7

Effects of Limited Irrigation on Yield and Water Use Efficiency of Winter Wheat on the Loess Plateau of China

Shaozhong Kang,[*] Lu Zhang,[‡] Yinli Liang[†] and Huanjie Cai[*]

Abstract

Crop yields on the Loess Plateau of China are mainly limited by available water. A field experiment was conducted for winter wheat (*Triticum aestivum* L.) during 1995–98 to evaluate the effects of limited irrigation on crop yield and water use efficiency (WUE). The results showed that evapotranspiration, grain yield, biomass, WUE and harvest index depended on soil water content. The effect of irrigation on yield varied considerably due to differences in soil moisture content and irrigation scheduling between seasons. High moisture treatment gave the greatest evapotranspiration and biomass, but did not produce the highest grain yield and gave relatively low WUE. Appropriately controlled soil water content could improve grain yield, WUE and harvest index. Consistently high values of grain yield, WUE, and harvest index were obtained under conditions of mild water deficit at the seedling and start of regrowth to stem-elongation stages, with further soil drying at the physiological maturity to harvest stage. We therefore suggest that for winter wheat periods of mild soil drying in the early vegetative growth period together with severe soil drying in the maturity stage is an optimum limited-irrigation regime in this region.

黄土高原粮食产量很大程度上受水分供应的制约。在1995到1998年进行了冬小麦田间试验，以评价有限灌溉对作物产量和水分利用效率（WUE）的影响。结果显示土壤水分含量决定了水分蒸发量、粮食产量、生物量、WUE和收获指数。灌溉对产量的影响因不同季节不同的土壤水分含量和灌溉方式而有相当大的变化。水分多产生的蒸发多，生物量多，但是产量不是最

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多，WUE 相对较低。适当控制土壤水份含量能提高产量、WUE 和收获指数。在出苗、拔节初期轻度的水分亏缺，生理成熟至收获期再进一步的缺水可以获得高产量、高 WUE 和高收获指数。因此对于本地区的冬小麦而言，保持土壤在植物生长初期的轻度干燥和成熟期的严重干燥是一个合理的有限灌溉方式。

LIMITED irrigation means that the soil water deficit is controlled at certain stages of crop growth, a practice that has become more important in recent years in areas where water resources are limited. Water use efficiency (WUE) is defined here as the ratio between grain yield and total evapotranspiration during the growing season. For other definitions, see the review of WUE in Chapter 4. Studies on the effects of limited irrigation show that crop yield can be largely maintained and product quality can sometimes be improved while substantially reducing irrigation volume (Li 1982; Shan 1983; Fapohunda et al. 1984; Sharma et al. 1986; Singh et al. 1991; Zhang et al. 1999).

These studies also show that the relationship between crop yield and seasonal evapotranspiration can take different forms and that the empirical coefficients vary with climate, crop type and variety, irrigation, soil texture, fertiliser and tillage methods. The relationship between WUE and evapotranspiration or irrigation water use also shows large spatial and temporal variability. Aggarwal et al. (1986) reported that WUE decreased with increasing evapotranspiration, whereas Musick et al. (1994) found that WUE did not change with seasonal evapotranspiration. Under limited irrigation, reductions in grain yield due to restricted water availability depend on the degree, duration and timing of the imposed soil moisture deficit. The impact of soil moisture deficit on crop yield depends on the particular phenological stage of the crop, and the most sensitive stage can vary regionally (Singh et al. 1991). Because these differences relate to regional variability in environmental and agronomic practices, region-specific information is needed for developing and refining limited irrigation schemes.

The Loess Plateau is a vast arid and semiarid area with average annual rainfall ranging from 300 to 600 mm. Rainfall distribution is uneven, with more than 60% occurring from July to September. Total annual rainfall also varies significantly from year to year. Winter wheat (*Triticum aestivum* L.) and corn (*Zea mays*) are the main crops in the region. Available water is the most important factor limiting crop yields. During the last decade, irrigation water has been pumped from the Yellow River or from surface dams, and average crop yield has substantially increased. However, recently there has been a rapid decline in available water resources from the Yellow River; consequently, there is an urgent need for more efficient water use in order to sustain agriculture in the area (Kang and Li 1997). The Overview provides background information on the region; Figure 1 of the Overview shows the location of the Loess Plateau.

