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Water use efficiency of dryland wheat in the Loess Plateau in response to soil and crop management

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ABSTRACT

Improvement of wheat water use efficiency (WUE = grain yield per unit seasonal evapotranspiration) in the dryland area of Loess Plateau of China is an imperative imposed by the critical situation of water resources, as well as by the demographic pressure. The aims of this study were (i) assessing WUE of dryland wheat in the Loess Plateau, and (ii) identifying management practices returning higher efficiencies. We compiled a data base of 39 sets of experiments spanning 20 years, where conventional practice was compared with alternatives including NT, no tillage without straw mulching; RT, reduced tillage without straw mulching; NTS, no tillage with straw mulching; SS, subsoiling with straw mulching; CTS, conventional tillage with straw mulching; PM, plastic film mulching 100%; RM, ridge mulched with plastic film + bare furrow; RMS, ridge mulched with plastic film + furrow mulched with crop straw.

Yield ranged from 818 to 7900 kg ha^{-1} and WUE from 3.4 to 23.4 kg ha^{-1} mm^{-1}; the maximum yield and WUE were achieved under RM and RMS and the minimum under NT/RT. Practices had small and inconsistent effect on seasonal evapotranspiration, hence variation in both yield and WUE were attributable to changes in the contribution of soil evaporation to total evapotranspiration, and the partitioning of seasonal water use before and after anthesis. The yield–evapotranspiration relationship indicated that present yields are limited by environmental (e.g. seasonal distribution of rainfall) and management factors. The range of WUE is very large for the same or various practices, and thus offers tremendous opportunities for maintaining or increasing WUE. Implications for crop management and further improvement in yield and WUE are discussed.

1. Introduction

Water stress and nutrient deficit are the main factors limiting primary production in arid and semi-arid environments (Hooper and Johnson, 1999; Austin, 2011; Rockstrom and deRouw, 1997; Sadras, 2005). In China, dryland farming is practiced on about a third of the arable land, a large part of which (about 40%) is situated on the mostly semi-arid Loess Plateau spanning 63×10^4 km^2 (Li, 2004). Groundwater resources are sparse and deep, so most of the farmland on the Loess Plateau relies solely on rainfall ranging from 150 to 300 mm yr^{-1} in the north to 500–700 mm yr^{-1} in the south (Li and Xiao, 1992). For many sites in the Loess Plateau, precipitation has declined at a rate of 1–2 mm yr^{-1} in the last five decades (Duan et al., 2009; Wang, 2009). With the population continuously increasing, the challenge is to increase food production with less water. Finding ways to effectively use water and to sustain productivity are crucial for dryland farming in the Loess Plateau.

Dryland winter wheat is widely grown in the Loess Plateau. About 30–40% of annual precipitation occurs from October through June when winter wheat is growing; hence, yield depends on both in-season rainfall and amount of soil water stored in the soil before the growing season, as in other systems (Nielsen et al., 2002; Unger et al., 2006; Schillinger et al., 2008). Well-drained, light and medium loams account for 90% of the soils in the region, with silt content (0.001–0.05 mm) around 60–75% (Li et al., 1985). The silt loam soils with thickness largely ranging from 30 to 80 m (Zhu et al., 1983) have gravimetric field water holding capacity of 20% ± 2 and gravimetric wilting point from 4% to 8% (Li et al., 1985). Deep soils with large potential plant available water are therefore critical reservoirs regulating water supply to the crop (Li et al., 1991).

Within this context, innovations in soil and crop management are sought to improve use of the water available for crop growth. In

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the past decades, conservation tillage and other field management practices, such as mulching with plastic film, have been applied to improve water use and ensure the food security of local people. This paper analyses the effect of various tillage and mulching practices on wheat yield, water use and water use efficiency (grain yield per unit seasonal evapotranspiration) in the Loess Plateau. The focus is agronomic factors that have the potential to increase yields and water use efficiency in dryland farming systems. A secondary aim of this paper is to make data originally published in Chinese available to a wider readership.

2. Method

Combining key words 'wheat'; 'evapotranspiration' and 'Loess Plateau'; we searched for papers published between 1996 and 2012 in three data bases: Elsevier ScienceDirect; SpringerLink and China Academic Journal Network Publishing Database. Yield and seasonal evapotranspiration (ET) data were taken directly from tables or digitized from graphs. Water use efficiency (WUE) is the ratio of yield and ET.

Reported ET was calculated as precipitation plus change in soil water content between sowing and harvest; where data were available, we also calculated pre- and post-flowering ET as precipitation plus change in soil water content between sowing and flowering or flowering to harvest, respectively. Sources of bias in the estimation of ET and WUE include (i) water extraction beyond the root zone depth, (ii) deep drainage and/or (iii) runoff. To account for the first of these factors, we only included studies reporting changes in soil water to 2 m depth; this accounts for root depth of wheat in the region (Yin et al., 1998). In the Loess Plateau, rainy season coincides with summer fallow, therefore deep drainage or runoff are less likely during the growing season in association with both lower rainfall and active crop growth (Zhang et al., 2007).

