OILSEED CROP WATER USE AND WATER PRODUCTIVITY

Rob Aiken, Research Crop Scientist

K-State Northwest Research--Extension Center, Colby, Kansas, Email: raiken@ksu.edu

Freddie Lamm, Research Irrigation Engineer

K-State Northwest Research--Extension Center, Colby, Kansas, Email: flamm@ksu.edu

Abdrabbo A. Aboukheira, Associate Research Scientist

Agricultural Water Management and Irrigation Technology, Columbia Water Center, The Earth Institute, Columbia University, New York, NY, Email: aas2243@columbia.edu

Abstract. *Oilseed crop water use is primarily affected by canopy formation and weather conditions. A 'yield threshold' indicates the amount of water use required before the first unit o yield is obtained; subsequent yield increases contribute to crop water productivity. The yield threshold is least for sunflower and largest for soybean; subsequent yield increases are greatest for soybean and least for sunflower; water productivity for canola is intermediate. Oilseed crop water productivity can increase by crop and irrigation management which increases the transpiration fraction of ET and crop water use, as well as crop improvement to increase transpiration efficiency and the conversion of biomass to oilseed yield.*

Keywords. Crop water use, water productivity, oilseed crops, transpiration fraction, crop improvement.

Introduction

Water use of a crop, with adequate available soil water supply, is primarily affected by its canopy and weather conditions (Tanner and Sinclair, 1983; Albrizio and Steduto. 2005; Suyker and Verma, 2010). These effects are represented by seasonal crop coefficients and the reference evapotranspiration (ETr) demand of the atmosphere (Allen et al., 2005). The crop coefficient indicates the fraction of ETr which the crop is expected to utilize on a given day. The crop coefficient value typically changes with crop stage. Crop water productivity (also known as water use efficiency) refers to the amount of "crop yield/ water consumptively used in ET" (Kassam and Smith, 2001, p. 15). This article will present oilseed crop water use and crop water productivity field results from the U.S. central High Plains. Also, we review findings of environmental and management factors which can improve the water productivity of oilseed crops in this region.

Oilseed crops

The primary oilseed crops considered here are soybean, sunflower and canola (winter or spring). Limited information is available for other spring oilseed crops (Indian Brown Mustard, Baltensperger et al., 2004; Crambe, Nielsen, 1998) and summer oilseed crops (Safflower, Istanbulluoglu et al., 2009; Lesquerella, Puppala et al., 2005). In the U.S. central High Plains, winter canola is typically planted in mid-August, flowering in mid-May and matures in early July (Rife and Salgado, 1996); spring canola can be planted early March, flowering in late-May and maturing in mid-July (Aiken, 2010). Figure 1 shows expected water use and crop productivity for spring canola (Nielsen, 1998). Soybean can be planted in early May, flowering in mid-July for