When the available water supply is severely limited, water deficits will be unavoidable during some periods of crop growth. Scheduling of irrigation times is then more complex because irrigation decisions must be based on the relationships between grain yield, crop growing phase and crop water use. Alternative irrigation schedules must be evaluated to determine which schedule maximises crop yield and WUE for a given level of water supply.

We lack adequate information on the relationships between grain yield and WUE under different irrigation regimes on the Loess Plateau; we also lack information about the degree of soil water deficit at different stages of growth, although many irrigation practices involve the control of soil water deficit.

The aim of this chapter was to study the effect of limited irrigation on crop yield and WUE for winter wheat in the field. The objectives were to:

- examine the impact of limited irrigation on crop yield;
- determine an optimum soil water deficit scheme under limited irrigation; and
- establish relationships between crop yield, WUE and the harvest index.

It was expected that the results of the study could be used to provide guidelines to farmers and irrigation managers on how to minimise water use while maintaining high wheat yields in the region.

Materials and Methods

Plant material and experimental design

The field experiments were conducted in Changwu, Shaanxi Province (see Figure 4 of the Overview) during 1995–98. The site is at an altitude of 1206 m, and has a semiarid, warm temperate climate with an average annual rainfall of 542 mm, falling mainly from July to September. Annual sunshine duration is 2226 hours, annual average temperature is 9°C and annual potential evaporation is 1552 mm. The groundwater table is about 50–80 m below the surface. The soil is a dark loess soil with a loam texture, which has been intensively cultivated over many centuries. Its major physical properties are given in Table 1. The top layer of the soil (30 cm) contains 1.55% total organic matter, 0.106% nitrogen (Bremner and Mulvaney 1982) and 0.095% available phosphate (Olsen and Sommer 1982). The experiments were carried out in lysimeters 3 m × 2 m in area and 3 m deep. Irrigation and fertiliser were applied to the top 30 cm before sowing. Each lysimeter had an aluminium tube 2 m in length installed for moisture measurements. During storms, a plastic rain shelter was installed above the lysimeters to control soil water status. Winter wheat (cultivar Changwu 89-134) was sown in late September. Seedling density was controlled to 200 plants/m^2. In total, 15 treatments of soil water deficit were included (Table 2) with three replicates. All plants were harvested in early July in the year following planting.

Measurements and statistical treatment

A neutron moisture meter (CPN503, United States) was used to measure water content every 10 cm to a depth of 2 m. Measurements were taken at weekly intervals. In controlling soil water deficit, average soil water content for the top 40 cm and 60 cm was monitored using time-domain reflectometry (Trase system, Soil Moisture Equipment Corporation, United States). When soil water content dropped to the lower limit of the designed range (see Table 2), the lysimeter was irrigated to its designated upper limit. The amount of irrigation water in each lysimeter was recorded and used to calculate total water consumption.

Table 1. Physical properties of the soils at Changwu.[a]

	Particle composition (mm)							
Size	>0.05	0.05–0.005	<0.005	Bulk density (g/cm^3)	Total pore space (%)	Field capacity (cm^3/cm^3)	Initial infiltration rate (mm/min)	Final infiltration rate (mm/min)
% in size class	3.5	65.6	30.9	1.21	50.6	0.255	5.9	1.6

[a] Data are the average value in the top 60 cm soil layer

A portable gas-exchange recording system (CID-301PS, CID Inc., Vancouver, WA, United States) was used to measure diurnal variations in the rate of photosynthesis and stomatal resistance on some clear days. The measurements were taken at hourly intervals from 7 a.m. to 7 p.m. At the end of each growing season, plants were harvested for estimation of dry matter in shoots and roots, and final grain yield.

