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Water productivity under strategic growth stage-based deficit irrigation in maize

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ABSTRACT

Water shortages are responsible for the greatest crop losses around the world and are expected to worsen. In arid areas where agriculture is dependent on irrigation, various forms of deficit irrigation management have been suggested to achieve high yields with less water used by the crop (i.e. evapotranspiration, ET). This study of maize evaluated twelve treatments with varying levels of deficit irrigation during late vegetative and maturation (grain filling) growth stages in semi-arid Northern Colorado. In particular, application of greater deficit during the late vegetative state with full or nearly full ET during the rest of the season consistently resulted in yield similar to full ET treatments while saving approximately 15–17% of ET. Maize given 40% of full ET during the late vegetative period had slightly reduced leaf area index (LAI) with significant leaf curling, thus reduced light interception during vegetative growth. However, when plants were fully watered during anthesis, all treatments had full canopy cover with no differences in light interception. The efficiency of photosystem II (quantum yield) declined with water stress but recovered with re-watering. The ability of photosystem II and light interception to recover after stress when well-watered suggests that reductions in biomass and yield resulted from stomatal closure, reduced photochemistry, or loss of xylem conductance that was temporary. With little indication of permanent decline in carbon assimilation after reducing ET in vegetative stages, maize appears able to achieve high grain yield if soil water is readily available during the reproductive and maturation stages. However, plants given full or nearly full irrigation during the entire vegetative period followed by stress later on during the maturation period, had dramatically greater yield loss than ET savings. Thus, while strategic deficit irrigation might maintain yield with less water, it may be especially important for buffering crops against yield losses due to end of season water shortfalls in water limited environments.

1. Introduction

Increased productivity and yield stability of cropping systems is vital to meet the challenge of expanding human populations and increased needs for food and fiber (Boyer et al., 2013; Howell, 2001). Given that expansion of agricultural areas and cropping intensification is limited, increased production is anticipated to be achieved primarily from irrigated agriculture (FAO, 1988, 2003; Rhoades, 1997). Irrigated agriculture currently delivers 40% of the world's food supply from just 20% of the cultivated land, and provides crucial stability to global food security (Garces-Restrepo et al., 2007). With crop productivity steadily rising in the 20th century due in part to improved crop management such as increased planting densities and control of weeds, pests and diseases, irrigation is anticipated to play an increasingly important role in reducing yield gaps (e.g., preventing under-production) and stabilizing yields closer to the maximum attainable yield among growing seasons (Egli and Hatfield, 2014a, b; Lobell et al., 2009). Yields of several crops, including maize, appear to be increasing in sensitivity to water limitations despite improvements in germplasm, likely due to increases in planting density and other changes in crop management (Lobell et al., 2014). However, effective management of cropping systems and irrigation water in the face of limited water resources will depend crucially on our ability to maximize crop water productivity (yield per unit water used by the crop), rather than simply maximizing yield (Debaeke and Aboudrare, 2004).

Producers in semi-arid regions face increasing scarcity of irrigation water due to the growing demand from urban centers and industry, depletion of groundwater aquifers, increased environmental and recreational demand, and a shifting and more volatile climate (Derner et al., 2015; Knapp et al., 2008; Seager and Vecchi, 2010). Past research in agronomic water-use has focused on improving irrigation efficiency (i.e., water consumed as a fraction of water applied). However, poor

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irrigation efficiency at the farm-scale may not necessarily result in a marked decline in watershed-scale efficiency because some water "losses" (runoff and deep percolation) may return to the watershed and be used downstream. However, as water supplies have become over-allocated and basin-wide efficiencies have increased, crop water productivity (i.e., yield per unit water consumed by the crop) represents an opportunity to further improve irrigation water use efficiency.

Water productivity (WP) is defined as crop yield per total evapotranspiration (ET) of the cropping system required to bring the crop to maturity. Regulated deficit irrigation (RDI), which strategically supplies less water than required to achieve maximal yield, has been a primary strategy targeted in water limited environments for maximizing WP (English et al., 2002; Fereres and Soriano, 2007; Geerts and Raes, 2009; Pereira et al., 2002). Linear relationships between yield and ET indicate that maximal water productivity and economic return will be achieved when water is supplied in sufficient quantity to achieve maximal yield. A WP function must be curvilinear and concave downward for deficit irrigation to provide increased water productivity (Trout and DeJonge, 2017). In some crops (e.g., cotton, soybean, wheat), the relationship between yield and ET is curvilinear and convex, such that WP may be maximized at less than maximum ET (Henggeler et al., 2002; Sincik et al., 2008; Tavakkoli and Oweis, 2004). In the case of maize, WP is high relative to other agronomic crops, but yield decreases steeply with decreasing ET, often linearly, particularly when water is withheld evenly across the season, with about one-third of total ET consumed before reproduction (Farré and Faci, 2006; Igbadun et al., 2006; Oktem et al., 2003; Pandey et al., 2000; Payero et al., 2006; Tolk et al., 1999; Yilmaz et al., 2010). However, curvilinear water production functions (WPFs) have been found when deficit irrigation was unevenly applied across the season, with more water supplied during the anthesis and initial grain-fill stages (Trout and DeJonge, 2017), when maize yields are known to be most sensitive to water stress (Salter and Goode, 1967; Westgate and Boyer, 1985b).