late-September harvest (Kranz et al., 2005). Sunflower is planted in mid-June to avoid pests, flowering in mid-August for harvest in late-September or early October (Rogers et al., 2005). Double-cropped soybean or sunflower can be planted after wheat harvest in early-July with flowering in late August and early October maturity. Figures 2 and 3 show expected crop productivity and water use for these summer oilseed crops. These spring and summer oilseed crops provide opportunities to shift irrigation applications among fields throughout the growing season (Klocke et al., 2006). Aiken and Lamm (2006) discussed crop development stages and yield sensitivities to water deficits for these crops.
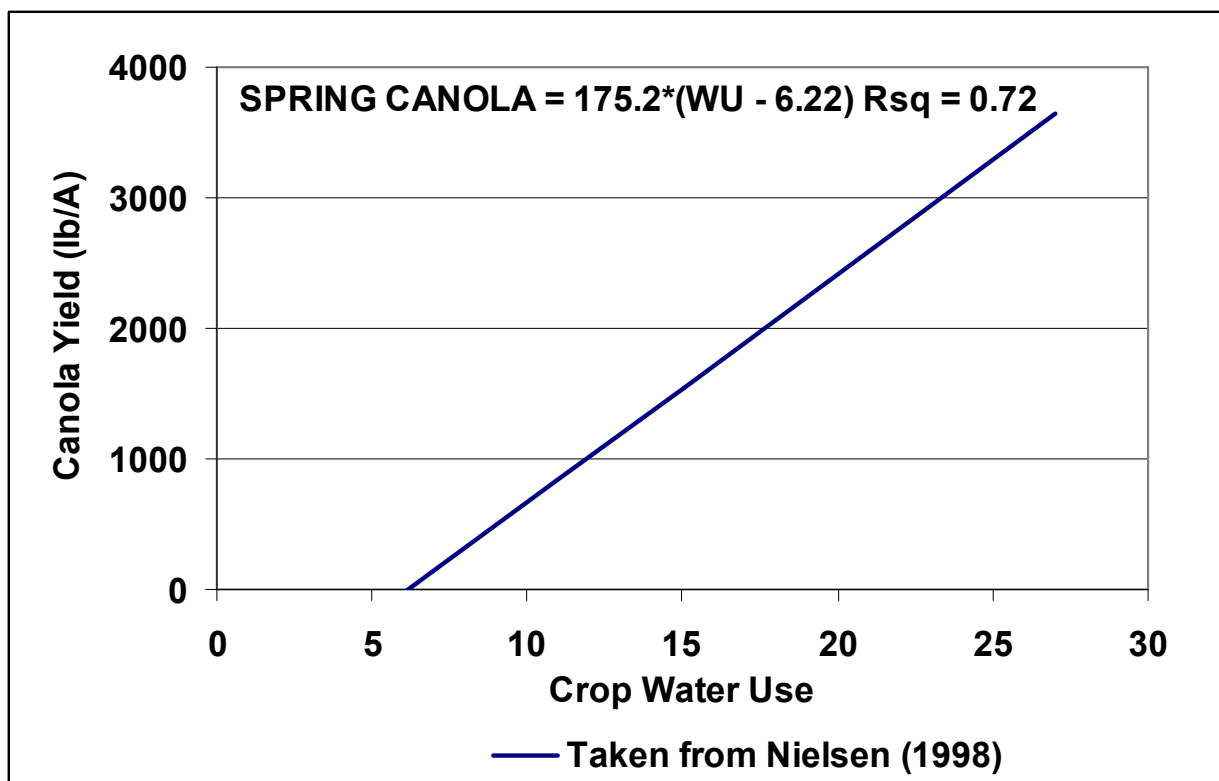

Figure 1. Expected oilseed yields of spring canola are presented, in relation to expected crop water use (soil water depletion plus precipitation and irrigation) in this crop water production function (taken from Nielsen, 1998).