Meteorological data — air temperature, air humidity, wind speed and rainfall — were recorded at a standard weather station located at the experimental site. Maximum and minimum temperature, maximum vapour pressure deficit and average wind speed were also recorded each day, as was daily potential evapotranspiration from an evaporation pan with a diameter of 601 mm.

All data were statistically analysed; Duncan's multiple range test was used to compare treatments.

Estimation of evapotranspiration, water use efficiency and harvest index

Crop evapotranspiration between two soil moisture content measurements or in the whole growing season was estimated from the equation:

$$ET = \Delta W + I + P + S_g - D - R_f \qquad (1)$$

where ET is crop evapotranspiration, ΔW is the change in soil water storage between two soil moisture content measurements, I is irrigation, P is rainfall, S_g is capillary rise from the water table to the crop root zone, D is downward drainage from the crop root zone and R_f is surface runoff from the lysimeter.

Because the water table was below 50 m, capillary contribution from the groundwater can be ignored (Zhang et al. 1995). During heavy storms, a mobile plastic rain shelter eliminated runoff from the

Table 2. Controlled minimum soil water content of different treatments in the winter wheat growing season.

Treatment no.	Treatment type[a]	Soil water content maintained (% of field capacity) Seeding to before winter freezing	Regrowth to stem elongation	Booting to heading	Flowering to milk ripeness	Maturity to harvest
1	LLLLL	45	45	45	45	45
2	LLLHM	45	45	45	70	55
3	LHMLL	45	70	55	45	45
4	HLMHM	70	45	55	70	55
5	MMMMM	55	55	55	55	55
6	LMLLM	45	55	45	45	55
7	MLLMH	55	45	45	55	70
8	MHLLH	55	70	45	45	70
9	MHMLL	55	70	55	45	45
10	HHLML	70	70	45	55	45
11	LMHMH	45	55	70	55	70
12	HHHHH	70	70	70	70	70
13	HMHLM	70	55	70	45	55
14	HMHHL	70	55	70	70	45
15	MMHHL	55	55	70	70	45

[a] The growing season was divided into five periods and soil water content in the top 60 cm (40 cm before the jointing stage) was maintained during different growth stages. When soil water content approached the minimum value, water was supplied up to field capacity. H = high soil moisture content (no soil water deficit); M = medium soil moisture content (mild soil water deficit); L = low soil moisture content (severe soil water deficit).

lysimeters. The measured rainfall during such events was applied as irrigation and allowed to infiltrate. Since irrigation water was applied to the topsoil and moisture content was controlled below field capacity (Table 2), deep drainage was assumed to be negligible.

Crop water use efficiency was calculated as grain yield divided by seasonal evapotranspiration. Harvest index was estimated as grain yield divided by total biomass.

Results and Discussion

Evapotranspiration, grain yield and biomass

Table 3 lists the average values of evapotranspiration, grain yield and biomass for different treatments in 1995–98. The growing season reference evapotranspiration calculated by a modified Penman equation was 534.2, 429.9, and 479.3 mm for the respective growing seasons. Actual evapotranspiration was considerably lower than for winter wheat in the Southern High Plains of the United States (Howell et al. 1995; Schneider and Howell 1997) or the North China Plain (NCP) (Zhang et al. 1999). The differences may be due to different climatic conditions.

The plants in treatment 1 were grown in rainfed conditions, with no irrigation in the growing season. Seasonal evapotranspiration varied from 213 to 267 mm. In 1996 and 1998, evapotranspiration was balanced by the growing-season rainfall. However, because of drought in 1997, 80 mm of stored soil water was used in addition to the seasonal rainfall. Grain yields varied between 1612 and 2493 kg/ha under rainfed conditions. In the irrigated treatments, seasonal evapotranspiration ranged from 227 to 519 mm and grain yield from 1771 to 4920 kg/ha, depending on the amount of water applied and the time of irrigation. Evapotranspiration and yield depend on the level of soil water deficit at different growth stages. In treatment 12 (high soil moisture), seasonal evapotranspiration was 358–519 mm during the three years of the study. These high values may have been due partly to relatively high soil evaporation resulting from more frequent wetting of the soil surface, especially early in the season, when crop cover was low.