We identified 39 studies carried out in smallholder farms and experimental stations under rain-fed field conditions in the Loess Plateau (Appendix 1). Data from the same experiment but reported in more than one publication were not repeated; the publication with the most complete dataset or combination of data from different periods was used. All the data reported in this paper were under balanced fertilization or sufficient nutrient level except one study including both low and high nitrogen rates (Wang et al., 2004). This reflects the high fertilization rates that are common practice in the region. In all these papers, conventional tillage (CT) was compared with one or more alternative practices including: NT, no tillage without straw mulching; RT, reduced tillage without straw mulching; NTS, no tillage with straw mulching; SS, subsoiling with straw mulching; CTS, conventional tillage with straw mulching; PM, plastic film mulching 100%; RM, ridge mulched with plastic film + bare furrow; RMS, ridge mulched with plastic film + furrow mulched with crop straw.

Descriptive statistics were calculated for all three traits, i.e. yield, evapotranspiration and water use efficiency. Using conventional tillage (CT) as reference, we calculated the percent change in yield, ET and WUE as:

$$\text{Change in trait} \quad (\%) = \frac{\text{Trait}_{AP} - \text{Trait}_{CT}}{\text{Trait}_{CT}} \qquad (1)$$

where subscripts indicate conventional (CT) and alternative practices (AP) listed above. Frequency distributions of changes in yield, ET and WUE were calculated for the pooled data.

One-way ANOVA was used to assess the effects of the management practices on yield, ET and WUE. When ANOVA returned a significant *F*-value, multiple comparisons of means were performed using the least significant difference (LSD). The SPSS software package (v16.0) was used for all the statistical analyses.

3. Results

3.1. Yield

Yield ranged from 818 to 7900 kg ha^{-1} across soils, seasons, and treatments (Table 1). The average for each practice ranged from 3223 for NT/RT to approx. 4500 kg ha^{-1} for RM and RMS (Table 1). On average, alternative practices increased yield relative to conventional by 9% under NTS to 33% under RMS; the only exception was NT/RT which showed an average 6% reduction (Fig. 1AB). Both yield and yield responses to management practices relative to conventional had a wide range of variation (Table 1).

Frequency distributions of change in yield need to be considered with caution particularly in the treatments with low number of data points; nonetheless plots of frequencies highlight the spread of yield responses (Fig. 1AB). The same note of caution applies to evapotranspiration and water use efficiency (Fig. 1C–F). Yield under reduced or no till without stubble retention showed variation between 21% reduction and 11% increase (Fig. 1AB). Where stubble mulch was used under no till (NTS) or subsoiling (SS), yield responses were largely neutral to positive, with yield increase up to 20–40%. Four practices, CTS, RMS, PM and RM, had neutral to large positive effects on yield, with several records of improvement larger than 50% (Fig. 1AB).

3.2. Evapotranspiration

Seasonal ET ranged from 123 to 589 mm, but means for different practices showed a relatively narrow range, between 305 and 353 mm (Table 1). Frequency distributions of changes in ET also showed an overall neutral effect, with few cases where alternative practices increased ET (Fig. 1CD).

The small variation in ET under alternative practices (Table 1) compared to robust improvements in storage of soil water at sowing (Table 2) suggest some degree of decoupling between these variables, as shown in Fig. 2. Where change in ET correlates with change in initial soil water, the proportionality between variables is well below one-to-one (slopes in Fig. 2AB). The relationship between change in seasonal evapotranspiration and change in initial soil water breaks down for example, where changes in initial soil water are small (<25 mm; Fig. 2C) or where large changes in initial soil water are followed by high in-season rainfall (circled data in Fig. 2D).

3.3. Relationships between yield and water use

3.3.1. General relationships

Fig. 3 shows grain yield as a function of evapotranspiration for the pooled data. A boundary line with slope 22 kg grain ha^{-1} mm^{-1} (accounting for attainable transpiration efficiency, TE) and *x*-intercept = 60 mm provided an upper limit for all the data. These parameters are the same as given by Sadras and Angus (2006).

Slopes and coefficients of correlations of the relationships between wheat yield and soil water at sowing and between yield and precipitation during the growing season were of similar magnitude, reinforcing the view that both water sources were equally important in this region (Fig. 4). In addition, wheat yield was also positively correlated with the ratio of post to pre-anthesis water use (Fig. 5).

3.3.2. WUE responses to alternative practices

Crop WUE ranged from 3.4 to 23.4 kg ha^{-1} mm^{-1} across soils, seasons, and treatments, whereas averages for each practice ranged from 9.3 to 14.7 kg ha^{-1} mm^{-1} (Table 1). In the absence of stubble mulch, no till and reduced till had neutral or negative effects on WUE in comparison with conventional practice (Fig. 1EF). Water

Table 1
Wheat yield, evapotranspiration (ET) and water use efficiency (WUE) under various management practices in the Loess Plateau.

