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Field water supply:yield relationships of grain sorghum grown in three USA Southern Great Plains soils

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ABSTRACT

Field water supply (FWS) combines the three sources of water used by a crop for evapotranspiration (ET), and consists of available soil water at planting (ASWP), rainfall, and irrigation. Examining the grain yield and FWS relationship (Y_g:FWS) may provide insight into the reported variability in crop water production functions such as water productivity (WP) and irrigation water productivity (IWP). Since water is most productive when entirely consumed in ET, diversion of FWS into non-ET losses such as drainage and excessive soil water evaporation results in declines in WP and IWP. The objective of this experiment was to examine the Y_g:FWS and Y_g:ET relationships of grain sorghum grown under a range of irrigation treatments (0, 25, 50, and 100% replacement of ET), beginning soil water contents, evaporative demands, in the Amarillo, Pullman, and Ulysses soils of the Great Plains. The purpose was to determine the amount of FWS beyond which declines in WP and IWP began to occur due to non-ET losses as indicated by a change in the slope and intercept of the Y_g:FWS and Y_g:ET relationships. Large amounts of non-ET irrigation application losses occurred in the finer-textured soils in the T-100 irrigation treatment. In both years, the T-100 irrigation application amounts and ASWP resulted in a FWS ranging from 750 to 870 mm which exceeded the maximum ET requirement of 530–630 mm and which reduced WP and IWP. Piecewise regression analysis of the Y_g:FWS and Y_g:ET relationships for the crops in the Pullman and Ulysses soils identified the knot point, or change in slope and intercept, in the FWS where both WP and IWP tended to be optimized. This was about 500 mm in both soils, and involved the utilization of about 250 mm in ASWP, irrigation applications averaging about 250 mm, and about 60–130 mm remaining in the soil at harvest. For the coarser-textured Amarillo soil, the yield response to increasing FWS was linear, because non-ET application losses such as drainage gradually increased with the irrigation application amount. The linear Y_g response in the sandy Amarillo soil and the piecewise Y_g responses in the clay and silt loams of the Pullman and Ulysses soils to FWS also reflected the difference in water-holding capacities of the soils that affected the amount of available water as irrigation increased. Irrigating without considering FWS resulted in non-ET irrigation application losses and declines in WP and IWP.

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1. Introduction

As world population increases and fresh water supplies per capita decline, the domination of irrigated agriculture over the world's fresh water supply is rapidly coming to an end, requiring agriculture to rethink its approach to irrigation (English et al., 2002; Fereres and Soriano, 2007; Hsiao et al., 2007). Deficit irrigation, defined as the deliberate under-

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irrigation of a crop (English, 1990), aims at maximizing the net income per unit irrigation water used rather than per unit land used, and is practiced when water supplies are limited (Fereres and Soriano, 2007). After reviewing literature that reported yield versus water use experiments world-wide, Zwart and Bastiaanssen (2004) found that deficit irrigation improved crop water productivity sometimes by more than 200%. Crop water productivity (WP) is defined as

$$WP = \frac{Y}{ET} \tag{1}$$

where WP is in kg m^{-3}, Y is the marketable crop yield (kg ha^{-1}) and ET is evapotranspiration (m^3 ha^{-1}).

The strong linkage between yield and transpiration and later yield and ET has been studied by researchers since the beginning of the 20th century (Vaux and Pruitt, 1983; Howell et al., 1990). When examined over a range of irrigation treatments, the grain yield versus ET (Y_g:ET) relationship has typically been described as linear (Stewart et al., 1975, 1983; Hanks, 1983; Lamm et al., 1994; Howell et al., 1995; Al-Jamal et al., 2001), although curvilinear relationships have also been reported (Grimes et al., 1969; Zhang et al., 2004). According to Stewart and Hagan (1973), non-linear relationships are explicable only if the harvest index (ratio of grain biomass to total biomass) changes with increasing water deficit. Grimes et al. (1969), however, stated that a curvilinear Y:ET relationship for cotton was due to a probable decrease in efficiency of water utilization by the plants and drainage below the effective rooting depth at the highest irrigation levels. Musick and Dusek (1971), in reporting on a 3-year study on the effect of number, timing, and size of seasonal irrigation on grain sorghum yield, concluded that the lower-yielding treatments had a linear Y_g:ET relationship, while the higher-yielding treatments a curvilinear one.