The high soil moisture treatment did not produce the highest grain yield. In fact, the highest grain yield was attained in treatment 15, which was subject to mild water deficits at the seedling, regrowth and stem-elongation stages, followed by soil drying during the period from physiological maturity to harvest. Seasonal evapotranspiration in this treatment was 7.4–24.9% less than that in the high soil moisture treatment. Hence, this treatment combines the benefits of reduced irrigation water (7.4–24.9%) and higher grain yield (0.4–18.0%). The results are only a first indication for a single area, but they support the idea that water resources can be conserved through a process of mild soil drying in the early vegetative growing periods followed by severe soil drying in the maturity stage. This can assist in developing sustainable agriculture and may help in preventing further depletion of water resources. Thus, limited irrigation may be of real value in making winter wheat production part of a program of sustainable agriculture.

Table 4 shows that the regulated soil water deficit reduced leaf and stem development and stimulated root development. An advantage of smaller shoots is that crops consume less water. Canopy transpiration is largely a function of net energy absorbed by the leaves when available water is not limiting (e.g. Monteith 1981), and smaller leaf area will reduce light interception. In addition, soil water deficit may reduce water loss through physiological regulation, such as by reduced stomatal conductance (e.g. Davies and Zhang 1991). The data indicate that total water consumption was reduced by both smaller leaf area and lowered rate of leaf transpiration.

Table 3. Total evapotranspiration (ET), grain yield, harvest index and water use efficiency (WUE) of winter wheat plants, 1995–98.

Year	Treatment	Rainfall (mm)	Irrigation (mm)	ET (mm)	Biomass (kg/ha)	Grain yield (kg/ha)	Harvest index	WUE (kg/m^3)
1995–96	1	239.6	0	213	6000	1750	0.292	0.822
	2		97	300	9250	3180	0.344	1.060
	3		107	278	10251	3375	0.329	1.214
	4		269	385	11401	3905	0.343	1.014
	5		167	359	10451	3570	0.342	0.994
	6		183	291	10526	3505	0.333	1.204
	7		241	338	11426	3870	0.339	1.145
	8		281	387	13726	4020	0.293	1.039
	9		216	323	11901	4080	0.343	1.263
	10		268	389	12401	4230	0.341	1.087
	11		302	403	14551	4245	0.291	1.053
	12		408	519	16726	4200	0.251	0.809
	13		302	420	14051	4600	0.327	1.095
	14		383	383	12976	4775	0.368	1.247
	15		390	390	14351	4920	0.343	1.262
1996–97	1	137.0	0	220	6598	1612	0.244	0.734
	2		60	277	8294	3060	0.369	1.105
	3		112	231	7794	2039	0.262	0.883
	4		246	232	5598	1771	0.316	0.765
	5		158	310	9181	4079	0.444	1.315
	6		197	235	7984	2040	0.256	0.869
	7		280	296	8225	3060	0.372	1.036
	8		302	285	8026	2788	0.347	0.978
	9		235	254	9223	3076	0.334	1.212
	10		293	285	10746	3852	0.358	1.353
	11		284	227	6982	2045	0.293	0.902
	12		391	358	13001	4060	0.312	1.133
	13		306	330	12016	4749	0.395	1.439
	14		378	340	12717	4811	0.378	1.417
	15		361	329	10732	4792	0.447	1.458
1997–98	1	267.4	0	267	8726	2493	0.286	0.933
	2		88	308	8727	3520	0.403	1.143
	3		120	304	8409	3089	0.367	1.018
	4		217	310	9293	3533	0.380	1.138
	5		174	301	8126	3060	0.377	1.016
	6		198	339	9974	3506	0.352	1.035
	7		271	356	10314	3441	0.334	0.966
	8		296	370	10653	3659	0.343	0.990
	9		204	362	9860	3672	0.372	1.014
	10		253	305	9180	3680	0.401	1.205
	11		267	292	9066	3294	0.363	1.130
	12		350	399	13860	4533	0.327	1.135
	13		297	354	11334	4325	0.382	1.223
	14		324	367	11106	4485	0.404	1.224
	15		319	370	10314	4553	0.441	1.232