Water Production Functions

Crop Water Use

Oilseed yield is expected to increase with water use, up to a maximum yield potential (Anastasi et al., 2010; Demir et al., 2006; Payero et al., 2005). The oilseed yield-water use relationships (Fig. 1 - 3) show that a certain amount of water use (i.e. intercept of line with water use axis) is required before oilseed yield is expected. This apparent 'yield threshold' (6.2" for spring canola, 6.1" for soybean and 3.6" for sunflower) indicates the amount of water use required before the first unit of yield is obtained. The magnitude of this yield threshold can vary, to some extent, depending on early season soil water evaporation, prevailing humidity conditions and water used in vegetative growth. The rate of yield increase, relative to increased water use (slope of the yield response line), represents a measure of water productivity (175 lb/A-in for spring canola, 219 lb/A-in for soybean and 167 lb/A-in for sunflower). This factor is affected by
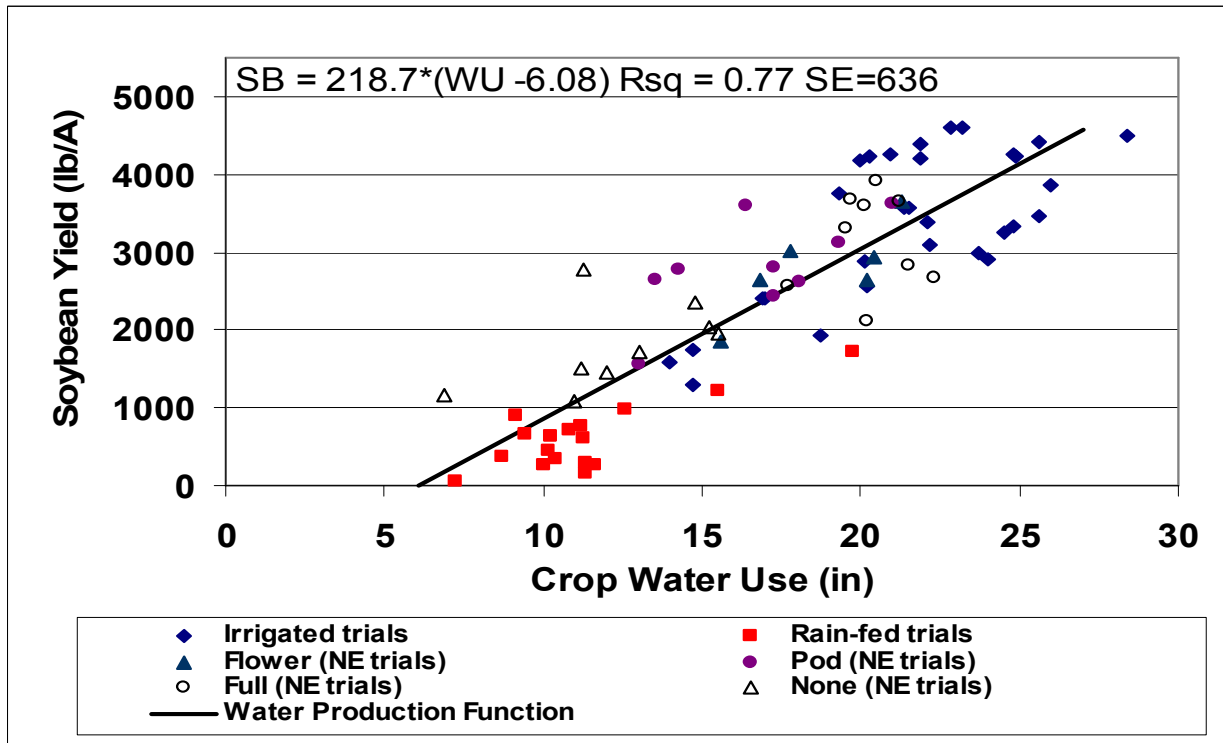
Figure 2. Expected oilseed yields and crop water use of soybean are derived from Colby, KS and Nebraska trials (NE trials indicate irrigation delayed to begin at flowering or pod development (Ellmore et al., 1988, Specht et al., 1989).
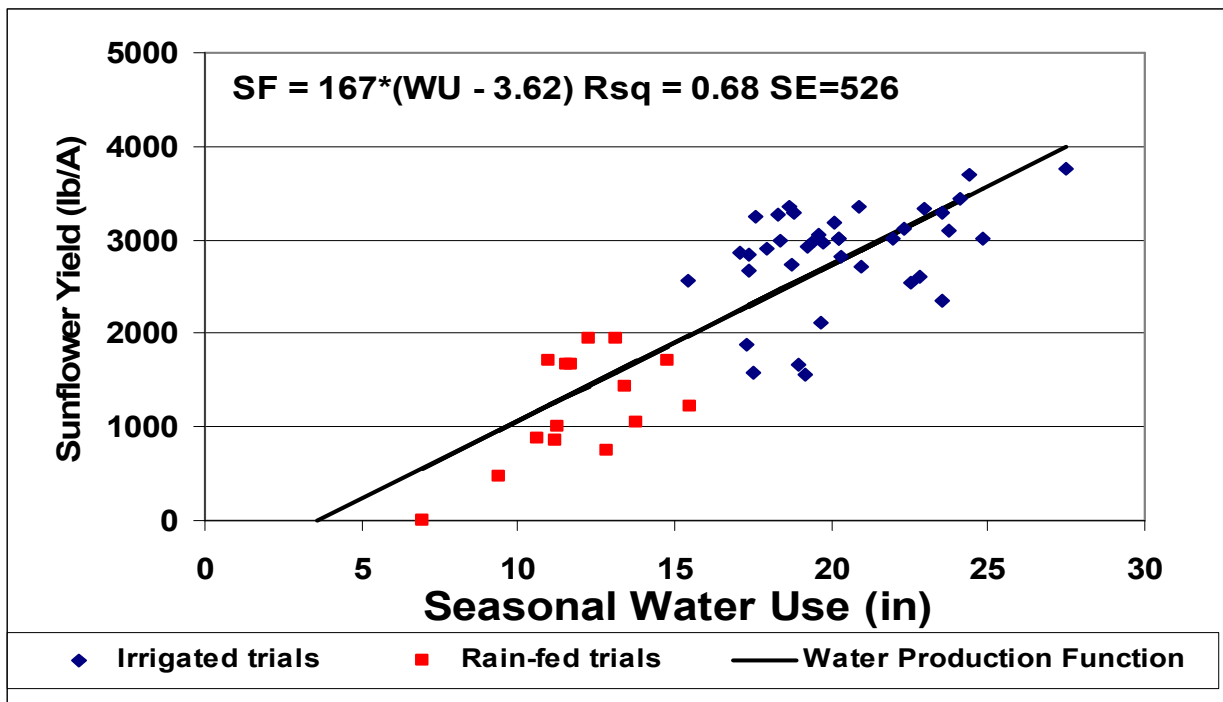

