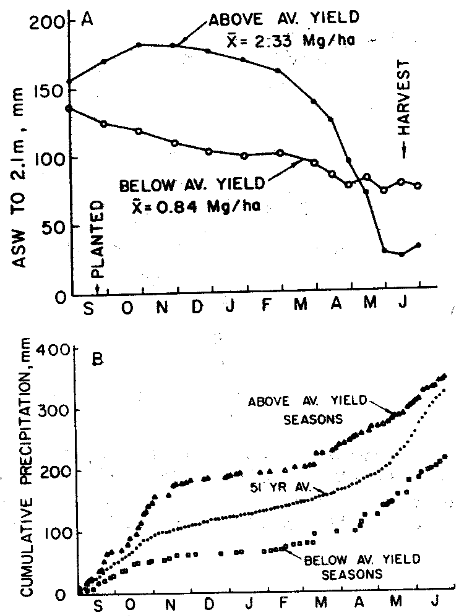

Fig. 4. Average seasonal trend in available soil water (ASW) contents to the 2.1-m depth for four dryland crop seasons with above-average yields and four with below-average yields (Graph A) and average cumulative precipitation for the above- and below-average yield seasons compared with the long-term average for Bushland (Graph B). Adapted from Johnson and Davis (1980).

above the lower limit in the entire 2.1-m profile. In one season, soil water contents were depleted by 1 June (late grain filling) to the lower limit values in the entire 2.1-m profile. The dryland data presented in Fig. 4 indicate a strong yield association between high soil water content at planting (which establishes potential for deep rooting), above-average fall precipitation, and average to above-average spring precipitation.

Illustrative ASW profiles with time to the 2.4-m sampling depth are presented in Fig. 5 for a dryland treatment included in the 1992 irrigated test. Soil water was maintained by 74 mm above-average precipitation until 6 March. Mild afternoon stress began in early April and continued with increasing severity until spring rains started on 22 May. The ASW contents for 4 May and 19 May illustrate continued soil water depletion during a time of major plant water stress. The relatively high dryland yield of 3.9 Mg ha^{-1} compares with 6.5 Mg ha^{-1} for the adequately irrigated treatment, which received 400 mm of spring irrigation. The dryland treatment response illustrates the importance of high ASW contents at planting and at the beginning of spring growth and the ability of winter wheat to develop a deep root system that can maintain continued soil water extraction into grain filling under increasing stress severity. Having high ASW contents at planting is also important for successful practice of limited irrigation, for efficient use of both precipitation and applied irrigation.

Yield Relationship to Stored Water at Planting

In the relatively dry climate of the semiarid western Great Plains, stored soil water at planting has long been emphasized as important for dryland wheat production. The practice of growing winter wheat after summer fallow has widespread use as the major cropping system man-

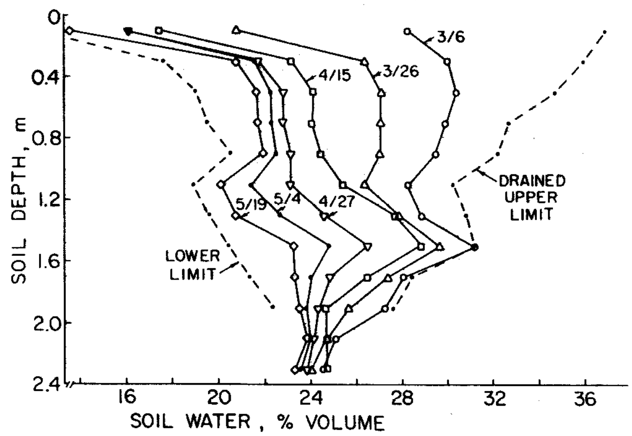

Fig. 5. Time sequence of soil water depletion by depth for the dryland treatment in the 1992 irrigated test (yield = 3.9 Mg ha⁻¹). Soil water contents are for sampling dates ranging from spring tillering (3 March), heading (27 April), to late grain filling (19 May).

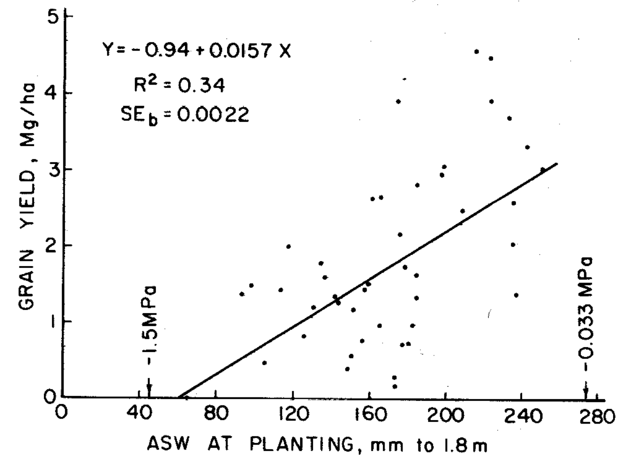

Fig. 6. Relationship of grain yield to available soil water to the 1.8-m depth at planting.

