The wheat yields and water-use efficiency in the Loess Plateau: straw mulch and irrigation effects

Yilong Huang, Liding Chen^{*}, Bojie Fu, Zhilin Huang, Jie Gong

Key Lab of Systems Ecology, Research Center for Eco-Environmental Sciences,
Chinese Academy of Sciences, P.O. Box 2871, Beijing 100085, China

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Abstract

The yield of spring wheat (*Triticum aestivum* L.), one of the major crops planted in the Loess Plateau, China, is mainly affected by available water. Straw mulch and irrigation are efficient ways of influencing wheat yield and water-use efficiency. To develop better semiarid crop and water management practices, a 13-year experiment in spring wheat monoculture was conducted at the Dingxi Soil and Water Conservation Institute of the Loess Plateau. The influence of rainfall during the growing season (March–July) on yields of rain-fed wheat was studied for 13 years (1982–1992 and 1997–1998). The influence of straw mulch and irrigation on wheat yield, and water-use efficiency, was studied for 2 years (1997–1998). We found that growing season rainfall had a significant ($P < 0.05$) influence on biomass and grain yield of spring wheat in rain-fed conditions during the 13 years. Both biomass and grain yield were very low and varied significantly due to the low and significant variability of growing season rainfall. Straw mulch increased wheat yields significantly during both dry (1997) and wet (1998) years. It increased biomass and grain yield by 37 and 52%, respectively, in 1997, and by 20 and 26%, respectively, in 1998. Straw mulch also significantly decreased evapotranspiration ($P < 0.05$), soil water depletion ($P < 0.01$), and increased water-use efficiency ($P < 0.001$). Biomass and grain yield both increased ($P < 0.01$ or $P < 0.001$) with increasing irrigation in 1997 and 1998. The three irrigation levels increased the biomass yield from 34 to 66% in 1997, and from 34 to 77% in 1998. The irrigation levels also increased grain yield from 53 to 102% in 1997, and from 22 to 57% in 1998. Water-use efficiency for biomass and grain yield also increased with increasing irrigation. On the other hand, irrigation water-use efficiency for biomass and grain yield decreased with increasing irrigation. The results suggest that higher crop

^{*} Corresponding author. Tel.: +86 10 62943840; fax: +86 10 62943840.
E-mail address: liding@mail.rcees.ac.cn (L. Chen).

yields in the semiarid Loess Plateau may be achieved by using irrigation, or a proper combination of straw mulch and irrigation.

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1. Introduction

The semiarid Loess Plateau is the major region of rain-fed agriculture of China with a production area of about 6.6 million ha. Spring wheat (*Triticum aestivum* L.) is one of the major crops, accounting for 30–40% of the total agricultural area (Yang et al., 1999). Traditional rain-fed agriculture has a long history in this region; however, spring wheat grain yield is less than 2000 kg ha⁻¹, and as low as 1500 kg ha⁻¹ in some areas due to water deficit, which is one-third of the national average. Consequently, there is great potential of increasing crop yield, if the water is available. Development of effective semiarid crop and water management practices plus improvement of crop yield in the Loess Plateau region are important since it would improve the food security and lead to sustainable development in the 21st century.

The main environmental factors responsible for diminished crop yields are lacked timely precipitation plus temperature and salinity stress (Boyer, 1982). In the Loess Plateau region, however, crop yield is mainly affected by the availability of water (Yang et al., 1999; Yan and Wang, 2001). The available water is limited by stored soil water, summer dominant precipitation and its significant variability in the Loess Plateau. In addition, water-use efficiency (WUE) also influences the crop yield given constant water conditions. Thus, crop yields can be improved by increasing available water and WUE in this region.