Practice	No. of data	Grain yield (kg ha^{-1})		ET (mm)		WUE (kg ha^{-1} mm^{-1})	
		Mean	Range	Mean	Range	Mean	Range
CT	96[a]	3502 d	818–6337	323 a	123–589	10.9 d	3.4–18.8
NT/RT	24	3223 d	1400–4574	353 a	234–559	9.3 e	4.7–14.8
NTS	35	3860 bcd	2000–5996	338 a	197–572	11.6 cd	6.1–18.0
SS	25	4173 abc	2233–6373	347 a	223–584	12.0 cd	7.8–17.1
CTS	37	4116 abc	1240–6391	333 a	200–543	12.7 bc	5.6–18.6
PM	47	3895 bcd	886–6813	326 a	200–521	11.7 cd	4.4–19.5
RM	31	4551 a	1548–7898	305 a	138–431	14.7 a	8.2–22.4
RMS	20	4452 ab	3036–6547	330 a	207–502	14.1 ab	7.1–23.4

Note. CT, conventional tillage; NT, no tillage without straw mulching; RT, reduced tillage without straw mulching; NTS, no tillage with straw mulching; SS, subsoiling with straw mulching; CTS, conventional tillage with straw mulching; PM, plastic film mulching 100%; RM, ridge mulched with plastic film + bare furrow; RMS, ridge mulched with plastic film + furrow mulched with crop straw. Different letters within the same column mean significant different tested by LSD ($P < 0.05$).

[a] This number included conventional management data from all references regardless of corresponding alternative practices.

use efficiency improved an average of 5–14% with NTS, CTS and SS, and between 25 and 30% with RM, PM and RMS (Fig. 2EF).

4. Discussion

4.1. Yield, ET and WUE responses to alternative practices

In relation to conventional practice, the effect of alternative practices on yield was neutral to positive, except for no till or reduced tillage with no stubble mulch. In the absence of straw retention, the adverse yield response to no till could be attributed to top soil compaction (Zhang et al., 2010) and exacerbating surface runoff and erosion (Jin et al., 2007; Huang et al., 2008). All the other practices increased yield up to 40% for SS and NTS, and larger effects were recorded for CTS, RMS, PM and RM (Fig. 1). Consistently, NTS showed minor effect on wheat yield in six out of 14 experiments in dry areas of Morocco, and considerably yield increase over CT in eight experiments (Mrabet et al., 2012).

An extensive literature review compared NTS and CT for maize and soybean yield in the United States and Canada (DeFelice et al.,

