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Physiological mechanisms contributing to the increased water-use efficiency in winter wheat under deficit irrigation

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Summary

Deficit irrigation in winter wheat has been practiced in the areas with limited irrigation water resources. The objectives of this study were to (i) understand the physiological basis for determinations of grain yield and water-use efficiency in grain yield (WUE) under deficit irrigation; and (ii) investigate the effect of deficit irrigation on dry matter accumulation and remobilization of pre-anthesis carbon reserves during grain filling. A field experiment was conducted in the Southern High Plains of the USA and winter wheat (cv. TAM 202) was grown on Pullman clay loam soil (fine mixed thermic Torretic Paleustoll). Treatments consisted of rainfed, deficit irrigation from jointing to the middle of grain filling, and full irrigation. The physiological measurements included leaf water potential, net photosynthetic rate (Pn), stomatal conductance (Gs), and leaf area index. The rainfed treatment had the lowest seasonal evapotranspiration (ET), biomass, grain yield, harvest index (HI) and WUE as a result of moderate to severe water stress from jointing to grain filling. Irrigation application increased seasonal ET, and ET increased as irrigation frequency increased. The

Abbreviations: DOY, day of year; ET, evapotranspiration; Gs, stomatal conductance; HI, harvest index; Pn, net photosynthetic rate; SL, stem loss; WUE, water-use efficiency in grain yield; WUEbm, water-use efficiency in biomass; Ψ_s, soil water potential; Ψ_w, leaf water potential

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seasonal ET increased 20% in one-irrigation treatments between jointing and anthesis, 32–46% in two-irrigation treatments, and 67% in three- and full irrigation treatments. Plant biomass, grain yield, HI and WUE increased as the result of increased ET. The increased yield under irrigation was mainly contributed by the increased number of spikes, and seeds per square meter and per spike. Among the irrigation treatments, grain yield increased significantly but the WUE increased slightly as irrigation frequency increased. The increased WUE under deficit irrigation was contributed by increased HI. Water stress during grain filling reduced Pn and Gs, and accelerated leaf senescence. However, the water stress during grain filling induced remobilization of pre-anthesis carbon reserves to grains, and the remobilization of pre-anthesis carbon reserves significantly contributed to the increased grain yield and HI. The results of this study showed that deficit irrigation between jointing and anthesis significantly increased wheat yield and WUE through increasing both current photosynthesis and the remobilization of pre-anthesis carbon reserves.

Introduction

Winter wheat is widely grown under rainfed, full irrigation, and deficit irrigation production systems and produced for both grain and winter cattle forage in the Southern High Plains of the USA (the area includes the Texas High Plains, the Oklahoma panhandle, parts of eastern New Mexico, and southwestern Kansas) (Howell et al., 1995; Musick and Dusek, 1980; Musick et al., 1994). The area has a semi-arid climate with annual precipitation ranging from 380 mm in the southwest to 580 mm in the northeast and averages about 480 mm. Growing season precipitation for wheat production averages about 250 mm (Musick et al., 1994). The seasonal evapotranspiration (ET) for winter wheat growth ranges from 700 to 950 mm when irrigation is used to prevent plants from water stress (Howell et al., 1995; Musick and Porter, 1990; Musick et al., 1994). Therefore, the seasonal precipitation for winter wheat can only meet one-third of the ET required for maximum grain yield, and rainfed wheat yield and water-use efficiency in grain yield (WUE) are primarily limited by soil water stress from late spring to early summer (Howell et al., 1997; Musick et al., 1994). In the Texas High Plains, dryland winter wheat yield mostly ranges between 1000 and 2000 kg ha^{-1}, while WUE is about 0.4 kg m^{-3} (Jones and Popham, 1997; Musick et al., 1994). For the irrigated wheat, yield is in the range of 3000–8000 kg ha^{-1} and WUE is in the range of 0.5–1.2 kg m^{-3} (Eck, 1988; Howell et al., 1995; Musick et al., 1994). Irrigation in this area is primarily from the Ogallala aquifer. The declining water table and high energy pumping cost have reduced irrigation in winter wheat (Musick et al., 1994). Because wheat is a relatively drought-tolerant and deep-rooted crop, deficit irrigation is a viable alternative irrigation regime. Deficit irrigation is the application of less water than is required for potential ET and maximum yield, resulting in conservation of limited irrigation water (Musick et al., 1994). Studies have shown that deficit irrigation significantly increased grain yield, ET and WUE as compared to rainfed winter wheat (Eck, 1988; Musick and Dusek, 1980; Musick et al., 1984; Oweis et al., 2000; Schneider et al., 1969). However, previous studies in deficit irrigation focused on the seasonal ET, yield response and WUE (e.g., Eck, 1988; Musick et al., 1984; Oweis et al., 2000), few studies have explored the underlying mechanisms of improved yield and WUE under deficit irrigation (e.g., Zhang et al., 1998).

The reduction of photosynthesis and acceleration of leaf senescence by water stress during grain filling have been recognized as major causes reducing grain yield in wheat (Kobata et al., 1992). At the same time, the reduction in photosynthesis increased the demand for pre-anthesis carbon reserves (Palta et al., 1994). Studies showed that water stress during grain filling significantly increases the remobilization of pre-anthesis carbon reserves from stems, leaves and sheaths to grains (Foulkes et al., 2002; Kobata et al., 1992; Palta et al., 1994; Rawson et al., 1977; Yang et al., 2000). The remobilization of pre-anthesis carbon reserves can be important for wheat yield and harvest index (HI) under water stress (Richards et al., 2002). Lopez-Castaneda and Richards (1994) showed that, between anthesis and maturity, grain yield increased linearly as stem weight loss increased in wheat, barley (*Hordeum vulgare*), triticale (*x Triticosecale*), and oats (*Avena sativa*) under rainfed conditions. Zhang et al. (1998) proposed that increased remobilization of reserved carbon from stems and sheaths under water stress may contribute to increased HI in deficit irrigation treatments. However, no study has been conducted