Several soil and crop management practices can increase the crop yields and WUE (Ludlow and Muchow, 1990). Fertilization can increase the use of stored soil water and increase crop yield in semiarid regions; however, in the long term, increasing fertilization may not be sufficient to maintain higher yields (Huang et al., 2003). Plastic or straw mulch is an efficient practice, which can alter water distribution between soil evaporation and plant transpiration (Raeini-Sarjaz and Barthakur, 1997). Otherwise, mulches modify the microclimate and growing condition of crops (Albright et al., 1989). It is known that water shortage restricts crop productivity and the purpose of irrigation is to minimize crop water stress and to achieve maximum yield (Wang et al., 2001). However, maximizing yield should not be the sole objective; other constraints (e.g. water availability, irrigation cost, etc.) should also be considered, especially in the Loess Plateau. The response of crop yields to irrigation has been studied extensively (Skogerboe et al., 1979). Hagan et al. (1967) asserted that excessive irrigation delays maturity, harvesting, encourages vine growth, and decreases yield. To achieve better control and management of water in crop production and irrigation efficiency, the irrigation should match crop requirements (Maggio et al., 2002; Bauerle et al., 2002).

There has been an ongoing effort to understand the relationships between crop yield, soil water balance, and water-use efficiency in order to develop better semiarid crop and water management practices (Halitligil et al., 2000; Wiedenfeld, 2000). These studies are,

however, very limited, especially in the semiarid Loess Plateau. The objectives of this study are: (1) to determine the relationship between wheat yields and growing season rainfall (March–July) under rain-fed conditions; (2) to determine the influence of straw mulch and irrigation on biomass and grain yield; and (3) to determine the influence of straw mulch and irrigation on water balance and water-use efficiency.

2. The study area and methodology

2.1. Study area

Field experiments were carried out during the 1982–1992 and 1997–1998 growing seasons at the Dingxi Soil and Water Conservation Institute farm (1895 m a.s.l., 35°33'N latitude and 104°35'E longitude), situated on the west part of the Loess Plateau in the center of the Gansu Province of China (Fig. 1).

The region has a semiarid continental climate with an average annual temperature of 6.3 °C. Monthly mean temperatures range from 34.3 °C in July to –27 °C in January. The average annual precipitation is 426.6 mm (Fig. 2) with high annual variation. Almost 60% of the rainfall occurs from July to September. Potential evaporation averages 1445 mm, with monthly average evaporation ranging from 20 to 80 mm in the winter months and from 150 to 270 mm in the summer months. There are 141 frost-free days and an average of 2409 h of sunshine each year. The growing season for wheat is from late-March to late-July. The total growing season is almost 125 days.

The microclimate station, near the experimental sites, recorded data on rainfall, temperature, potential evaporation, and radiation during the study period.

The soil, developing on wind-accumulated loess parent material, is 40–60 m deep, on average. The predominant soil in the region is loess with clay ranging from 33.12 to 42.17%. Organic matter ranges from 0.37 to 1.34%, and soil density is from 1.09 to 1.36 g cm^{–3}. It is weakly resistant to erosion (Fu, 1989; Fu and Gulick, 1994). Groundwater level remained at a depth of about 100 m below soil surface for the duration of the study.

2.2. Field experimental layout

The experimental design was in rain-fed conditions (no straw mulch and irrigation) in 1982–1992. The experiment had four replicates; each plot measuring 5 m × 10 m.

The site was divided into plots of 4 m × 5 m, which were separated by waterproof concrete walls buried 200 cm deep from soil surface, in the experiments of 1997 and 1998. The experiment had five treatments (Table 1) involving a combination of: (1) straw mulch, (2) no straw mulch, (3) irrigation, and (4) no irrigation. Each treatment had four replicates in a randomized design. In the experiment, the straw mulch material was wheat straw and the irrigation type was drip-irrigation. The straw mulch treatment (treatment T₂) used wheat straw at a coverage of 3000 kg ha^{–1} in 1997 and 1998. In May and June of 1997, T₃, T₄ and T₅ received irrigation of 15, 30 and 45 mm (besides rainfall), respectively, while in June 1998, irrigation was 10, 20 and 30 mm (besides rainfall), respectively (Table 1). Treatment T₁ was the control (no straw mulch or irrigation).

Fig. 1. Location of the experimental site (Dingxi).

Fig. 2. Annual and growing season rainfall (March–July) in 1982–1998.

The spring wheat (*T. aestivum* L.) variety was Dingxi 82579 with a rooting system which may extend to a maximum of 200 cm in the soil under field conditions. The wheat crop was sown at a rate of 180 kg ha^{-1} , which is common practice in the region.

