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Full Length Research paper

Effects of limited irrigation on yield and water use efficiency of two sequence-replaced winter wheat in Loess Plateau, China

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The effects of irrigation on grain yield and water use efficiency was studied on two sequence replaced dryland winter wheat (Triticum aestivum L.) cultivars, Changwu 135 (CW, a new cultivar) and Pingliang 40 (PL, an old cultivar). Field experiments were carried out on Changwu country on Loess Plateau, China. Whereas the control plots were not irrigated at all, the treatment plots were irrigated three times, the quantity of irrigation being the same (40 mm) each time: at the jointing stage, at booting, and at flowering. Irrigation increased root biomass in each layer of soil in PL. Irrigation made PL produce greater root biomass in deeper soil, enabling the plants to tap larger quantities of water. CW had a harvest index (HI) greater by 0.11 than that of PL under both conditions, and lower shoot and root biomass, which indicates that more dry matter was transported to productive organs, leading to higher yields than PL. CW consumed more water to produce a unit quantity of root biomass and use irrigation less efficiently showing undercompensation, whereas PL showed overcompensation. Higher yield and greater water use efficiency in wheat appear to be associated with smaller root systems and higher harvest index irrespective of irrigation.

Key words: Loess Plateau, winter wheat, limited irrigation, yield, water use efficiency, root growth.

INTRODUCTION

On Loess Plateau in China, the main limiting factor to crop production is water. Changwu country, Shaanxi, belongs to a typical dryland (rainfed) farming region with the mean annual precipitation being 584 mm (Liang, 1997). Although this is greater (in total) than the water requirement of winter wheat (450 – 525 mm) grown in this area (Zhong et al., 2000), its distribution does not favor winter wheat. Only about 300 mm (about 40%) is received during the growth period when the demand is critical while rains are plentiful from July to September (data from Changwu station of the meteorological observatory). Water deficiency during the critical period results in poor shoot growth and low yield (Wei and Zhao, 1995; Wei et al., 2000; Wang and Li, 2002). Although water deficit is unavoidable in the dry environment, studies have shown that judicious irrigation can to some extent counter the adverse effects on the deficit (Musick and Dusek, 1980; Misra and Chaudhary, 1985), especially when applied during the critical period (Fox and Rockström, 2003; Gajri and Prihar, 1983). Some researchers found that the timing of irrigation changes root density and distribution when the quantity of water is limited (Chaudary et al., 1980; Sharma, 1987). Zhang et al. (1999) applied game theory to this situation and concluded that a small root system is advantageous to higher yield.

In this paper, we compare the response of two

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Table 1. Grain yield, shoot biomass, root biomass and root/shoot ratio of two wheat cultivars.

Treatment	Grain yield ($kg \cdot m^{-2}$)	Shoot biomass ($kg \cdot m^{-2}$)	Root biomass ($g \cdot m^{-2}$)	Root biomass/Shoot biomass	Harvest index
NCW	0.62c	1.19c	249.8c	0.21b	0.52b
NPL	0.53d	1.30b	293.1b	0.23b	0.41c
ICW	0.79a	1.28b	275.9b	0.22b	0.62a
IPL	0.71b	1.39a	357.0a	0.26a	0.51b

Means in each water treatment followed by the same letter are not significantly different at $p \leq 0.05$. NCW: non-irrigated Changwu 135; NPL: non-irrigated Pingliang 40; ICW: irrigated Changwu 135; IPL, irrigated Pingliang 40.

sequence-replacement winter wheat (*Triticum aestivum* L.) cultivars to irrigation particularly with reference to the role of root biomass in increasing grain yield.