Figure 3. Expected oilseed yields and crop water use of sunflower are derived from Colby, KS trials.

inherent crop productivity, growing conditions (particularly amounts of sunshine and effects of atmospheric temperature and humidity) and harvest index (the fraction of biomass represented by economic yield). These water productivity functions have been developed from experimental data (e.g. Colby, KS, Tribune, KS, Akron, CO, North Platte, NE). The similarity in predicted yield responses to water use indicates applicability throughout the region.

A comparison of yield production functions (Figure 4) for spring canola, soybean and sunflower (corn is also shown, for comparison) indicates the apparent yield threshold is least for sunflower, but largest for soybean (among oilseed crops). In contrast, the marginal water productivity (yield increase per additional unit of water use beyond the yield threshold) is largest for soybean and least for sunflower; water productivity for spring canola is intermediate. The inherent productivity of corn exceeds that of oilseed crops. Suyker and Verma (2010) reported that corn had 50% greater assimilation, 100% greater biomass productivity than soybean. Figure 4 indicates that expected corn yields are more than three times that of soybean, at 25" of crop water use. This difference is primarily due to the greater inherent productivity[1] of warm-season grasses as well as the larger energy content of oilseeds, which require greater use of assimilates[2]. However, when oilseed yields are converted to a glucose equivalent, the productivity responses of spring canola (175 lb/A-in) and sunflower (167 lb/A-in) to increased
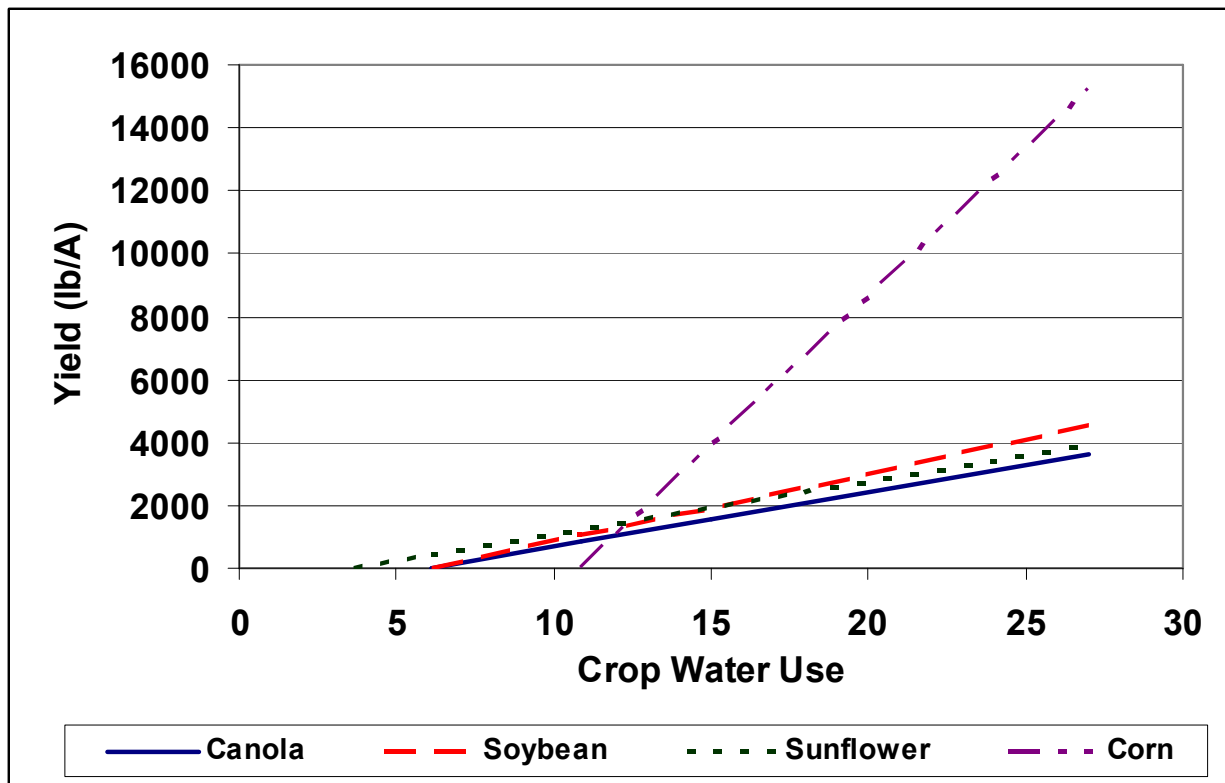

Figure 4. Crop water production functions for spring canola, soybean, sunflower and corn. The crop water production for corn was taken from Stone (2003); those for oilseeds are presented in Figures 1-3 (Grassini et al., 2009).

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[1] Plants with C4 physiology characteristically have greater CO_2-fixing efficiency than plants with C3 physiology--due to Kranz anatomy and PEP carboxylase which permit sequestration of the Rubisco enzyme in bundle sheath cells where O_2 concentrations are typically maintained at less than 2%.
[2] The fraction of a sugar molecule which results in oil (33%) or protein (40%) is substantially less than that for starch (83%); see Tanner and Sinclair (1983), p. 13.

water use is similar to that of cool-season crops (e.g. wheat, ~300 lb/A-in), which also rely on C_3 physiology. Further, the yield thresholds of oilseed crops appear to be less than that of corn; and the harvest price of oilseeds are typically greater than that of corn. As a result oilseeds may provide greater economic returns to water use than other crops at intermediate levels of irrigation.

Crop Water Productivity

Opportunities to increase crop water productivity are indicated by analysis of water use and yield formation components. Oilseed yield can be represented as a linear function of above-ground (shoot) biomass (Vega et al., 2000). Note a threshold shoot biomass, B_T, below which no oilseed yield is expected.

$$Y = k_{YF} \cdot (B - B_T)$$ [1]

where Y = oilseed yield (lb/A)

k_{YF} = oilseed yield fraction of shoot biomass, greater than threshold (B_T)
B = shoot biomass of oilseed crop (lb/A)
B_T = threshold shoot biomass, below which no yield is expected (lb/A)

In principle, shoot biomass of an oilseed crop can be represented as a linear function of transpiration (Tanner and Sinclair, 1983).

$$B = k_B \cdot T$$ [2]

where B = shoot biomass of oilseed crop (lb/A)

k_B = oilseed shoot biomass productivity, relative to transpiration (lb/A in)
T = transpiration of oilseed crop (in)