2.3. Measurements

In the wet season of 1998, soil bulk density was determined at different depths on bare plots of the experimental site. At that point in time, the soil profile on these plots was well wetted and the measured bulk density was at its minimum (Gardner et al., 1990). Bulk density was measured at 20 cm interval to a depth of 200 cm. Fig. 3 shows the soil bulk density profile at depths from 0 to 200 cm.

Soil was removed using a drill and soil water content measured from 0 to 200 cm in 20 cm intervals. Each plot has four random locations within a 1-m diameter circle and the mean soil water content was used as the final value for the plot. During the growing season, soil water content was measured at interval of 3 weeks. In addition, the soil water also measured before sowing and at the end of harvest.

At the end of the growing season, 1 m^2 quadrates of wheat were harvested by cutting at soil surface level, dried in an oven (70°C , 48 h), and weighed. After separating the plants into straw (leaves and stem) and ears, grains were trashed from the ears and weighed. Final aboveground biomass yield and grain yield were obtained by harvesting four replicates of each treatment.

Table 1
Experimental treatments of 1997 and 1998

Year	Treatments				
	T ₁	T ₂	T ₃	T ₄	T ₅
1997	No straw mulch	Straw mulch	No straw mulch	No straw mulch	No straw mulch
	No irrigation	No irrigation	Irrigation = 15 mm	Irrigation = 30 mm	Irrigation = 45 mm
1998	No straw mulch	Straw mulch	No straw mulch	No straw mulch	No straw mulch
	No irrigation	No irrigation	Irrigation = 10 mm	Irrigation = 20 mm	Irrigation = 30 mm

Fig. 3. Minimum soil bulk density profile at depth from 0 to 200 cm.

2.4. Analysis methods

2.4.1. Soil water balance

Accumulated evapotranspiration (ET) was calculated using the water balance equation:

$$ET = (P + I + C) - (R + D) - \Delta S \quad (1)$$

where P is precipitation, I is irrigation, C is upward flow into the root zone, R is surface runoff, D is downward drainage out of the root zone, and ΔS is the change in stored soil water of the soil profile.

Since the experimental field was terraced, and located in the semiarid Loess Plateau, surface runoff was ignored. The groundwater table was very low, so the upward flow into the root zone was negligible. Consequently, the soil water balance equation was reduced to

$$ET = (P + I) - \Delta S \quad (2)$$

Changes in soil water storage of the soil profile (ΔS in mm) were calculated as (Yule, 1984):

$$\Delta S = \sum_{i=1}^n \frac{\Delta w_i \times \rho_{\min,i} \times z_{\text{ref}}}{\rho_w} \quad (3)$$

where Δw_i is the difference in gravimetric moisture content between any two sampling times from the i th depth increment (g g^{-1}), $\rho_{\min,i}$ the minimum value of the bulk density (g cm^{-3}) for depth increment i , z_{ref} the depth (cm) of the soil sampling interval at minimum bulk density, ρ_w the density of water, and n the number of depth increments, each of length z_{ref} .

2.4.2. Water-use efficiency

Water-use efficiency was calculated as (Hussain and Al-Jaloud, 1995):

$$\text{WUE}_B = \frac{BY}{ET} \quad (4)$$

or

$$WUE_G = \frac{GY}{ET} \quad (5)$$

where WUE_B is water-use efficiency for the biomass yield ($\text{kg ha}^{-1} \text{mm}^{-1}$), WUE_G the water-use efficiency for the grain yield ($\text{kg ha}^{-1} \text{mm}^{-1}$), BY the biomass yield (kg ha^{-1}), GY the grain yield, and ET the total cumulative evapotranspiration (mm) over the growing season.

Irrigation water-use efficiency (IWUE) can be calculated as (Li et al., 1995):

$$IWUE_B = \frac{IBY}{IW} \quad (6)$$

or

$$IWUE_G = \frac{IGY}{IW} \quad (7)$$

where $IWUE_B$ is the irrigation water-use efficiency for the biomass yield ($\text{kg ha}^{-1} \text{mm}^{-1}$), $IWUE_G$ the irrigation water-use efficiency for the grain yield ($\text{kg ha}^{-1} \text{mm}^{-1}$), IBY the improved biomass yield (kg ha^{-1}), IGY the improved grain yield and IW the total irrigation water (mm) over the growing season.

