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Deficit Irrigation in Winter Wheat

- The U.S. Southern High Plains and North China Plain -

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Abstract: Winter wheat is a major crop in the U.S. Southern High Plains (SHP) and North China Plain (NCP). In both regions, water is the most important limiting factor for wheat production. Drought stress often significantly reduces wheat yield and water use efficiency (WUE) since the seasonal precipitation only can partially meet the evapotranspiration (ET) requirement for high yields. Irrigation can help to maintain high yields and productivity in wheat. However, the dramatic increase in water extraction for crop irrigation resulted in a significant decline in the water table in both regions. Deficit irrigation, application of less water than required for full ET and maximum yield, has shown to be a viable management practice for improving wheat yield and WUE in the SHP and NCP. We compare the relationships among yield, ET and WUE in the two regions and explore the physiological mechanisms for increasing yield and WUE under deficit irrigation. Wheat yield increases linearly with increasing ET in both regions. The relationship between WUE and yield is a linear in NCP but a curvilinear in SHP. Although higher WUE generally can be achieved with higher yields, the curvilinear relationship between WUE and yield in the SHP indicates that WUE may not be the highest when yield was in the high range. For both regions, maintaining high available soil water at planting, applying irrigation at critical stages, and achieving high harvest index are important for successful practice of deficit irrigation.

Key Words: Drought, Evapotranspiration, *Triticum aestivum* L., Water use efficiency

1. Introduction

In the U.S. Southern High Plains (SHP), winter wheat is grown under a wide range of water regimes for producing both grain and cattle forage (Musick *et al*., 1994). In 2013, about 14 million ha of wheat were harvested in the SHP (NASS, 2013). The region has a semi-arid climate with annual rainfall ranging from 380 to 580 mm. Growing season precipitation averages about 250 mm. The seasonal evapotranspiration (ET) for wheat growth ranges from 700 to 950 mm under full irrigation (Howell *et al*., 1995). Therefore, the seasonal rainfall can only meet one-third of the ET required for maximum yield. As a result, wheat yield and water-use efficiency (WUE, the ratio of yield and ET) are primarily limited by drought stress from late spring to early summer (Musick *et al*., 1994). Under dryland conditions, wheat production is largely determined by the amount and effective use of soil water storage and seasonal rainfall (Jones and Popham, 1997). However, dryland wheat yields are generally much lower than irrigated wheat (Musick *et al*., 1994).

Winter wheat is also a major crop in the north China Plain (NCP). The region produces about 69% of wheat in the whole country on about 14 million ha of arable land (Mo *et al*., 2009). The average annual rainfall in the region ranges from 500 to 650 mm.

However, the majority of precipitation occurs during the summer months (Jul.-Sep.). Rainfall during the wheat growing season ranges from 100 to 180 mm, or approximately 25-40% of crop water requirement over the growing season (Zhang *et al*., 1999). Therefore, drought is also an important factor affecting dryland wheat yield.

Irrigation application provides a means to maintain high yields in wheat in the SHP and NCP. For both regions, irrigation water is mainly from underground. In the SHP, irrigation from Ogallala Aquifer significantly increased during the 1950's. However, the dramatic increase in water extraction for crop irrigation resulted in a significant decline in the water table. In the meantime, irrigated land area has decreased from a peak of 2.4 million ha in 1974 to 1.9 million ha in 2000 in the Texas High Plains (Colaizzi *et al*., 2008). Similarly, groundwater levels have decreased considerably in the NCP due to irrigation (Zhang *et al*., 2003). Since water tables will continue to decrease, application of less irrigation will be the primary practice for wheat production in SHP and NCP. Deficit irrigation, application of less water than it is required for full ET and maximum yield, has shown to be a viable management practice for improving wheat yield and

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WUE. In this article, we briefly review the long-term field research on deficit irrigation in wheat in US SHP and China's NCP. Our objective is to better understand the ecological and physiological basis for improving yield and WUE under water-limited conditions.