The transpiration fraction of ET, T_F, can be represented as the ratio of T/ET.

$$T_F = \frac{T}{ET}$$ [3]

where T_F = transpiration fraction of ET

T = transpiration of oilseed crop (in)
ET = crop consumptive use of water as evapotranspiration (in)

The threshold biomass, the minimum biomass at which oilseed yield is expected, can be related to ET as

$$B_{YT} = k_B \cdot T_F \cdot ET_{YT}$$ [4]

where B_{YT} = threshold biomass, less than which no oilseed yield is expected (lb/A)

k_B = oilseed above-ground biomass productivity, relative to transpiration (lb/A in)
T_F = transpiration fraction of ET, adjusted for apparent soil evaporation prior to canopy closure)
ET_{YT} = crop consumptive use of water as evapotranspiration, corresponding to threshold biomass, (in)

Substituting equations 2, 3 and 4 into equation 1, oilseed yield can be related to ET by

$$Y = (k_{YF} \cdot k_B \cdot T_F \cdot ET) - (k_B \cdot T_F \cdot ET_{YT})$$ [5]

where Y = oilseed yield (lb/A)

k_{YF} = oilseed yield fraction of biomass, greater than threshold

k_B = oilseed shoot biomass productivity, relative to transpiration (lb/A in)

T_F = transpiration fraction of ET, adjusted for apparent soil evaporation prior to canopy closure)

ET = crop consumptive use of water as evapotranspiration (in)

ET_{YT} = crop consumptive use of water as evapotranspiration, corresponding to threshold biomass, (in)

Combining terms and dividing by ET, we obtain a relationship between crop water productivity and components of crop productivity and crop water use.

$$\frac{Y}{ET} = k_B \cdot T_F \cdot \left(k_{YF} - \frac{ET_{YT}}{ET} \right)$$ [6]

where all terms are as previously defined. This relationship indicates that oilseed water productivity can increase with increasing k_B, k_{YF}, T_F and ET, and with decreasing ET_{YT}. These opportunities to increase crop water productivity, by improved irrigation and crop management, as well as crop improvement, are discussed below.

IMPROVING CROP WATER PRODUCTIVITY

An upper limit to water productivity of oilseed crops is likely constrained by the characteristics of C_3 physiology and the large assimilation requirements for oil or protein biosynthesis. Crop water productivity may approach this upper limit when 1) irrigation is delayed (minimizing evaporation from soil surface) when available soil water is sufficient for vigorous canopy expansion to intercept radiation and increase the crop transpiration fraction of ET; 2) harvest index approaches the maximum potential; and 3) growing conditions are optimal, with minimal pest damage.

Increase Transpiration Fraction

Delaying initial irrigation can reduce evaporation from the soil surface prior to canopy closure (Conner et al., 1985) and increase the crop transpiration fraction of ET. Specht et al. (1989) reported soybean yields equivalent to scheduled irrigation when irrigation was delayed to flowering or mid-pod stages. A similar response was reported by Lamm (1989a) with greater or equal soybean yields occurring with reduced irrigation during the vegetative period. However, maintaining sufficient soil moisture for vigorous canopy formation may require irrigation prior to canopy closure. Rapid canopy formation is vital to productivity as conversion of sunlight into biomass requires light interception by a healthy crop canopy (Albrizio and Steduto, 2005; Suyker and Verma, 2010).

Soybean and sunflower crops appear to differ in response to soil water deficits. Soybean exhibited tolerance of soil drying by maintaining non-stress photosynthetic rates when available soil water was 47% of full water-holding capacity (Wang et al., 2006). Also, soybean reduced crop transpiration by 67% under these deficit conditions. In contrast, sunflower maintained crop water use near non-stress rates when available soil water was 40% of water-holding capacity (Casadebaig et al, 2008). Also, sunflower reduced leaf expansion rates when available soil water was 60% of full capacity, indicating sunflower producitivity declines under water deficits

while water use continues at rates near the expected maximum. These results indicate a potential advantage to soybean--maintaining productivity while reducing transpiration under vegetative water deficits. Lamm (1989b) demonstrated increased water productivity for soybean by reducing irrigation during vegetative development.