2.5. Statistical method

Analysis of variance (ANOVA) was used to test the difference in biomass yield, grain yield and water-use efficiency among different treatments. Mean comparisons were made by the LSD (the least significant difference) method with $P < 0.05$. The analyses were conducted using the SPSS program (SPSS Inc., 1993).

3. Results and analysis

3.1. Climate conditions for crop growth

Annual rainfall was significantly variable in this region. Fig. 2 shows the annual and growing season rainfall between 1982 and 1998. Over 17 years (1982–1998), the annual rainfall varied from 253.0 to 539.9 mm. The average annual rainfall and standard deviation was 426.6 ± 74.8 mm. The coefficient of variation in annual rainfall was 20%. Over the 17 years, 1982 and 1997 were very dry years, while 1983–1985 and 1990 were wet years.

The growing season rainfall also showed significant variability in this region. Over 17 years (1982–1998), the growing season rainfall varied from 98.2 to 300.6 mm. The average growing season rainfall and standard deviation was 229.8 ± 68.8 mm. The coefficient of variation in growing season rainfall was 30%.

The distribution of rainfall throughout the growing season varied greatly in 1982–1998 (Fig. 4). The early and middle stages of the growing period in 1997 were very dry. This is not uncommon for the semiarid region of the Loess Plateau (Yan and Wang, 2001). Compared to 1997, 1998 was a wet year.

Fig. 4. Distribution of rainfall in the growing season of 1982–1998 at Dingxi City.

3.2. Biomass and grain yield

Fig. 5 shows the biomass and grain yield of rain-fed wheat for 1982–1992 and 1997–1998. Over the 13 years, the biomass and grain yield were 5706 ± 1893 and $1633 \pm 643 \text{ kg ha}^{-1}$ (mean and standard deviation), respectively. Biomass and grain yield both showed significant variability. The coefficients of variation were 33.2 and 39.4% in biomass and grain yield, respectively. The highest wheat yield occurred in 1991, when the biomass and grain yield reached 8325 and 2605 kg ha^{-1} , respectively. The lowest yield occurred in 1992: biomass and grain yield being 2537 and 627 kg ha^{-1} , respectively. The biomass and grain yield of 1991 were 4.15 and 3.28 times higher than those of 1992.

Fig. 6 shows the relationship between average biomass yield and growing season rainfall for the period 1982–1992 and 1997–1998. The relationship between average biomass wheat yield and growing season rainfall can be described with an exponential model, which was consistent with the findings of Mu et al. (1992). The regression equation was $y = 362.9 e^{0.0061x}$, with $R^2 = 0.5987$ ($P < 0.05$).

Fig. 7 shows the relationship between average grain yield and growing season rainfall for the period 1982–1992 and 1997–1998. The relationship between average grain yield and growing season rainfall can also be described with an exponential model. The regression equation was $y = 1767 e^{0.0047x}$, with $R^2 = 0.6602$ ($P < 0.05$).

Fig. 5. Biomass yield and grain yield of wheat in 1982–1992 and 1997–1998.

Fig. 6. Relationship between biomass yield and growing season rainfall (March–July).

These results indicate that rainfall in the growing period has significant influence on biomass and grain yield under rain-fed condition. In addition, distribution of growing season rainfall also influenced biomass and grain yield due to the different water demands for different growing periods of crops (Li and Shu, 1991). For example, the biomass and grain yield in 1982 were 1.45 and 1.5 times higher than those of 1992, but the growing season rainfall of 1982 was only 0.56 times as that of 1992.

Table 2 shows the biomass and grain yield of spring wheat under different treatments in 1997 and 1998. The biomass and grain yield in treatment T_1 was 7120 ± 310 and $2061 \pm 99 \text{ kg ha}^{-1}$, respectively, in 1998, which were significantly higher ($P < 0.01$) than the same treatment in 1997. The biomass and grain yield in treatment T_2 was, respectively, 37 and 52% higher ($P < 0.01$) than treatment T_1 in 1997. The biomass and grain yield in treatment T_2 was, respectively, 20 and 26% higher ($P < 0.01$) than treatment T_1 in 1998. This indicates that straw mulch has a significant influence on biomass and grain yield in the 2 years. Because straw mulch can increase soil water storage, decrease soil evaporation, and increase plant transpiration (Raeini-Sarjaz and Barthakur, 1997), it can regulate the available water to suit the water demand of the crop and satisfy the key water demand period (Zhao et al., 1996). The result was consistent with the studies of Rudich

Fig. 7. Relationship between grain yield and growing season rainfall (March–July).