2. Definition of Deficit Irrigation

Deficit irrigation is defined as the application of less water than it is required for full ET and maximum yield (English *et al*., 1990; Musick, *et al*. 1994). It is called by a variety of other names such as partial irrigation, regulated deficit irrigation, ET deficit irrigation, and limited irrigation (English *et al*., 1990; Kang *et al*., 2002). The overall goal of deficit irrigation is to increase WUE, either by reducing irrigation frequency or by eliminating the least productive irrigations. Management of deficit irrigation is very different from full irrigation management. Rather than working to minimize crop water stress, plants must be allowed to certain levels of water stress (English *et al*., 1990; Zhang *et al*., 1998).

3. Yield, Evapotranspiration (ET) and Water Use Efficiency

In the U.S. SHP, the long-term dryland wheat yields were mostly 1-2 Mg ha^{-1} (Jones and Popham, 1997). However, dryland yields in irrigation studies were frequently over 3 Mg ha^{-1} (Xue *et al*., 2006). The irrigated wheat yields ranged from 3.0 to 7.7 Mg ha^{-1} and ET from 400 to over 900 mm, depending on irrigation timing and frequency (Xue, 2012). Wheat yields under full irrigation were in the range of 5.3-7.7 Mg ha^{-1} and required about 700-950 mm ET (Howell *et al*., 1995). Under dryland conditions, WUE ranged from 0 to 0.8 kg m^{-3}, with an average of 0.4 kg m^{-3}. The WUE in irrigated wheat was higher and ranged from 0.5 to 1.2 kg m^{-3} (Musick *et al*., 1994; Xue *et al*., 2006). In the NCP, wheat yields ranged from 2.9 to 9.5 Mg ha^{-1} and ET from 200 to 600 mm. The WUE in NCP was much higher than SHP, ranging from 0.9 to 2.3 kg m^{-3} (Zhang *et al*., 1998, 2003, 2004, 2010; Hu *et al*., 2005; Qiu *et al*., 2008; Hao and Wang, 2013, personal communications). **Figure 1** shows that there was a significant linear relationship between yield and ET for both areas. The data in NCP were more scattered because of the multi-locations across the NCP while data in SHP were mainly from Bushland, Texas. The linear regression of yield and ET in NCP had a greater slope (1.17 kg m^{-3}) in NCP than that in SHP (1.06 kg m^{-3}).

Figure 2 shows the relationship between WUE and wheat yield. The WUE-yield relationship was a quadratic function when the full range of yield was considered for SHP. The WUE increased linearly when yield increased up to 4-5 Mg ha^{-1}. When yield increased further, WUE maximized and even tended to decrease. In NCP, the WUE increased linearly as yield increased.

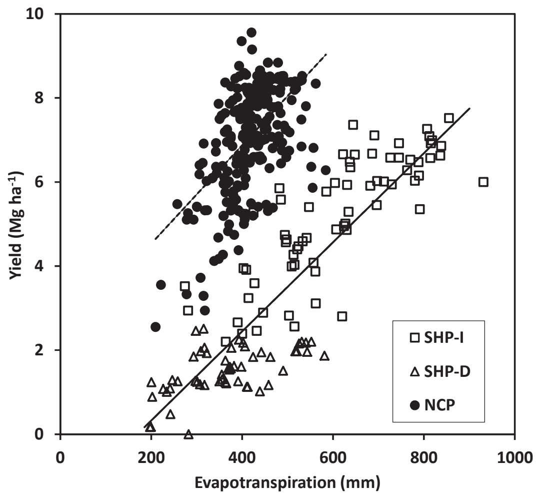

Fig. 1. The linear relationship between yield and evapotranspiration (ET) in the U.S. Southern High Plains (SHP) and North China Plain (NCP). I-irrigated; D-dryland. Regression equations: SHP-Y=0.0106X-1.7393, R^2=0.75, p<0.001; NCP-Y=0.0117X+2.1945, R^2=0.31, p<0.001 (Data sources: Xue *et al*., 2012; Zhang *et al*., 1998, 2003, 2004; Hu *et al*., 2005; Qiu *et al*., 2008; Hao and Wang 2013, personal communications).