Spring oilseed crops such as spring canola avoid evaporative losses, as crop canopy is established under cool conditions with modest evaporative demand. Water productivity can be increased by minimizing evaporative losses from soil by delaying initial irrigation, seeking rapid canopy closure, or planting a early spring oilseed which forms canopy under conditions of low evaporative demand.

Managing Harvest Index

Increasing harvest index (the fraction of biomass represented by economic yield, related to k_{YF}) can improve crop water productivity. Establishing yield potential involves components of yield (plant population, potential seeds per plant[3], actual seeds per plant and seed mass). Vega et al. (2001) showed that seeds per plant increased with plant growth rate during seed set for soybean and sunflower. The indeterminate growth of soybean permitted branching and continued flowering, for continued increase in seeds per plant for plants with large growth rates. However, the rate of seed set for sunflower was smaller at the greatest growth rates, compared to rate of seed set at intermediate growth rates due to limits in the potential number of seeds per head. It follows that yield formation in sunflower is more sensitive to sub-optimal populations than indeterminant crops such as soybean. Likewise, the indeterminant spring oilseed crops, such as canola, should be able to compensate for low population with increased branching and flowering.

Maintaining vigorous growth during floral development and seed set is critical for all grain crops, but can depend on weather conditions as well as crop management. Grassini et al., (2009) found that harvest index in sunflower was reduced under cloudy or hot conditions (low photothermal quotient, ratio of photosynthetically-active radiation to temperature) during the flowering period. Andrade (1995) reported that soybean yield formation was most sensitive to water deficits during seed fill, while sunflower yield was sensitive to water deficits during flowering and seed fill stages; canola exhibits yield sensitivity during flowering and seed fill (Champolivier and Merrien, 1996; Istanbulluoglu et al., 2010). Increased harvest index can be favored by planting optimal populations, selecting appropriate planting dates, varieties or hybrids, and avoiding water deficits for vigorous growth during floral development and seed fill.

Genetic Advance

Genetic gain in crop water productivity may result from restricted transpiration, crop tolerance of soil water deficits and increased harvest index. Hufstetler et al., (2008) compared adapted soybean lines with non-adapted accessions; adapted lines had greater crop water productivity and lower transpiration rates at night than accessions. Lines also differed in sensitivity of transpiration to soil water deficit thresholds and in recovery upon re-wetting. Sinclair et al. (2000) screened 3,000 soybean lines and identified eight with substantial tolerance of N2 fixation to soil drying. This trait could enhance the growth response of soybean to a delayed irrigation strategy (see Increase Transpiration Fraction, above). Developing varietals and

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[3] Components of yield for indeterminant crops, such as soybean and canola, include pods per plant and seeds per pod. Determinant crops, such as sunflower, typically have seeds arranged in a single head.

hybrids which maintain crop productivity and yield formation under water deficits and environmental stress can increase crop water productivity.

Conclusions

Seasonal crop growth, in relation to crop water use, is known as a crop water productivity function; typically, these consist of a yield threshold (water use prior to expected economic yield) and a yield response (rate of yield increase per unit water use). Field studies in the U.S. central High Plains indicate sunflower has least yield threshold as well as least yield response; soybean has greatest yield threshold as well as greatest yield response. An upper limit to oilseed crop water productivity is primarily set by characteristics of the C3 physiology, which governs CO_2 fixation by oilseed crops, and the large energy requirements for oil and protein biosynthesis. An adaptive management strategy can help growers achieve the maximum crop water productivity expected for oilseed crops. Components of this strategy include selecting crops and managing vegetative water supply to minimize the evaporative component of ET during vegetative growth, selecting seeding rates, planting dates and water management to ensure vigorous growth during flowering and seed-fill growth stages, and developing varieties and hybrids which tolerate water deficits to maximize harvest index.

Acknowledgement

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