agement practice for increasing stored water at planting. In the winter wheat region of the High Plains, planting after summer fallow has historically varied from ≈30% of planted area in the southern High Plains to ≈90% in northwestern Kansas and northeastern Colorado (annual reports, State Agricultural Statistics Services). Other practices to increase soil water storage at planting are tillage, surface residue management, and prevention of storm runoff (including snowmelt runoff in the central and northern High Plains). The widespread use of summer fallow emphasizes the importance given to increasing stored water at planting for increasing winter wheat yields. In long-term comparisons from cropping system studies in the central High Plains, wheat–fallow yields averaged about double the yields of continuous cropping (Norwood et al., 1990), but averaged 44 to 47% higher at Bushland (Jones, 1975, 1992). The yield response to summer-fallow compared with continuous cropping is lower in the southern compared with the central High Plains, primarily because of the higher evaporative demand climate and less favorable soils for high ASW storage at planting.

We performed regression analysis of the dryland database and dryland treatments from irrigation tests to determine the relationship between ASW (to the 1.8-m depth) at planting and grain yield. Including dryland treatment data from irrigation tests permitted extending the data range to higher soil water contents and higher yields than occurred from dryland tests. The extension of the data range increased the statistical significance of the linear regression relationship. Linear regression analysis that included all the dryland data resulted in $R^2 = 0.23$ for yield vs. ASW at planting. By excluding the 1958 to 1972 dryland data sets representing drier-than-normal climate and below-average yields and using only the 34-yr dryland database (1958 to 1991 data from the graded-terrace wheat–sorghum–fallow study) and the dryland treatment data from irrigated tests, linear regression R^2 was increased to 0.34 (Fig. 6). The fairly low R^2 value indicates that factors other than ASW at planting have major effects on wheat yield. A previous dryland study at Bushland (Army et al., 1959) found that seasonal precipitation (October through June) accounted for major variability in yield ($R^2 = 0.55$).

The linear regression slope of yield related to ASW at planting was determined as 1.57 kg m^{-3} for storage to the 1.8-m depth, with a yield threshold of 60 mm ASW at planting, based on a field-measured profile lower limit value of 347 mm to the 1.8-m depth (Fig. 6). The 60 mm of ASW for the yield threshold is similar to the 34-yr average of 68 mm ASW storage after harvest of dryland wheat (O.R. Jones, unpublished data). The yield relationship to ASW content at planting emphasizes the importance of preseason storage from precipitation prior to planting dryland wheat. The regression slope of yield related to ASW content at planting, 1.57 kg m^{-3}, is relatively high and exceeds the slope of yield related to ET of 1.22 kg m^{-3} above the yield threshold (Fig. 1).

Storage efficiency of preseason (fallow) precipitation for wheat grown in the wheat–sorghum–fallow rotation averaged 17.1% during 1958 to 1972 (Jones, 1975) and 17.9% for the 34-yr graded-terrace data set through 1991. The wheat–sorghum–fallow rotation has 11 mo fallow for precipitation storage between each crop. This resulted in nearly identical average ASW contents at planting time of both crops. Storage efficiency for continuous wheat, which has only ≈3 mo for storage, averaged 22% of precipitation. The wheat–fallow system, which has 15 mo fallow, averaged only 13% precipitation storage efficiency. The declining storage values with longer preseason periods between crops (22% for continuous wheat, 18% for wheat in a wheat–sorghum–fallow sequence, and 13% for wheat–fallow) illustrate the characteristically low storage efficiency of precipitation and the decline in storage efficiency of the longer storage periods with higher precipitation amounts between crops. Once profile storage is attained below a surface tillage zone that is subject to rapid evaporation, the potential for ASW to contribute to grain yield is high, but also highly variable, as indicated by the $R^2 = 0.34$ value and the data scatter shown in Fig. 6. The variability was to be expected, because of the predominating association of yield to growing-season precipitation.

SUMMARY

In summary, we conclude that the linear relationship of yield to seasonal ET and the curvilinear relationship of

WUE to yield emphasize the importance of attaining relatively high yields for efficient use of water by dryland and irrigated wheat grown in the southern High Plains. The high yield response to irrigation resulted in doubling the average WUE attained by dryland wheat, which resulted in efficient use of both irrigation and precipitation. Having high ASW contents at planting is important for successful practice of limited irrigation for efficient use of both precipitation and applied irrigation. Management of limited irrigation relative to critical development stage for plant water stress permits attaining relatively high WUE over a range of seasonal ET. For dryland management, we demonstrated the importance of soil water at planting and at the beginning of spring growth for maintaining yield potential and the ability to take advantage of the late spring rainfall characteristic of the area.

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