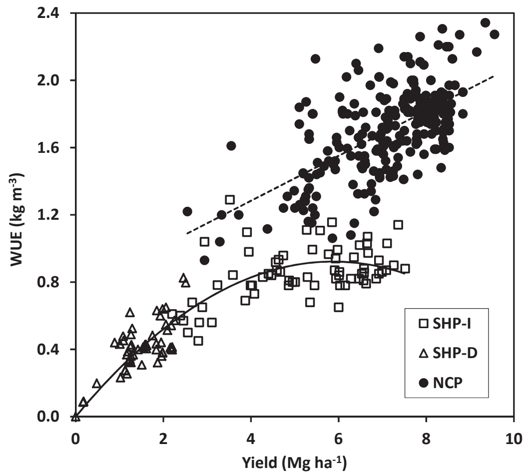

Fig. 2. The relationship between WUE and yield in the U.S. Southern High Plains (SHP) and North China Plain (NCP). I-irrigated; D-dryland. Regression equations: SHP-Y = -0.0267X^2 + 0.3138X, R^2 = 0.79, p<0.001; NCP-Y = 0.1338X + 0.7482, R^2 = 0.40, p<0.001) (Data sources: see Fig. 1).

Figure 2 indicates that higher WUE generally can be achieved with higher yields. However, curvilinear relationship between WUE and yield in the SHP showed that WUE might not be the highest when yield was in the high range. The ET demand could be as high as 12 mm per day and was frequently over 60 mm per week in irrigated wheat due to high winds and associated high vapor pressure deficit (Howell *et al*., 1995). In the NCP, daily ET was generally less than 10 mm (Liu *et al*., 2002; Hu *et al*., 2005).

4. Improving Yield and WUE under Deficit Irrigation

In the SHP, Schneider and Howell (2001) studied the responses of wheat yield, WUE, ET, irrigation water use efficiency (IWUE) and harvest index (HI) to different irrigation levels (from deficit to full irrigation) in two growing seasons at Bushland, TX. Irrigation application increased wheat yield and WUE as compared to dryland treatment. Deficit irrigation (25% and 50% ET requirement of full irrigation) resulted in highest WUE and IWUE. For 50% ET treatment, yield was 86-95% of full irrigation (100% ET). In another field study at the same location, Xue *et al*. (2006) showed that deficit irrigation of 100 mm at booting stage increased yield by 46% and WUE by 23% as compared to dryland treatment. Compared to full irrigation of 400 mm, a deficit irrigation of 220 mm at jointing and anthesis achieved 84% of the yield at full irrigation and resulted in 45% irrigation water savings. In the NCP, Zhang *et al*. (1998) showed that wheat yield at one-irrigation (80 mm) were 84-100% that under four -irrigation (320 mm). As a result, WUE was increased to 1.55 kg m^{-3} at one-irrigation treatment from 1.22 kg m^{-3} at four-irrigation treatment (Zhang *et al*., 1998). More recent studies confirmed the above results in the NCP (Qiu *et al*., 2008; Zhang *et al*., 2011).

5. Mechanisms for Increased WUE under Deficit Irrigation

Many field studies have been conducted in both the SHP and NCP to elucidate the mechanisms for increased yield and WUE under deficit irrigation. First, maintaining high available soil water (ASW) at planting and allowing soil drying at early stage are important for successful practice of deficit irrigation. Musick *et al*. (1994) showed that wheat yield increased linearly as ASW at planting increased. High ASW at planting not only ensured the vigorous early shoot growth but also resulted in deep root system. Xue *et al*. (2003) showed that mild soil water stress in the spring promoted root growth and development. For example, root length density along the soil profile was higher in dryland than in irrigated treatment at booting. With the deep root system, irrigation can be delayed until booting stage or anthesis if only one-irrigation is allowed (Xue *et al*., 2003). Similarly, Zhang *et al*. (1998) and Zhang *et al*. (2011) also reported that mild water stress at early stage led to a relatively deeper root system in NCP environment.