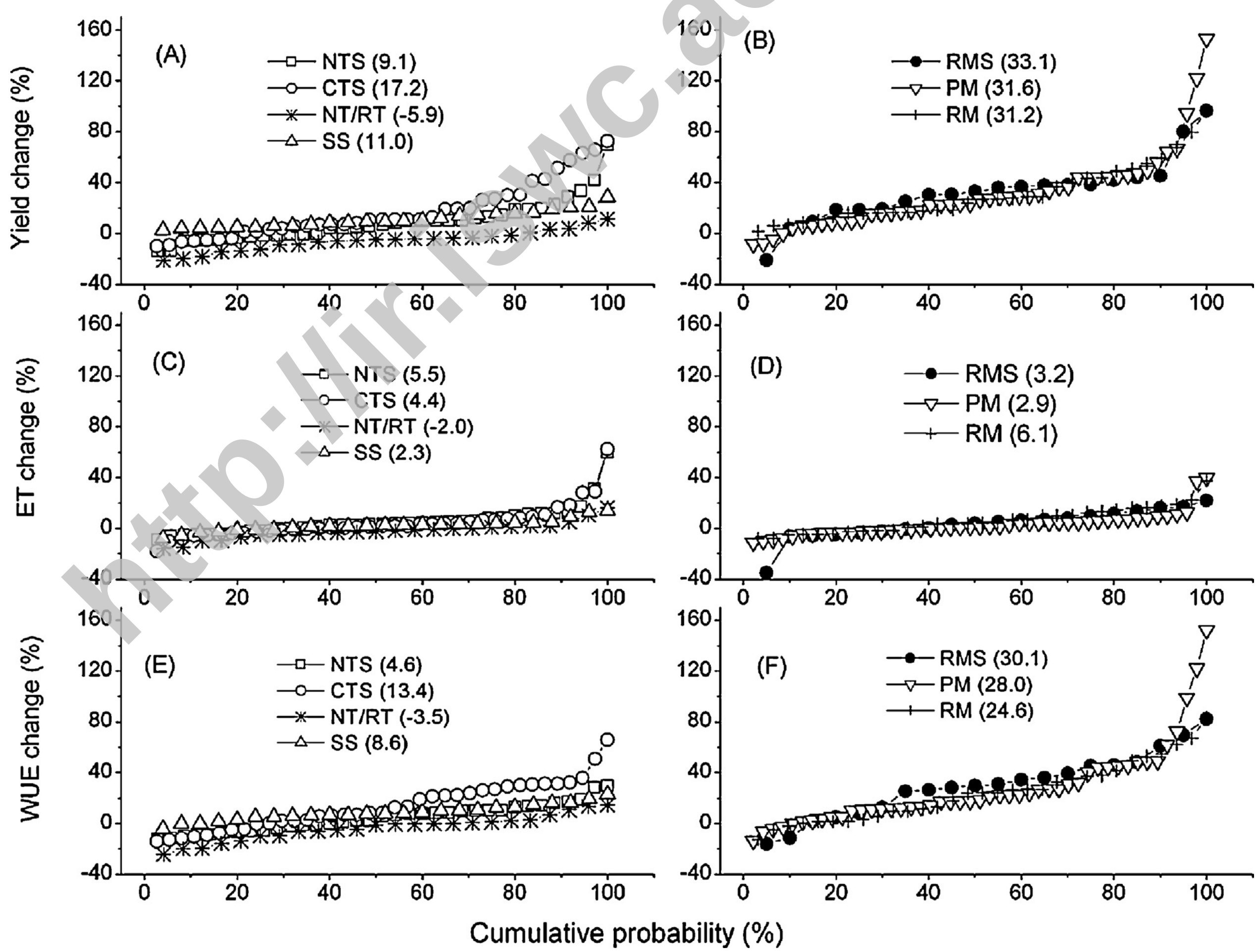

Fig. 1. Frequency distribution of change in (AB) yield, (CD) evapotranspiration and (EF) water use efficiency of wheat in the Loess plateau. Changes are the value of the variable under alternative practice relative to conventional tillage. Alternative practices are NT/RT, no tillage or reduced tillage without straw mulching; NTS, no tillage with straw mulching; SS, subsoiling with straw mulching; CTS, conventional tillage with straw mulching; PM, plastic film mulching 100%; RM, ridge mulched with plastic film + bare furrow; RMS, ridge mulched with plastic film + furrow mulched with crop straw. Practices in left and right panels were separated for clearer presentation of data.

Table 2
Change in water content in soil profile at wheat sowing under various management practices compared with conventional tillage in the Loess Plateau.

Practice	Location	Fallow season	Min.–max. (mm)	Average (mm)	Soil depth (cm)	Experimental years	Reference
NTS	Linfen, Shanxi	Summer	5–120	48	150	1999–2005	Wang et al. (2009)
	Dingxi, Gansu	Winter	7–10	8	200	2002–2004	Li et al. (2005)
	Luoyang, Henan	Summer	26–62	45	200	1999–2005	Su et al. (2007)
	Heyang, Shaanxi	Summer	26–78	49	200	2002–2004	Zhang et al. (2007)
	Changwu, Shaanxi	Summer	41–47	44	200	2008–2010	Liu et al. (2012)
	Pengyang, Ningxia	Summer	–	31	200	2007–2009	Hou et al. (2012)
SS	Luoyang, Henan	Summer	3–51	30	200	1999–2005	Su et al. (2007)
	Pengyang, Ningxia	Summer	–	35	200	2007–2009	Hou et al. (2012)
CTS	Linfen, Shanxi	Summer	2–119	49	150	1999–2005	Wang et al. (2009)
RM	Heyang, Shaanxi	Summer	76–123	91	200	2008–2010	Yang et al. (2011)
	Dingxi, Gansu	Winter	−4 to 1	−2	200	2002–2004	Li et al. (2005)
	Zhengyuan, Gansu	Summer	–	62	200	1997–2003	Fan et al. (2005)
	Zhengyuan, Gansu	Summer	56–67	61	200	2007–2009	Li et al. (2011a,b)
	Changwu, Shaanxi	Summer	81–102	91	200	2008–2010	Liu et al. (2012)

Note. NTS, no tillage with straw mulching; SS, subsoiling with straw mulching; CTS, conventional tillage with straw mulching; RM, ridge mulched with plastic film + bare furrow.

2006). No-till with residue cover tended to have greater yields than conventional tillage in the south and west regions of the United States, similar yields in the central region, and lower yields in the northern United States and Canada. NTS yields were typically higher than CT yields on moderate- to well-drained soils and low rainfall years or areas (DeFelice et al., 2006). In the Loess plateau, yield limitations under CTS and NTS were more likely related to low soil temperatures, especially in wet years (Gao and Li, 2005; Lu, 2013). Strip tillage systems (similar to SS treatment in our analysis) have been developed that take advantage of the benefits of NTS but help overcome yield limitations often associated with finer-textured, poorly drained soils and colder climates (Vetsch and Randall, 2002; DeFelice et al., 2006).

The comparison of plastic film mulch and conventional practice showed 8% of cases were PM reduced yield and about 60% of cases with yield increase over 20% (Fig. 1AB). Reduced yield under PM was attributed to fast depletion of soil water in the vegetative phase caused by favorable soil water and thermal condition, leading to water stress during grain filling compounded with higher soil temperature, especially in drought year (Li et al., 2001a). The RM and