Table 2

Biomass yield and grain yield in 1997 and 1998 for different treatments

Year	Yield (kg ha ⁻¹)	Treatments				
		T ₁ ^a	T ₂	T ₃	T ₄	T ₅
1997	Biomass	3356 ± 390	4584 ± 350 ^{**}	4500 ± 364 ^{**}	4903 ± 510 ^{***}	5556 ± 493 ^{***}
	Grain	818 ± 125	1240 ± 84 ^{**}	1250 ± 104 ^{**}	1384 ± 156 ^{***}	1650 ± 131 ^{***}
1998	Biomass	7120 ± 310	8563 ± 439 ^{**}	9546 ± 480 ^{***}	10970 ± 570 ^{***}	12580 ± 520 ^{***}
	Grain	2061 ± 199	2601 ± 203 ^{**}	2520 ± 195 ^{**}	2883 ± 228 ^{***}	3230 ± 213 ^{***}

^a Details of treatments are shown in Table 1.^{**} Statistical significance at $P < 0.01$ level, when compared to the T₁ treatment within the same row and same year.^{***} Statistical significance at $P < 0.001$ level, when compared to the T₁ treatment within the same row and same year.

et al. (1977), Pill and Lambeth (1980), Albright et al. (1989), Zhao et al. (1996), and Raeini-Sarjaz and Barthakur (1997), who reported significantly increased crop yields through mulching.

In 1997 and 1998, biomass and grain yield both increased with increasing irrigation. The three irrigation levels (Table 1) increased biomass yield from 34 to 66% in 1997 and from 34 to 77% in 1998. The three irrigation levels increased grain yield from 53 to 102% in 1997 and from 22 to 57% in 1998. Multiple comparisons revealed that biomass and grain yield under treatments T₃, T₄ and T₅ were significantly ($P < 0.01$ or $P < 0.001$) higher compared to that of treatment T₁. The results were similar to the findings of Hagan et al. (1967) and Gajri et al. (1997), who noted rational irrigation significantly increased biomass and grain yield.

3.3. Evapotranspiration and soil water depletion

Table 3 shows the influence of straw mulch and irrigation on evapotranspiration and soil water depletion in 1997 and 1998. The wheat evapotranspiration of T₁ reached 369.6 mm in 1998. It was 130.4 mm higher than that of T₁ in 1997. This indicates that growing season rainfall significantly influences the evapotranspiration of spring wheat.

Water consumption in treatments T₁ and T₂ were supplied by rainfall and soil water. The evapotranspiration for T₁ was 19.7 and 14.3 mm higher ($P < 0.05$ or $P < 0.01$) than T₂ for 1997 and 1998, respectively. Straw mulch also significantly ($P < 0.001$) decreased soil water depletion in the 2 years. This was mainly due to the reduction of water loss through evaporation (Raeini-Sarjaz and Barthakur, 1997).

The water consumption of treatments T₃, T₄ and T₅ were supplied by rainfall, soil water and irrigation in 1997 and 1998 (Table 3). Compared with treatment T₁, treatments T₄ and T₅ significantly ($P < 0.01$ or $P < 0.001$) increased evapotranspiration and decreased soil water depletion in 1997. Compared with treatment T₁, treatments T₃ and T₄ significantly ($P < 0.01$ or $P < 0.001$) decreased evapotranspiration and soil water depletion in 1998. This demonstrates that irrigation changed the component of soil water balance and water cycle of the soil–crop–atmosphere system, which was consistent with the findings of Li et al. (1992).