Under the rainfed conditions of treatment 1, minimum total above-ground biomass was 6000–8726 kg/ha (see Table 3); the maximum biomass was recorded in the high soil water conditions of treatment 12 (13,000–16,726 kg/ha). The linear curve fit through the data in Figure 1 indicates that early-season soil evaporation was about 28 mm. With limited irrigation and a controlled soil water deficit, the biomass was lower than with a high soil water content. However, the reduction in biomass was small in treatment 15 and even less in treatments 13 and 14 in 1997 and 1998. This was due to a compensatory effect of photosynthesis after rewatering under controlled soil water deficit (Table 5). Soil water deficit at the seedling stage substantially reduced leaf photosynthesis, but it recovered a few days after rewatering, suggesting that stomatal inhibition was the main reason (Cornic 1994). Further soil water deficit between the start of regrowth and stem elongation had less effect on the photosynthesis rate in treatment 15, especially for plants subjected to soil water deficit at the seedling stage. This could be related to a larger and deeper root system (Table 4) following soil drying at the seedling stage. A deep root system is beneficial under water-limited conditions as it allows water to be extracted from depth. Studies on dryland crops have shown that utilisation of water deep in the profile may be limited by root density (e.g. Jupp and Newman 1987; Zhang and Davies 1989; Kang et al. 1992; McIntyre et al. 1995).

Regression analysis shows that the relationship between grain yield and seasonal evapotranspiration is a quadratic function (Fig. 1). Grain yield did not increase when seasonal evapotranspiration exceeded a critical value: in this study about 434 mm, or approximately 84% of the measured maximum evapotranspiration. However, biomass increased linearly with evapotranspiration. Both biomass and grain yield showed good correlation with evapotranspiration (Fig. 1), but not with the amount of irrigation water applied (Table 3). These results suggest that the effect of irrigation on grain yield varied considerably due to differences in the soil moisture content and irrigation scheduling between seasons. A high soil moisture content throughout the season required a high water consumption but did not lead to higher grain yields. In some cases, high soil moisture content even resulted in lower grain yields (Table 3). Similar relationships have been reported for wheat, corn and cotton in Northwest China (Kang and Dang 1987), wheat in India (Rajput and Singh 1986;

Table 4. Distribution of root, stem, and leaf dry mass (%) at different development stages of winter wheat grown in the field under different treatments,[a] 1995–96.

	Root			Stem			Leaf		
Sampling date	LLLLL	MMMMM	HHHHH	LLLLL	MMMMM	HHHHH	LLLLL	MMMMM	HHHHH
4 Nov	22.6	22.6	22.6	38.0	38.0	38.0	39.4	39.4	39.4
6 Dec	19.6	12.3	10.1	35.8	40.0	34.8	44.6	47.7	55.1
6 Jan	19.9	14.2	12.0	45.6	42.6	32.0	34.5	43.3	56.0
6 Feb	16.3	15.2	13.8	40.8	39.7	34.1	42.9	45.1	52.1
13 Apr	14.6	14.9	14.1	53.2	49.2	49.1	32.1	35.9	36.8
21 May	12.4	11.0	8.7	69.2	67.6	73.5	18.4	21.4	17.8
29 May	13.4	12.0	7.2	60.6	61.8	58.9	10.4	11.9	12.0