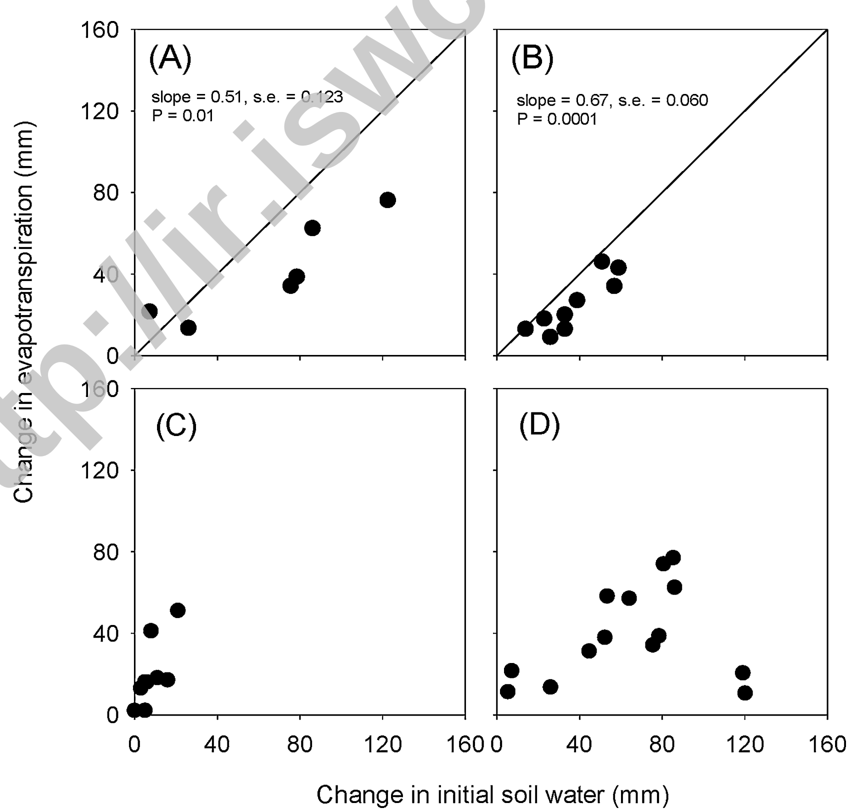

Fig. 2. Relationship between change in soil water content at sowing and change in seasonal evapotranspiration of wheat in the Loess Plateau. Changes refer to values measured under alternative management relative to conventional practice. In (A and B) the lines are $y = x$. In (D) the circled data emphasizes the break down of the relationship between initial soil water and evapotranspiration at high level of change in initial soil water content. Alternative practices are: (A) RM, (B and C) RT, NTS, SS, and (D) NTS and CTS; where RT is no tillage or reduced tillage without straw mulching; NTS is no tillage with straw mulching; SS is sub-soiling with straw mulching; CTS is conventional tillage with straw mulching; RM is ridge mulched with plastic film + bare furrow.

Sources: (A) Yang et al. (2011), (B) Su et al. (2007), (C) Jin et al. (2007), and (D) Wang et al. (2009).

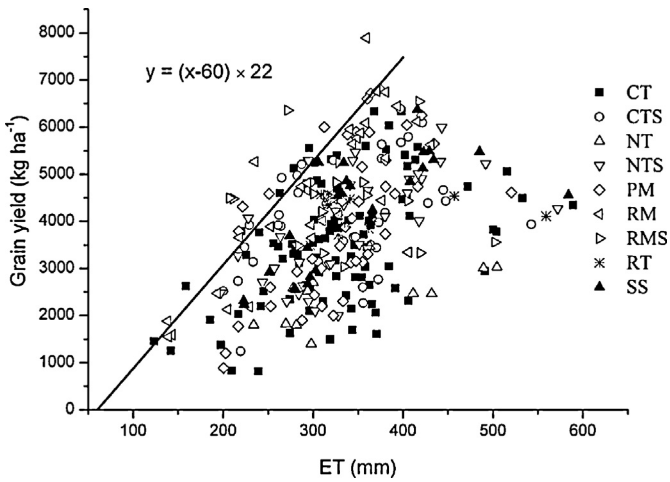

Fig. 3. Relationship between wheat grain yield and evapotranspiration (ET) on the Loess Plateau of China (n = 318). The boundary line is from Sadras and Angus (2006). Practices are CT (conventional), NT, no tillage without straw mulching, RT reduced tillage without straw mulching; NTS, no tillage with straw mulching; SS, subsoiling with straw mulching; CTS, conventional tillage with straw mulching; PM, plastic film mulching 100%; RM, ridge mulched with plastic film + bare furrow; RMS, ridge mulched with plastic film + furrow mulched with crop straw.

RMS practices increased yield in all studies except one high-rainfall year from one study in which yield was lower under RMS (Liu et al., 2007). Moreover, 50% of RM and 70% of RMS cases returned yield increase over 20% (Fig. 1AB). Combining plastic film in ridges and stubble in furrows (RMS) seems therefore superior to plastic film and bare furrow (RM).

Wheat yield was influenced not only by total available water but also by the seasonal pattern of water use, as demonstrated in many studies (French and Schultz, 1984a; Passioura, 1977, 1983; Sadras and Connor, 1991; O'Leary and Connor, 1997). Under the experimental conditions of Passioura (1983), a 2:1 ratio of water use before: after anthesis favored wheat yield; similar ratios favored wheat yield in Loess Plateau (Fig. 5). Nitrogen supply (van Herwaarden et al., 1998; Nielsen and Halvorson, 1991) and population density (Fang et al., 2010; Wang, 2010) influence this ratio, and provide potential tools for management, as discussed in next section.

Despite improvement in initial soil water content (Table 2), alternative practices generally had small impact on seasonal water use (Table 1, Fig. 1CD). This stems from the lack of or small proportionality between change in initial soil water content and change in seasonal evapotranspiration (Fig. 2). This derives, in turn, from increased contribution of unproductive components of the water budget under alternative management practices; for example, practices that improve storage of water at sowing increase the likelihood of deep percolation (Zhang et al., 2007; Diaz-Ambrona et al., 2005). In the Loess Plateau, high amounts of residual water in the soil at harvest are not uncommon (Jin et al., 2007; Wang et al., 2011).