Current equations for estimating irrigation requirements (e.g., FAO 56, Penman-Monteith based equations) assume a constant marginal water productivity throughout plant development and maturation but it is well known that crop sensitivity to drought varies across plant developmental stages, such that these equations may be over simplified and have room for improvement. Questions also remain on how to apply deficit irrigation across the season for highest water productivity, assuming the producer does not have access to adequate water to maximize production. Typical recommendations for maize under RDI include supplying ET during anthesis and initial grain-fill, which are recognized as the most sensitive stages to drought stress, (Çakir, 2004; Kirda et al., 1999; Yilmaz et al., 2010), but optimal times to apply deficits are not well established. Deficit irrigation in early vegetative stages may negatively affect yield in corn by producing weak plants or limiting the number of rows on the developing ear (Huang et al., 2002; Kirda et al., 1999; Stevens et al., 1986) (but see Kang et al., 2000; Pandey et al., 2000). However, applying irrigation during vegetative stages could accelerate increases in leaf area, light interception and photosynthesis and, thus, increase yield per total plant water consumption (Geerts and Raes, 2009). Nonetheless, stress during vegetative stages may precondition plants to tolerate greater drought stress during later stages in crop development, such as the grain-filling stage in maize (Harb et al., 2010). Thus, the optimal timing for applying water deficits to achieve the highest water productivity by maize has yet to be determined.

Approximately one quarter of the irrigated crop area in the US is within the Northern Great Plains, represented by Colorado, Montana, Nebraska, North Dakota, South Dakota, and Wyoming (Derner et al., 2015). Within the Northern Great Plains, more irrigated land is planted to maize than any other crop. This trend is increasing, with an unprecedented transition in agricultural land use from grassland to annual crops (Derner et al., 2015; Wright and Wimberly, 2013). Maize generates the greatest economic revenue in the Northern Plains at ca $13.3 billion with the next valued crop generating less than half of this revenue (Derner et al., 2015). Globally, maize is one of the top four staple crops supporting human populations (FAO, 2003). It is also an important feed for livestock with growing importance as people in developing counties increasingly demand a diet with more meat and dairy (FAO, 2012; USDA, 2012).

The aim of this paper is to investigate maize yield responses to seasonally-distributed deficit irrigation and identify underlying factors causing these responses to better understand improvements that can be made in irrigation management and crop physiology that determines water productivity. Specifically, we sought to: 1) examine yield responses to ET deficits independently targeted during two stress periods, the late vegetative (V8-VT) and grain-filling (R4-R6) stages, to determine the shape of the response curve and identify treatments that hinder or maintain yield; and 2) identify if water productivity was limited by canopy development or photosynthetic processes.

2. Methods

2.1. Experiment location and treatments

The experiment was conducted at the USDA-ARS Limited Irrigation Research Farm (LIRF) located near Greeley, CO USA (40°26′50″N, 104°38′12″W, 1425 m elevation), which receives approximately 215 mm of precipitation during the growing season (May – October) (PRISM Climate Group, 2015). Soils are predominately Olney fine sandy loam with Otero sandy loam in small areas. The low seasonal rainfall and coarse-textured soils allow for control of soil water content through managed irrigation. The experimental field was divided into two sections with twelve treatments laid out in a complete block design with four blocks in each section. A common commercial hybrid of maize in the region (Dekalb DK 52-04, 102 day maturity class) was grown in alternating fields with a common variety of mid-oleic sunflower (*Helianthus annuus*). These two crops were rotated annually to reduce pest problems and accommodate potential soil differences. A population of 84,000 seeds ha^{-1} was planted on April 30 in 2012 and 85,500 seeds ha^{-1} on May 15 in 2013, and resulted in a final population of 80,496 and 77,665 in 2012 and 2013, respectively. Twelve irrigation treatments (described below) were replicated in separate plots within each block. Each plot was 43 m long by 9 m wide (12 north-south rows at 0.76 m spacing). Locations of irrigation treatments were superimposed on similar treatments in previous years (i.e. ET targets remained the same when crops rotated), allowing an evolution of soil water storage appropriate to the treatment. The field was managed with conservation practices and strip-tilled once annually. Total applied nitrogen ranged between 266–349 Kg ha^{-1} in 2012 and 230–294 Kg ha^{-1} in 2013, depending on the treatment. A liquid starter nitrogen of 41 Kg ha^{-1} was applied at planting each year with approximately 170 Kg ha^{-1} applied as fertigation over four irrigation events in 2012 and 160 Kg ha^{-1} applied over five irrigation events in 2013 in July prior to tasseling. The remainder of nitrogen (97–175 Kg ha^{-1} in 2012, 74–127 Kg ha^{-1} in 2013) was applied through the season with the well water used for irrigation which contained high nitrate content (approximately 25 ppm N). We note that differences in N input among treatments largely mirror expected differences in yield potential associated with the varying water levels of water deficit in most years.

Irrigation deficits were applied independently during two stress periods corresponding with late vegetative (V8-VT) and grain-filling (R4-R6) stages (Fig. 1). Stress periods were chosen to avoid stress during the formation of rows on the developing ear at V7 (Stevens et al., 1986). Treatments with similar ET targets between the two stress periods were used to establish the WP function used as a baseline for comparison. Combinations of irrigation deficit, varying timing and amount, were established to test the hypotheses of preconditioning plants to maintain yield under stress through prior exposure to stress,