MATERIALS AND METHODS

Growth conditions and plant material

Experiments were conducted from September 2005 to June 2006 in Northwest China at the Changwu Agro-ecological Experiment Station of the Institute of Soil and Water Conservation in Wangdong Gully region of Loess Plateau, Changwu County, Shaanxi Province (35°12′N, 107°40′S, altitude 1200 m). The experimental site is a typical rainfed farming area in China characterized by wide seasonal variation in the weather. The mean annual precipitation (average of 44 years) is 576 mm and the mean annual temperature is 9.1□C. The dominant soil is a Calcic Kastanozemsand (pH 8.24, 6.5 g•kg-1 soil organic carbon, 0.8 g•kg-1 total nitrogen, 37 mg•kg-1 alkaline hydrolysis and 4.58 mg•kg-1 available phosphorus). The precipitation is unevenly distributed throughout the year, 55% being received in just three months (July-September). The actual precipitation from September 2005 to June 2006 was 547.9 and 326.9 mm was received during the growing season of winter wheat.

Two cultivars of winter wheat (T. aestivum L.) were selected from the rainfed farming area of Loess Plateau: Pingliang 40 (PL), the older of the two, and Changwu 135 (CW), which has replaced the former and is now the common wheat cultivar grown in the area.

Experiment methods

Plots 2 m × 2 m were laid out in randomized block design with three replications. Irrigation treatments comprised the check plot (no irrigation) and the irrigation plots, which received 120 mm of water in total but divided equally over three applications (40 mm of water each time): first when the plants were at the jointing stage (3 April 2006), then at the booting stage (21 April 2006), and finally at the flowering stage (20th May 2006). Irrigated plots (I) were located 50 m away from the control plot (N) to eliminate the possibility of the plot receiving any water from underground through percolation from the irrigated plots. Within each irrigation treatments, the two cultivars were compared. Seeds were sown on 20 September 2005 and the seedlings were planted 100 to a row oriented east-west with rows 20 cm apart, giving a plant density of 600,000 seedlings ha–1. Extra seedlings were removed until the 3-leaf stage to maintain a population of 900 plants in each plot.

Thus the four subpopulations in the experiment were as follows: irrigated Changwu 135 (ICW), irrigated Pingliang 40 (IPL), non-irrigated Changwu 135 (NCW), and non-irrigated Pingliang 40 (NPL).

Measurements

Yield and shoot biomass were measured at maturity. The plants were harvested manually. Samples were oven-dried at 105°C for 10 min and then at 75°C for 24 h and weighed in an electronic balance (accuracy = ± 1 mg). Root biomass was measured at the flowering stage by carefully collecting the roots from six layers of soil up to a depth of 1 m: two top layers each 10 cm deep, followed by four more, each 20 cm deep. The soil was washed and the roots collected on a fine nylon nets (400 pores per square cm). After that, the roots were washed in clear water, all the debris was removed, and the root biomass was oven-dried at 105°C for 10 min and then at 75°C for 24 h and weighted. Water content of the deeper layers (form 40 cm to 2 m at 20 intervals) of soil was determined by using a neutron probe (CNC-503DR, Beijing HeAn Company, China), whereas that of the surface layer (0 - 40 cm) was measured by weighing both freshly collected and oven-dry soil samples. Every plot was sampled three times.

The results were analyzed by running MultiCompare at the 0.05 confidence level. Harvest index (HI) = yield (kg.m-2)/shoot biomass (kg.m-2). Water use efficiency (WUE) (kg.mm-1hm-2) = yield per unit area (kg.hm-2)/water consumption (mm). Irrigation water use efficiency (IWUE) (kg.mm-1hm-2) = increased yield per unit area by irrigation (kg.hm-2)/amount of supplemental irrigation (mm) (Cassel and Edwards, 1985).