The attainable yield in the Loess Plateau was bounded by transpiration efficiency of 22 kg grain ha^{-1} mm^{-1} (Sadras and Angus, 2006) which is higher than the 20 kg grain ha^{-1} mm^{-1} originally proposed by French and Schultz in the 1980s (French and Schultz, 1984a,b). This upper limit aligns with the long-term improvement

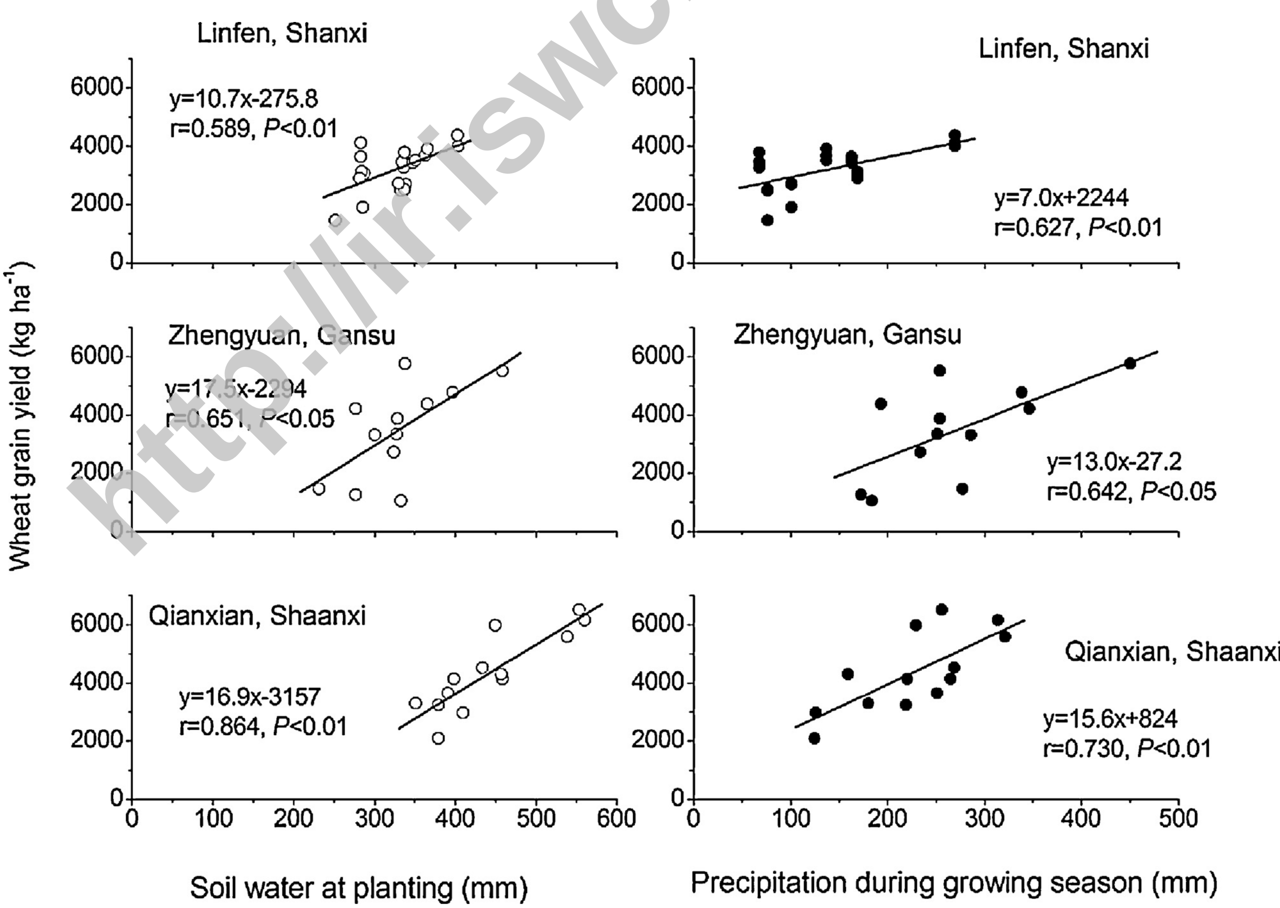

Fig. 4. Relationship between yield of wheat in the Loess Plateau and soil water content at sowing (left panels) and precipitation during the growing season (right panels). *Data sources*: Linfen, Shanxi (Wang et al., 2009); Zhengyuan, Gansu (Luo and Huang, 2009); Qianxian, Shaanxi (Liao et al., 2002).