[a] Table 2 shows details of treatments

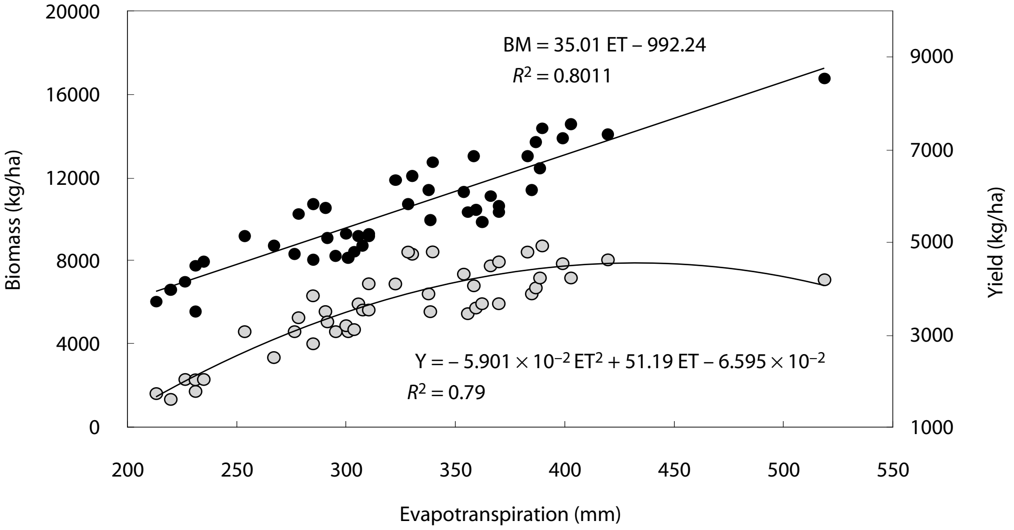

Figure 1. Relationships between growing season evapotranspiration (ET) and biomass (BM) and grain yield (Y) for winter wheat at Changwu.

Table 5. Photosynthesis rate (P_n) and relative photosynthesis (RP_n)[a] of winter wheat plants under different treatments.[b]

Variable	Treatment[c]	Date (day/month)								
		17/4	29/4	6/5	10/5	11/5	18/5	23/5	29/5	9/6
P_n (μmol/m^2/s)	LLLLL	3.90	4.52	6.31	3.33	3.01	7.64	5.19	3.95	4.45
	MMMMM	6.10	6.67	8.27	5.12	5.49	8.04	6.26	4.25	4.95
	HHHHH	6.20	6.97	8.74	4.85	4.74	7.94	5.71	5.32	4.81
	HMHHL	6.01	6.37	7.12	4.85	5.03	8.53	6.40	5.93	4.71
	MMHHL	6.10	6.26	7.44	4.80	4.94	8.41	6.47	5.82	4.60
RP_n (%)	LLLLL	62.9	64.9	72.7	68.7	63.5	96.2	90.9	74.3	92.5
	MMMMM	98.4	95.7	94.6	105.6	115.8	101.3	109.6	79.9	102.9
	HHHHH	100	100	100	100	100	100	100	100	100
	HMHHL	96.9	91.4	81.5	100	106.1	107.4	112.1	111.5	97.9
	MMHHL	98.4	89.8	85.1	99.0	104.2	105.9	113.3	109.4	95.6

[a] Relative photosynthesis is the ratio of photosynthesis rates in each treatment to the rate of the control treatment (HHHH)
[b] Data are the daily average value of measurements in 1996. Values are means of replicates for each treatment.
[c] See Table 2 for details of treatments

Kumar and Khepar 1980), cowpea and corn in Nigeria (Fapohunda et al. 1984), and sorghum in Northeast Brazil (Sharma and Alonso Neto 1986).

It can be deduced from Figure 1 that grain yield required a minimum evapotranspiration of 152 mm for winter wheat. This value is lower than the 206 mm for dryland and irrigated wheat reported by Musick et al. (1994), and higher than the 84 mm for winter wheat on the NCP (Zhang et al. 1999), but very close to the 156 mm for wheat in the Mediterranean region (Zhang and Oweis 1999).