RESULTS

Effects of limited irrigation on yield and biomass accumulation

Table 1 shows that yield of CW was significantly higher than that of PL both with and without irrigation. Irrigation increased the yields greatly, by 0.17 kg.m-2 in CW and 0.18 kg.m-2 in PL. Shoot biomass in PL are was much more than that in CW, and the difference widened from 0.11 kg.m-2 in non-irrigated plots to 0.19 kg.m-2 in the irrigated plots. The pattern was similar in the case of root biomass: irrigation increased it significantly, by 26.1 g.m-2 in CW and 63.9 g.m-2 in PL, although shoot: root ratio did not change appreciably because of irrigation. Irrigation also greatly increased the HI, its value being higher in CW. The results show that PL deploys the nutrients more for the growth of roots and shoots than for grains, leading to lower yield.

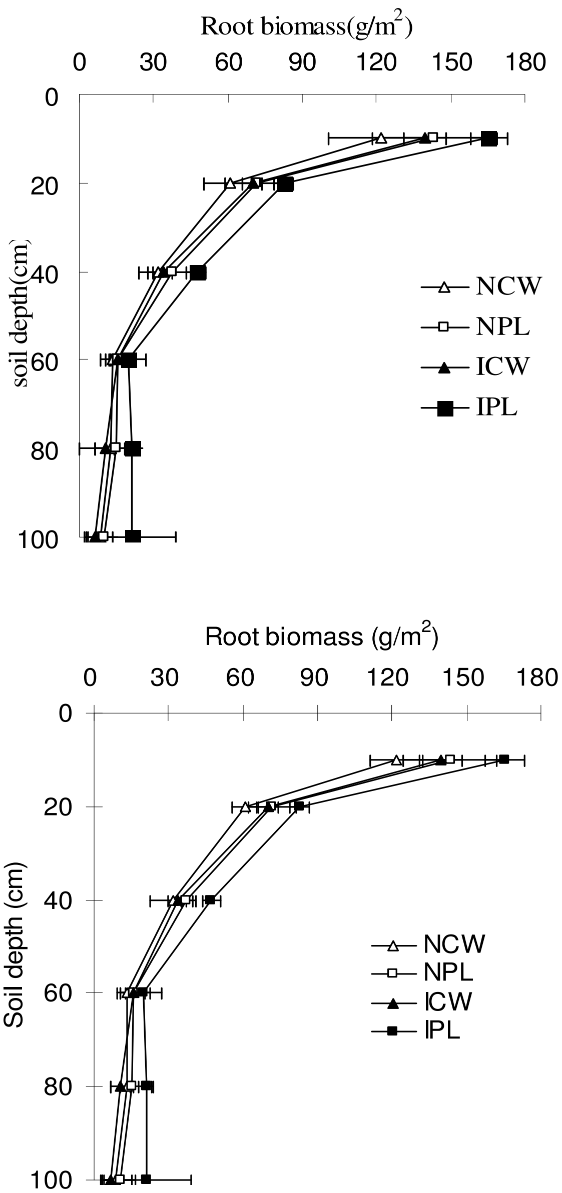

Figure 1. Distribution if roots of the two cultivars in different soil layers (%). Horizontal bars represent standard deviation (SD).

Root distribution in soil layers

The distribution of root biomass in the rhizosphere is shown in Figure 1. The treatments changed the root distribution in different soil layers, irrigation inducing the roots to penetrate deeper and spread wider. Root biomass in every layer was higher in PL and in the top layer (0 – 20 cm); irrigation widened the gap between the two cultivars (32.1 g.m–2 without irrigation and 38.6 g.m–2 with irrigation). In PL, irrigation greatly increased root biomass in all the soil layers whereas in CW, in deeper layers, root biomass was smaller with irrigation than without.

Water consumption and water use efficiency of limited irrigation of two cultivars

Water consumption and WUE were different in different treatments (Table 2). In non-irrigated plots, water consumption of PL was significantly more than that of CW but WUE was lower because of lower yield. For the same amount of water consumed, PL produced smaller amount of root biomass than CW, which showed strong root vitality. Although irrigation greatly increased water consumption and WUE of winter wheat, irrigated crops were less efficient than non-irrigated crops in using water to produce roots, which shows that lack of irrigation can stimulate root production, the difference widened from 0.03 mm.g -1m-2 in CW to 0.15 mm.g-1m-2 in PL. PL, which produced greater root biomass, had the highest irrigation water use efficiency (IWUE). IWUE/WUE of CW was below unity, which showed under compensation, whereas that of PL was greater than unity, which showed overcompensation, thereby indicating that irrigation affects water absorption and changes yields and WUE.