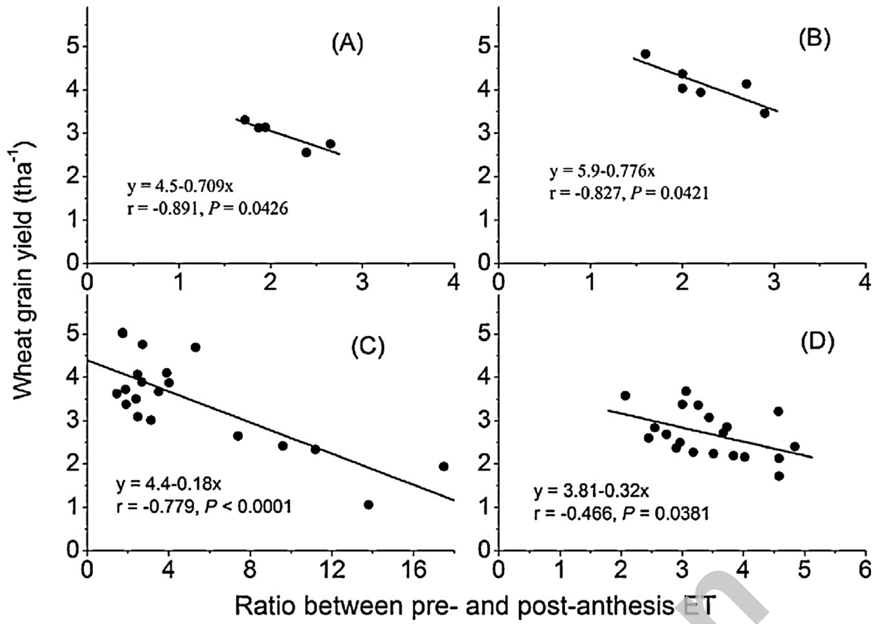

Fig. 5. Correlation between wheat yield and ratio between pre- and post-anthesis evapotranspiration in (A and B) Loess Plateau. Relationships for Australia (C and D) are shown for comparison.

Sources: Wang et al. (2003) (A); (B) Zhao et al. (1996); (C and D) O'Leary and Connor (1997) with (C) gray clay soil and (D) sandy loam soil.

of wheat yield in China (Zheng et al., 2011; Xiao et al., 2012) and elsewhere (Siddique et al., 1990; Sadras and Angus, 2006; Sadras and Lawson, 2013). The points under the boundary line in Fig. 3 represent yields that are limited by environmental (e.g. rainfall distribution), or management factors (e.g. untimely sowing).

The average WUE across all practices was 12.1 kg ha^{-1} mm^{-1}, which compares with the global average WUE of 10.9 kg ha^{-1} mm^{-1} for wheat (Zwart and Bastiaanssen, 2004). Among various practices in the region, the maximum WUE was under RM and/or RMS and the minimum was under NT. Small variation in ET indicated that increase in WUE under alternative practices was attributable to increase in yield (Table 1), which in turn relates to variation in both soil evaporation/transpiration ratio and pre/post anthesis ratio of water use (Zhang et al., 2007; Li et al., 2013) (Fig. 5).

4.2. *Implications for management*

Here we analyze practices with potential to improve water storage at sowing, reduce soil evaporation and increase crop transpiration, and modulate the partitioning of water use before and after flowering.

4.2.1. *Increase water availability and reduce water loss*

The relationship between soil water storage at sowing and yield emphasizes the importance of practices to capture both fallow and in season rainfall (Fig. 4). The alternative practices including NTS, SS, CTS and RM, consistently improved soil water storage at sowing (Table 2). On average, NTS increased initial soil water over CT from 31 mm to 49 mm for summer fallow, and similar effects were observed under SS and CTS. A larger benefit of RM in increasing soil water over CT during summer fallow was apparent. Two studies show only marginal benefits of alternative practices during winter fallow (Table 2). Overall, ridge mulched with plastic film was superior to both conventional practice and no-tillage with straw mulching in terms of capturing water during summer fallow. This was because the RM system reduces soil water evaporation by blocking exchange of water vapor at the soil–atmosphere interface (Li et al., 2001b), and increases water harvesting of small rainfall events (<5 mm) (Zhu et al., 2004b). Hence, encouraging farmers to apply this practice would contribute to higher yield.

Better management practices within the crop growing season could increase transpiration at the expense of soil evaporation. In the Loess Plateau, for example, straw mulching lowered soil evaporation by 7–16% compared with conventional tillage during a 3-year wheat experiment (Zhang et al., 2007). For spring maize, plastic mulching lowered soil evaporation by about 24% (Li et al., 2013). Hence, mulching during crop growing season is still necessary in reducing soil water loss besides mulching during fallow.

4.2.2. *Modulating the partitioning of water use before and after flowering*

Management practices that modulate the rate of canopy and root expansion, including genotype, plant population density, defoliation, root pruning and fertilizer management, can regulate the seasonal partitioning of water use.

There is significant genotypic variability in the cumulative amount of water used before and after anthesis, and this maybe relevant for drought adaptation (Solomon and Labuschagne, 2003). In the Loess Plateau, seeding density interacts with variety affecting soil water at heading and grain yield under conventional practice (Fig. 6, Wang et al., 2010). Soil water storage at heading decreased with the increased seeding density ($P < 0.05$), and grain yield showed a quadratic response to seeding density. For the tested conditions, yield peaked at 3,000,000 seeds ha^{-1} for varieties IR17 and Xifeng27 and 3,750,000 seeds ha^{-1} for Chang6818 (Fig. 6). However, yield peaked at lower sowing densities under ridge mulched with plastic film + bare furrow (<2800 thousand seeds ha^{-1}) (Shui et al., 2012; Wang and Dong, 2011). Nevertheless, local experiments have shown that high seeding rate combined with root pruning during the over-winter period can increase the accumulation of dry matter post-heading, ensure greater availability of water during grain filling and significant yield gains compared with un-pruned crops (Ma et al., 2008; Fang et al., 2010). In Australia, defoliation