Table 3

Evapotranspiration and soil water depletion as influenced by straw mulch and irrigation in 1997 and 1998

Year	Factor	Treatments				
		T ₁ ^a	T ₂	T ₃	T ₄	T ₅
1997	Evapotranspiration	239.2	219.5 ^{**}	250.6 NS ^b	260.8 ^{**}	271.1 ^{***}
	Soil water depletion	58.1	38.4 ^{***}	54.5 NS ^b	49.7 ^{***}	45.0 ^{***}
1998	Evapotranspiration	369.6	355.3 [*]	349.9 ^{**}	338.8 ^{***}	364.4 NS ^b
	Soil water depletion	91.2	76.9 ^{***}	71.5 ^{***}	60.4 ^{***}	85.7 NS ^b

^a Details of treatments are shown in Table 1.^b Statistical significance at $P > 0.05$ level, when compared to the T₁ treatment within the same row and same year.^{*} Statistical significance at $P < 0.05$ level, when compared to the T₁ treatment within the same row and same year.^{**} Statistical significance at $P < 0.01$ level, when compared to the T₁ treatment within the same row and same year.^{***} Statistical significance at $P < 0.001$ level, when compared to the T₁ treatment within the same row and same year.

3.4. Water-use efficiency

Table 4 shows the water-use efficiency for biomass and grain yield (WUE_B and WUE_G) of the five treatments in 1997 and 1998. In 1997, the WUE_G and WUE_B reached 5.65 and 19.16 kg ha⁻¹ mm⁻¹, respectively, which were significantly ($P < 0.01$) higher than T₁. In 1998, WUE_G and WUE_B of treatment T₂ reached 7.32 and 24.10 kg ha⁻¹ mm⁻¹, respectively, which were significantly ($P < 0.01$) higher than treatment T₁. This indicates that straw mulch significantly influences WUE_G and WUE_B in 1997 and 1998, which is in agreement with the results of Albright et al. (1989), Zhao et al. (1996), and Raeini-Sarjaz and Barthakur (1997).

Multiple comparisons revealed that WUE_G and WUE_B of treatments T₃, T₄ and T₅ were significantly ($P < 0.01$ or $P < 0.001$) higher than in treatment T₁ in 1997 and 1998. Both WUE_G and WUE_B increased with increasing irrigation in the 2 years. This shows that

Table 4

The water-use efficiency for grain and biomass yield as influenced by straw mulch and irrigation in 1997 and 1998

Year	WUE (kg ha ⁻¹ mm ⁻¹)	Treatments				
		T ₁ ^a	T ₂	T ₃	T ₄	T ₅
1997	WUE _G	3.41	5.65 ^{**}	4.99 ^{**}	5.31 ^{**}	6.09 ^{***}
	WUE _B	14.03	19.16 ^{**}	17.96 ^{**}	18.80 ^{**}	20.49 ^{***}
1998	WUE _G	5.58	7.32 ^{**}	7.20 ^{**}	8.51 ^{***}	8.87 ^{***}
	WUE _B	19.26	24.10 [*]	27.28 ^{***}	32.38 ^{***}	34.55 ^{***}

WUE_G: water-use efficiency for grain yield; WUE_B: water-use efficiency for biomass yield.^a Details of treatments are shown in Table 1.^{**} Statistical significance at $P < 0.01$ level, when compared to the T₁ treatment within the same row and same year.^{***} Statistical significance at $P < 0.001$ level, when compared to the T₁ treatment within the same row and same year.

Table 5

Irrigation water-use efficiency for grain and biomass yield as influenced by irrigation in 1997 and 1998

Year	IWUE (kg ha ⁻¹ mm ⁻¹)	T ₃ ^a	T ₄	T ₅
1997	IWUE _G	28.87	18.90 ^{***}	18.51 ^{***}
	IWUE _B	76.27	51.57 ^{***}	48.89 ^{***}
1998	IWUE _G	45.90	41.10 NS ^b	38.97 [*]
	IWUE _B	242.60	192.5 ^{***}	182.00 ^{***}

IWUE_G: irrigation water-use efficiency for grain yield; IWUE_B: irrigation water-use efficiency for biomass yield.^a Details of treatments are shown in Table 1.^b Statistical significance at $P > 0.05$ level, when compared to the T₃ treatment within the same row and same year.^{*} Statistical significance at $P < 0.05$ level, when compared to the T₃ treatment within the same row and same year.^{***} Statistical significance at $P < 0.001$ level, when compared to the T₃ treatment within the same row and same year.

irrigation is an efficient measure, capable of decreasing water stress and significantly increasing WUE_G and WUE_B of crops, which is consistent with the findings of Rudich et al. (1977) and Hedge (1987).