The relationship between grain yield and biomass is fitted with a quadratic function in Figure 2. Grain yield increased with biomass until it reached a value of 15,000 kg/ha, and then remained more or less constant, in line with the data in Figure 1.

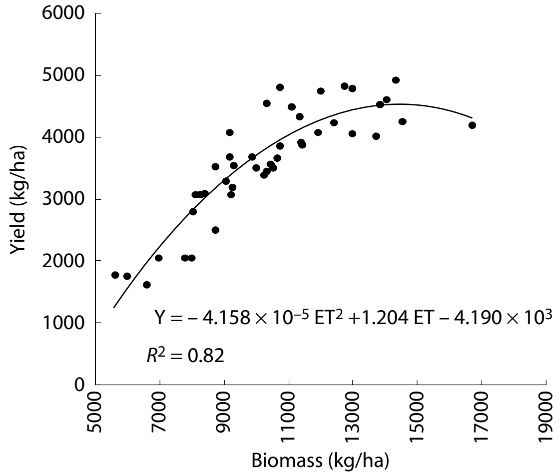

Figure 2. Relationship between biomass (BM) and grain yield (Y) for winter wheat at Changwu.

These relationships also indicate that the highest biomass was associated with maximum evapotranspiration, but not with the highest grain yield, which was reached by appropriately controlling soil water content and limiting evapotranspiration and biomass.

Water use efficiency and harvest index

WUE ranged from 0.73 to 0.93 kg/m^3 under rainfed conditions (Table 3) and from 0.77 to 1.46 under the irrigated treatments. The level of WUE depends on the controlled ranges of soil water deficit at different stages. WUE in the high soil moisture treatment (12) ranged from 0.81 to 1.14 kg/m^3 but the highest WUE values were recorded in treatment 15 (1.23–1.46 kg/m^3 over the three years of the study), as expected from the information on yield and seasonal evapotranspiration. The lower values for treatment 12 arose because seasonal evapotranspiration was the highest recorded in any treatment, but yield was not.

WUE values in our study were higher than those for winter wheat (0.40–0.88 kg/m^3: Howell et al. 1995; Schneider and Howell 1997) and for irrigated wheat (0.82 kg/m^3) in the US Southern Plains (Musick et al. 1994), but close to those (1.08–1.19 kg/m^3) for winter wheat in the Mediterranean region (Zhang and Oweis 1999) and for winter wheat (0.84–1.39 kg/m^3) on the NCP (Zhang et al. 1999).

The harvest index was 0.24–0.29 under rainfed conditions and 0.25–0.45 under irrigated conditions, meaning that appropriate irrigation and controlled soil water content can increase harvest index. Maximum harvest index was recorded in treatment 15. However, under treatment 12 (a high soil water treatment), the harvest index was only 0.25–0.33, much lower than under other irrigation treatments. This treatment resulted in high above-ground biomass (Table 4), causing lodging in the late growing stage, with adverse effects on grain filling. Sheng and Wang (1985) found that high soil moisture content during the grain-filling stage may result in lower 1000-seed weight and grain yield. Other investigators (e.g. Zhang et al. 1998) have reported similar results; it has been well established that remobilisation of carbohydrate reserves from the stem and the leaf sheath is a key factor for grain filling. In wheat, low soil moisture content during grain filling may lead to better use of the carbon reserves in stems and sheaths (Palta et al. 1994; Ricciardi and Stelluti 1995).

Regression analysis indicated a quadratic relationship between WUE and seasonal evapotranspiration (Fig. 3). WUE reached its maximum value at a seasonal evapotranspiration of 354 mm, then started to decrease with evapotranspiration. However, maximum WUE did not correspond to maximum grain yield (Figs 1 and 3). When evapotranspiration is relatively low, water availability is the limiting factor for grain yield and an increase in evapotranspiration results in significant increases in both grain yield and WUE. However, the rate of change starts to decrease as evapotranspiration further increases. Once WUE reaches its maximum value, an increase in total crop water use could still lead to a marginal increase in grain yield, but WUE would decrease. For example, at the maximum WUE the grain yield was 4134 kg/ha; a further increase of 20% in total crop water use would increase grain yield by only 8%. In economic terms, grain yield response to total crop water use is a diminishing-return function. Therefore, aiming for maximum grain yield under limited water resources is not economical and should not be encouraged. These results also indicate that it is possible to maintain relatively high grain yield and WUE by limiting the duration and severity of plant water stress under limited irrigation.