The relationships among yield, water use efficiencies and water consumption in different treatments

Water consumption was positively related to root biomass, and the line representing this relationship was steeply sloped (Figure 2). Under non-irrigated conditions, water consumption was negatively related to WUE and yield, but irrigation changed the relationship to a positive one. Irrespective of irrigation, yield and WUE were significantly and positively related, and unit increase in WUE led to greater increase in yield in the non-irrigated crop than in the irrigated crop.

DISCUSSION

Water is one of the most important factors that limit crop growth. The plant's response can be studied both at the level of the individual plant (competition with other plants) and at the population level (effect on total yield). Wheat is reported not to utilize water from deeper layers of soil on Loess Plateau (Zhang et al., 1995). Our experiments reported here show that root biomass of both the cultivars was greater in the irrigated crop than in the non-irrigated crop, and the increase occurred more or less throughout all the layers of soil, especially in PL. Irrigation therefore seems to benefit root growth. In the deeper layers (below 60 cm), root biomass of irrigated PL was greater by 20.55 g.m–2 than that of non-irrigated PL, which suggests that more vigorous root growth enables the plant to tap water from greater depths.

In a water-limited environment, there is an inevitable trade-off between investment in roots to increase water supply and reproductive growth (Manuela et al., 2003).

Table 2. Water consumption, WUE and IWUE of two cultivars under different treatments.

Treatments	Water consumption (mm)	WUE ($kg\cdot hm^{-2}\cdot mm$)	IWUE ($kg\cdot hm^{-2}\cdot mm$)	WC/RB ($mm\cdot g\cdot m^{-2}$)	IWUE/WUE
NCW	457.44d	13.63b	-	1.83a	-
NPL	463.70c	11.52c	-	1.58b	-
ICW	496.20b	15.89a	13.71b	1.80a	0.86b
IPL	511.95a	13.85b	14.45a	1.43c	1.04a

WC/RB: water consumption/root biomass. Means in each water treatment followed by the same letter are not significantly different at p ≤ 0.05. **Other abbreviations** are the same as in Table 1.