Compared with treatment T₃, the irrigation water-use efficiency for biomass yield and grain yield (IWUE_B and IWUE_G) under the treatments T₄ and T₅ both decreased with irrigation in 1997 and 1998 (Table 5). Wheat in treatment T₃ had the highest IWUE_B and IWUE_G among the three irrigation levels. This result was consistent with the findings of Li et al. (1995) in the Loess Plateau, who reported that irrigation water-use efficiency significantly decreases with increasing irrigation. The reason is that the water need of crops is decreased with increased irrigation in the Loess Plateau (Li et al., 1995).

4. Conclusions

In this study, the biomass and grain yield of spring wheat were very low and varied significantly under rain-fed conditions during the study period (1982–1992 and 1997–1998). In rain-fed agriculture, rainfall is the key factor that restricts crop yields and, hence, influences sustainable development in the Loess Plateau. However, straw mulch and irrigation effectively decrease the influence of rainfall on crop yields.

Straw mulch can both decrease evapotranspiration and soil water depletion, and increase water-use efficiency; thus, it significantly increased the wheat yields in 1997 and 1998. The wheat yields and water-use efficiency for the straw mulch treatment equaled to an irrigation of 15 mm in 1997 and 10 mm in 1998. The three irrigation levels all significantly increased the wheat yields in 1997 and 1998. Both biomass and grain yield increased with increased irrigation. Water-use efficiency for biomass and grain yields also increased with increased irrigation. On the other hand, irrigation water-use efficiency for biomass and grain decreased with increased irrigation.

Straw mulch could be widely employed in the region which is not irrigated due to its significant effect and its easy implementation. However, straw mulch can only decrease

water stress and increase wheat yields to a certain degree. Optimal irrigation can significantly increase wheat yields compared to those under straw mulch. Irrigation or a combination of irrigation and straw mulch may be the best option in achieving high crop yields and advancing the sustainable development of the agriculture in the region.

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References

- Albright, L.D., Wolfe, D., Novak, S., 1989. Modelling row straw mulch effects on microclimate and yield II. *J. Am. Soc. Hort. Sci.* 114, 569–578.
- Bauerle, W.L., Post, C.J., McLeod, M.F., 2002. Measurement and modeling of the transpiration of a temperate red maple container nursery. *Agric. For. Meteorol.* 114, 45–57.
- Boyer, J.S., 1982. Plant productivity and environment. *Science* 218, 443.
- Fu, B., 1989. Soil erosion and its control in the Loess Plateau of China. *Soil Use Manage.* 5, 76–82.
- Fu, B.J., Gulinkin, H., 1994. Land evaluation in area of severe erosion, the Loess Plateau of China. *Land Degrad. Rehabil.* 5 (1), 33–40.
- Gajri, P.R., Gill, K.S., Chaudhary, M.R., 1997. Irrigation of sunflower (*Helianthus annuus*) in relation to tillage and mulching. *Agric. Water Manage.* 34, 149–160.
- Gardner, E.A., Coughlan, K.J., Smith, G.D., 1990. Computation and use of bulk density in swelling soils. *Soil Tech.* 3, 343–349.
- Hagan, R.M., Howard, R.H., Talcoh, W.E., 1967. Irrigation of agricultural lands. *Am. Soc. Agron., USA* 680–681.
- Halitligil, M.B., Akin, A., Bilgin, N., 2000. Effect of nitrogen fertilization on yield and nitrogen and water use efficiencies of winter wheat (durum and bread) varieties grown under conditions found in central Anatolia. *Biol. Fertil. Soils* 31 (2), 175–182.
- Hedge, D.M., 1987. The effect of soil water potential method of irrigation, canopy temperature, yield and water use of radish. *Hort. Sci.* 62 (4), 507–511.
- Huang, M.B., Dang, T.H., Gillichand, J., 2003. Effect of increased fertilizer applications to wheat crop on soil–water depletion in the Loess Plateau, China. *Agric. Water Manage.* 58, 267–278.
- Hussain, G., Al-Jaloud, A.A., 1995. Effect of irrigation and nitrogen on water use efficiency of wheat in Saudi Arabia. *Agric. Water Manage.* 27, 143–153.
- Li, B.Q., Zhang, Y.Z., Zhao, J.Y., 1992. A study on transformation relation field soil moisture in different irrigation conditions. In: Xie, X.Q., Yu, F.N. (Eds.), *Study on Relationship Between Crops and Water*. China Press of Science and Technology, China, pp. 147–160 (in Chinese).
- Li, F.M., Zhao, S.L., Duan, S.S., 1995. The strategy for limited irrigation of spring wheat in semiarid Loess Plateau, China. *Chin. J. Appl. Ecol.* 6 (3), 259–264 (in Chinese).
- Li, Y., Shu, S., 1991. *A Comprehensive Research on High Efficient Eco-economic System in Wangdonggou Watershed of Changwu County*. Sci-Tech Document Press, Beijing, China.
- Ludlow, M.M., Muchow, R.C., 1990. A critical evaluation of traits for improving yields in water-limited environments. *Adv. Agron.* 43, 107–153.
- Maggio, A., Dalton, F.N., Piccinni, G., 2002. The effects of elevated carbon dioxide on static and dynamic indices for tomato salt tolerance. *Eur. J. Agron.* 16, 197–206.
- Mu, X.M., Chen, G.L., Guo, B.A., 1992. Ecological features and improving approaches of moisture in the spring wheat field on dryland. In: Xie, X.Q., Yu, F.N. (Eds.), *Study on Relationship between Crops and Water*. China Press of Science and Technology, China, pp. 52–61 (in Chinese).
- Pill, W.G., Lambeth, V.N., 1980. Effect of soil water regime and nitrogen form on blossom-end rot: yield relations and elemental composition of tomato. *J. Am. Soc. Hort. Sci.* 105 (5), 730–735.