By rearranging Eq. (1) and using a known WP value, it becomes tempting to predict yield based on available water supply. However, the range of Y:ET relationships summarized in Zwart and Bastiaanssen (2004) is large (e.g. for maize (*Zea mays* L.) a range from 1.1 to 2.7 kg m^{-3}) due to differences in climate, irrigation water management, and soil management, among others. Numerous proposals for the improvement of WP have been made, including reducing soil water evaporation (Wang et al., 2001), increasing transpiration efficiency (Wallace, 2000), and evaluating WP on a spatial or systems scale (Bouman, 2007; Hsiao et al., 2007).

Although useful in many analyses, WP as a function of water used does not clearly take into account the role of irrigation (Howell, 2001), which most likely is of greater interest than WP to producers. Bos (1980, 1985) developed an expression for irrigation water productivity (IWP) which related the increase in irrigated yield over dryland yield due to irrigation, given as

$$IWP = \frac{Y_i - Y_0}{IR} \tag{2}$$

where IWP is in kg m^{-3}, Y_i is irrigated yield in kg ha^{-1}, Y_0 is the dryland (unirrigated) yield in kg ha^{-1} and IR is irrigation in m^3 ha^{-1}.

Reported irrigation versus yield ($Y_i - Y_0$ or Y_i only) relationships for multiple irrigation levels have been both linear (Lamm et al., 1994) and curvilinear (Stewart et al., 1983; Bordovsky and Lyle, 1996; Tolk and Howell, 2003). Howell et al. (1995) showed a linear relationship for 1 year of a sprinkler irrigation study on maize and a quadratic relationship for the same study the following year.

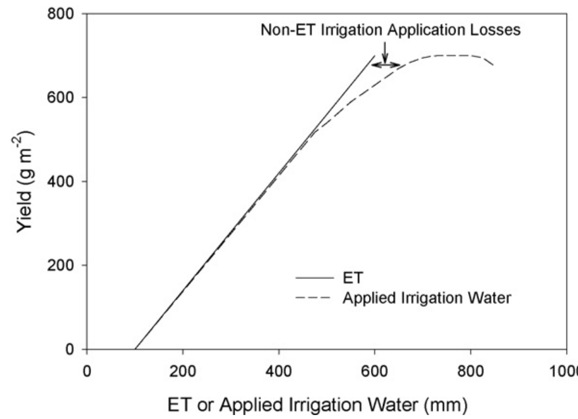

Fig. 1 – Generalized relationships between yield, evapotranspiration (ET) and applied irrigation water.

The generalized relationship between applied irrigation water, ET, and yield (Fig. 1) shows that, for a highly efficient irrigation system, low to moderate amounts of applied water are all initially consumed in ET producing a linear relationship with yield when there are no non-ET irrigation application losses. These losses include percolation, excessive soil water evaporation, and soil water storage in the profile. The largest irrigation water application efficiencies are achieved when the application amounts are entirely consumed in ET. At some point, irrigation application amounts exceed ET demand, the rate of yield increase due to irrigation slows, and the efficiency of irrigation begins to decline as the application losses increase. Finally, yield response to irrigation plateaus, even when irrigation continues to increase. When irrigation becomes excessive, the generalized relationship of Fig. 1 also shows that yield can decline.

Neither WP nor IWP adequately take into account all the water potentially available to the crop to be used in ET. In the case of deficit irrigation, which has also been defined as irrigation application amounts below the full ET requirements of a crop (Fereres and Soriano, 2007), the water needs of the crop may also be met by precipitation (PREC) and available soil water at planting (ASWP). Called field water supply (FWS) by Stewart and Hagan (1973), the totality of water that a crop can use in ET can be given as

$$FWS = IR + ASWP + PREC \tag{3}$$

How much water is used by the crop from each source can especially impact IWP. An example originally presented in Tolk and Howell (2003) showed the relationship between grain yield and ET, irrigation, and ASWP (Fig. 2). The solid line is the Y_g:ET relationship and the dashed line the Y_g:IR relationship, with the numbers advancing along each line representing the WP and IWP for the increasing irrigation levels. As can be seen by the difference between the slopes of the two relationships, "Non-ET" losses increased as irrigation amount increased. At

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