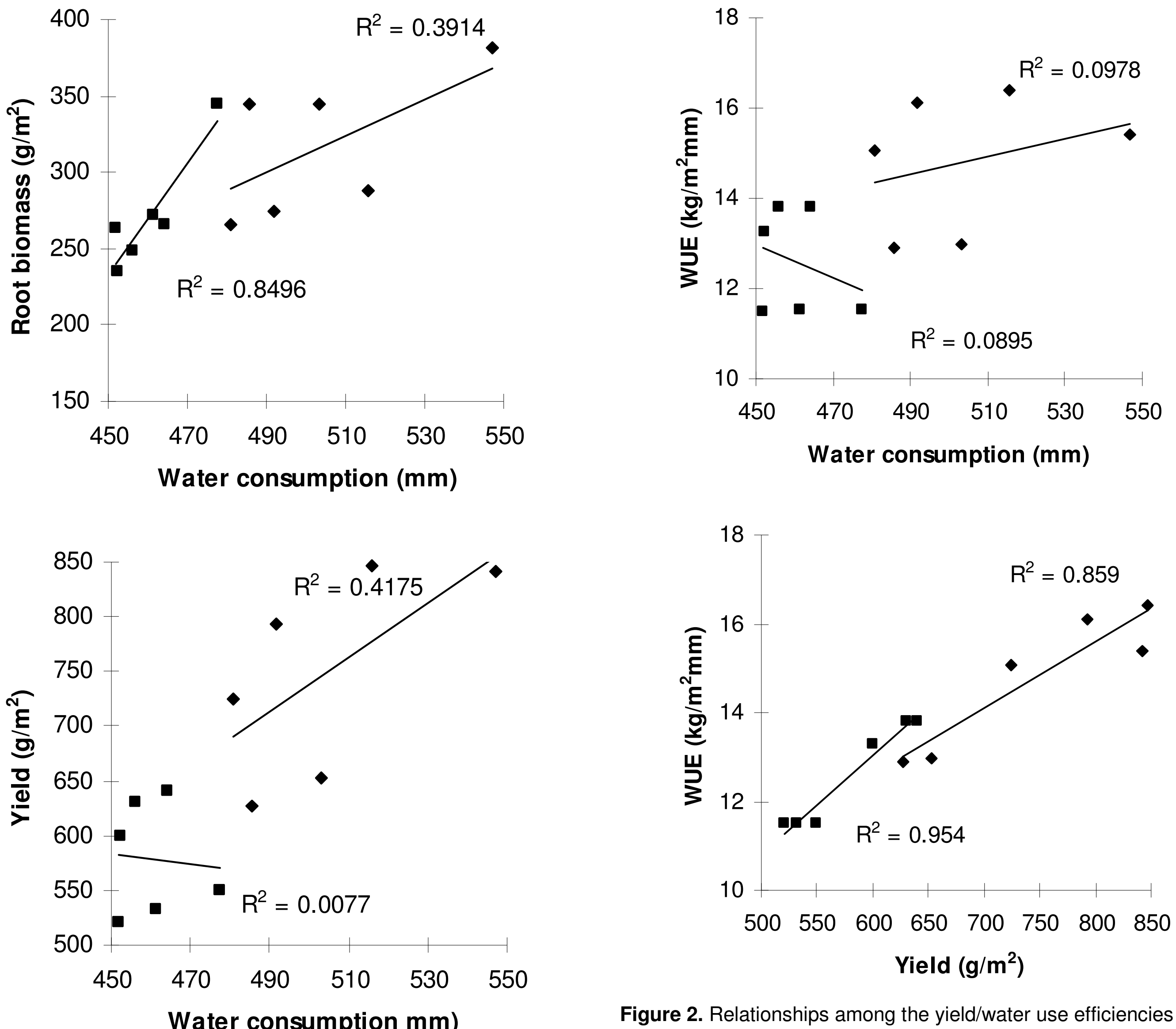

Figure 2. Relationships among the yield/water use efficiencies and total water consumption. All points 3-plots means (n = 6) with linear trend line shown. Irrigation treatments/non-irrigated treatments.

Root biomass and its distribution patterns under different water regimes affected shoot growth. Under non-irrigated conditions, CW had higher HI and lower shoot and root biomass, which indicates that more dry matter, was transported to reproductive organs, resulting in higher yield than that from PL. Under irrigation too, CW produced greater yield, and the differences between the two cultivars decreased. PL thus appears to be more efficient in exploiting available water.

Wheat yield is a function of WUE and HI (Bazzaz, 2000; Zhang et al., 2000), and a compensatory effect of water deficit is reported by many researchers. The compensatory effect is considered to take the form of overcompensation when IWUE/WUE is greater than unity, of undercompensation when lower than unity, and neutral when equal to unity (Gao et al., 1995; Shi et al., 2000). CW consumed more water than PL did to produce the same quantity of root biomass; however, CW used irrigation less efficiently, as evident from its lower IWUE and lower compensation.

In conclusion, between the two winter wheat cultivars with similar growth characters, Changwu 135 had a smaller root system and consumed more water to produce one unit of root biomass. Although absolute grain yield is proportional to water consumption, cultivars with greater WUE, which appears to be associated with a smaller root system and higher harvest index under both irrigated and non-irrigated conditions, will be useful in wheat breeding.

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