The relation between harvest index and seasonal evapotranspiration is also nonlinear (Fig. 3). Maximum harvest index, like maximum WUE and grain yield, did not coincide with maximum seasonal evapotranspiration but was recorded when the seasonal evapotranspiration was about 346 mm. Therefore, the maximum value of the harvest index is attained under an appropriate evapotranspiration deficit.

The nonlinear curves fitted through the data in Figure 3 also indicate that WUE increases linearly with harvest index, in agreement with results from other studies (Austin et al. 1980; Perry and D'Antuono 1989; Siddique et al. 1989). Passioura (1977) and Fischer (1979) have suggested that in water-limited conditions a relatively high harvest index is needed to obtain high WUE. In our study, the highest harvest index occurred when evapotranspiration was about 70% of its maximum; the index then started to decrease with increasing evapotranspiration (Fig. 3). Improving the harvest index led to improvement in WUE under limited irrigation conditions.

Conclusions

Evapotranspiration, grain yield, biomass, WUE and the harvest index of winter wheat were all affected by controlled ranges of soil water content during growing seasons. Grain yield response to irrigation varied considerably due to differences in soil moisture content and irrigation scheduling between seasons. Evapotranspiration was highest under continuous high soil moisture conditions, as was above-ground biomass. However, grain yield was not the highest in these conditions, and WUE was relatively low due to inefficient use of the stored soil water. Maximum values of WUE and the harvest index occurred under appropriately controlled soil water conditions. WUE appears to increase linearly with harvest index; improvement in WUE under limited irrigation conditions is thus the consequence of an increased harvest index.

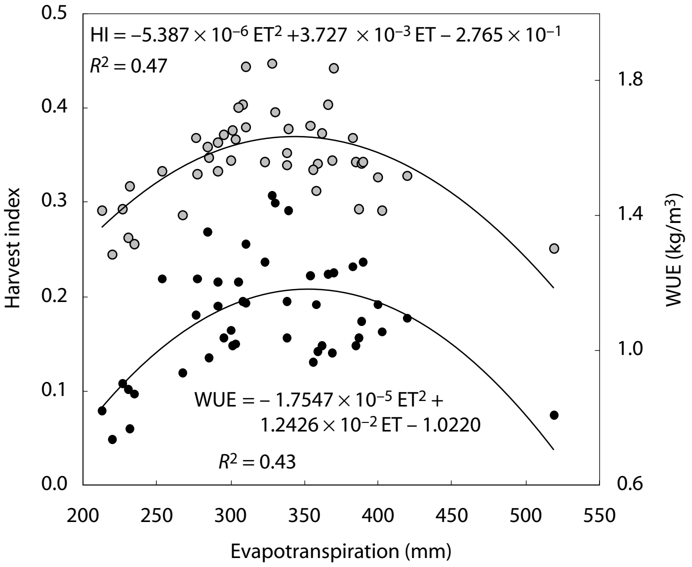

Figure 3. Relationships between seasonal evapotranspiration (ET) and water use efficiency (WUE) and harvest index (HI) for winter wheat at Changwu.

Appropriately limited irrigation and controlled soil water content level could lead to higher grain yield, WUE and harvest index. Compared to high water treatment, this practice has the advantage of lower above-ground biomass before flowering, greater net photosynthesis rates during grain filling, and larger grain yield. Hence, mild soil drying in the early vegetative growth period and severe soil drying in the maturity stage of winter wheat is an optimum limited irrigation regime in the Loess Plateau of China.

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