Second, irrigation must be applied at critical stages for wheat yield determinations when only limited irrigation is allowed. Critical growth stages for irrigating winter wheat generally occur from early spring growth to early grain development in the SHP. When only one-irrigation allowed, irrigation between jointing and anthesis resulted in same yield and WUE. However, irrigation at grain filling did not increase yield and WUE (Xue *et al*., 2003, 2006). Irrigation at critical stage also reduced the severity of soil water stress and allowed plants to use more water during grain filling (Zhang *et al*., 1998; Xue *et al*., 2003, 2006). Xue *et al*. (2003, 2006) demonstrated that one-irrigation at booting stage maintained high soil water content and significantly reduced water stress at anthesis. As a result, plants in one-irrigation at booting stage had higher photosynthetic rate and stomatal conductance than dryland and one-irrigation at jointing (Xue *et al*., 2006). Similar results were also found in the NCP (Zhang *et al*., 1998; Zhang *et al*., 2011).

Third, increased yield and WUE under deficit irrigation is related to increased harvest index (HI). HI is determined during grain filling by both current photosynthesis and remobilization of pre-anthesis carbon reserve from stems. For the maintenance of current photosynthesis to meet the carbohydrate supply, higher photosynthesis rate and longer green leaf area duration are advantageous under drought conditions. Zhang *et al*. (2011) showed that deficit irrigation changed wheat canopy structure and increased the proportion of non-leaf organs for photosynthesis. As a result, canopy photosynthetic capacity was improved during grain filling and grain yield was increased under deficit irrigation. When photosynthesis is reduced by drought stress during grain filling, remobilization of carbon reserves can be important. The contribution of remobilized carbon reserves to grain yield in wheat varied from 5% to 90%, depending on environmental conditions (Asseng and van Herwaarden, 2003; Xue *et al*., 2006). The increased HI under appropriate deficit irrigation was due to increases in both the current photosynthesis and the remobilization of pre-anthesis carbon reserves (Xue *et al*., 2006; Zhang *et al*., 2013). The best example is perhaps a treatment (T-6) in a field study by Xue *et al*. (2006). This treatment received irrigations at both jointing and anthesis. Irrigation at jointing increased the number of spikes and stems, and irrigation at anthesis increased seed weight. The more stems allowed plants to remobilize pre-anthesis carbon reserves to grains at late grain filling. As a result, the treatment had higher WUE and HI, and the yield only reduced 16% as compared to the full irrigation treatment (Xue *et al*., 2006).

6. Future Perspectives

The declining irrigation water continues to challenge the irrigated wheat production in the SHP and NCP. Although several management factors (improved cultivars, fertilization and pests control, etc.) contributed to higher yield and WUE, irrigation still plays a vital role to increase wheat yield and

WUE in these areas. For example, irrigated wheat yields can be 2-4 times higher than dryland yields in the SHP (Fig. 1). Therefore, irrigation will be an important management practice for long time. Since the irrigation water becomes limiting, deficit irrigation will be the primary practice in the future for irrigated wheat production. The future challenge will be integration of new irrigation technologies and better managing crops under drought stress. In the SHP, irrigation technologies have been improved significantly over the decades (*e.g.*, from furrow to sprinkler and sub-drip irrigation). However, the technologies in the NCP need more improvements since the majority of irrigation practices are still flood irrigation. Nevertheless, adoption of cultivars with more drought resistance will lead to more water savings and maintain yields as evidenced in both regions (Zhang *et al*., 2010; Xue *et al*., 2013). Improving drought resistance through breeding will provide benefits but is a long-term task. The current challenges are identifying important physiological traits and looking for high throughput field phenotyping tools. Currently we are conducting new field studies to address some of these challenges.

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