- Raeini-Sarjaz, M., Barthakur, N.N., 1997. Water use efficiency and total dry matter production of bush bean under plastic straw mulchs. *Agric. For. Meteorol.* 87, 75–84.
- Rudich, J., Kalmar, D., Geizenberg, C., Harel, S., 1977. Low water tension in defined growth stages of processing tomato plant and their effect on yield and quality. *J. Hort. Sci.* 52, 391–399.
- Skogerboe, G.V., Hugh, J.W., Treat, B.J., 1979. Potential effects of irrigation practices on crop yields in Grand Valley. US Environ. Proc. Agency Tech. Ser. Pep. No. EPA600/2-79-149. US Government Printing Office, Washington, DC.
- SPSS Inc., 1977. SPSS for Windows Base System User's Guide Release 6.0. Marija J. Norusis/SPSS Inc.
- Wang, H.X., Zhang, L., Dawes, W.R., Liu, C.M., 2001. Improving water use efficiency of irrigated crops in the North China plain. *Agric. Water Manage.* 48, 151–167.
- Wiedenfeld, R.P., 2000. Water stress during different sugarcane growth periods on yield and response to N fertilization. *Agric. Water Manage.* 43 (2), 173–182.
- Yan, X., Wang, J., 2001. The responses and their physio-ecological bases of spring wheat to limited irrigation in Loess Plateau. *Acta Bot. Boreal. Occident. Sin.* 21 (4), 1–795 (in Chinese).
- Yang, F.K., Gao, S.M., He, B.L., 1999. Research the rainwater collection and water-saving irrigation in west Loess Plateau of Gansu Province, China. *Soil Water Conserv.* 5, 24–27 (in Chinese).
- Yule, D.F., 1984. Volumetric calculations in cracking clay soils. In: McGarity, J.W., Hoult, E.H., So, H.B. (Eds.), *Properties and Utilization of Cracking Clay Soils. Reviews in Rural Science*, vol. 5. University of New England, Armidale, NSW, Australia, pp. 136–140.
- Zhao, J.B., Mei, X.R., Xue, J.H., 1996. The effect of straw mulch on crop water use efficiency in dryland. *Sci. Agric. Sin.* 29 (2), 59–66 (in Chinese).