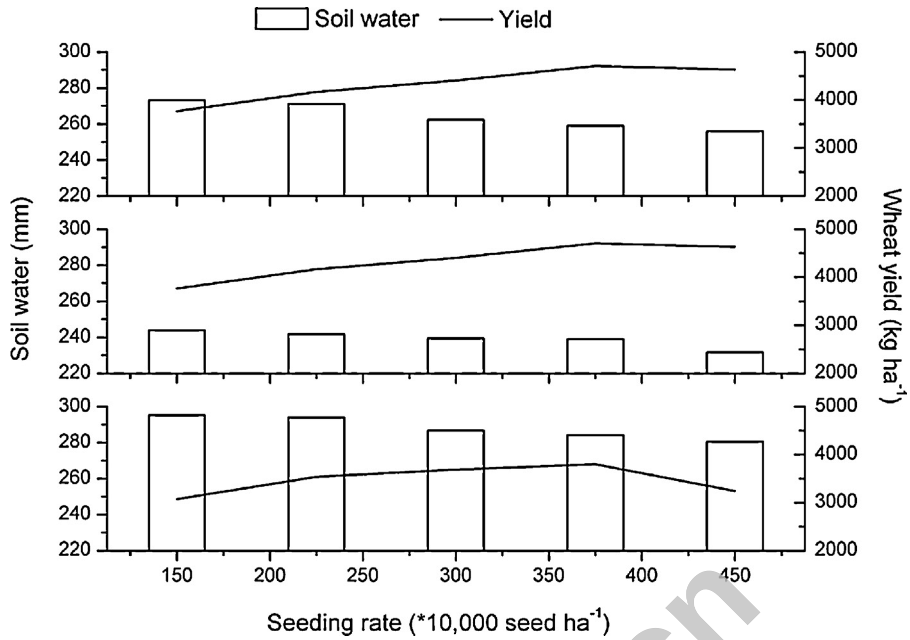

Fig. 6. Wheat yield and soil water at heading as affected by seeding rate and variety. Top panel, variety Xifeng27; middle panel, variety Chang6818; bottom panel, variety IR17.

Data source: Wang et al. (2010).

at mid to late tillering of early (April)-sown wheat could improve yield and WUE by shifting the pattern of seasonal water use (Zhu et al., 2004a).

Nutrient management, especially nitrogen application, significantly influences crop growth, water use, and yield. In the Loess Plateau, Dang et al. (1991) conducted a large number of fertilizer experiments at different sites for 8 years. They recommended rates of fertilizer ranging from 105 to 135 kg N ha^{-1} for initial available soil water >250 mm, from 98 to 120 kg N ha^{-1} for soil moisture between 200 and 250 mm, and from 83 to 105 kg N ha^{-1} for soil moisture <200 mm; the corresponding rates of P fertilizer were relative stable from 60 to 83 kg ha^{-1} in drier soil or 90 kg ha^{-1} in wetter soil. A 25-year field experiment in the same region, showed that the optimum N fertilization rates were lower in dry years (45 kg N ha^{-1}), compared with normal (135 kg N ha^{-1}) and wet years (180 kg N ha^{-1}), according to annual precipitation: dry <500 mm; normal, 500–600 mm, wet >600 mm (Guo et al., 2012). Furthermore, single and split application of nitrogen made no difference in wheat yield in dry year (400 mm yr^{-1}), while wheat yield was higher under split application for normal or wet years (Miao et al., 1997). Surveys from 2009 to 2012 in the Loess Plateau highlighted the dominance of both large rates of N fertilizer use (>200 kg ha^{-1} for about 42% of crops) and the reluctance for split application (12% of growers use a split application) (Zhao et al., 2013). The overuse of N is common, hence the opportunities to tailor better nitrogen fertilization to target yields, site and rainfall in the Loess Plateau.

5. Conclusions

Soil and crop management offers a wide range of solutions to increase and stabilize wheat yield in water-limited Loess Plateau. Comprehensive studies of soil-crop management are required that scale up from common 1–2 factors investigated in most experiments. Based on past research, the strategies for water management of dryland wheat production in the Loess Plateau include practices to (i) increase the capture and retention of both fallow and in-season rain; (ii) increase the proportion of that water productively transpired by the crop and (iii) regulate the partitioning of water use before and after anthesis. Mulching, cultivar selection, and canopy management using sowing density and fertilizer management need to be integrated. Modeling techniques in combination with GIS may facilitate the development of management options which are better tailored to a specific farmer's conditions and therefore, have a better chance of being adopted.

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Appendix 1. Database used in Fig. 3, which plots the relationship between grain yield versus ET in the Loess Plateau of China

Location	Latitude	Altitude (m)	Annual mean prec. (mm)	Annual mean temp. (°C)	Practices	Wheat type	Experimental years	Reference
Binxian, Shaanxi	35°07′	1160	582	9.3	CT, CTS, PM, RMS	Winter	2002–2005	Liu et al. (2006, 2007)
Changwu, Shaanxi	35°12′	1220	584	9.1	CT, RM, RMS	Winter	2002–2003	Dang et al. (2008)
Changwu, Shaanxi	35°12′	1220	584	9.1	CT, CTS, PM	Winter	2008–2009	Guan et al. (2011)
Changwu, Shaanxi	35°12′	1220	584	9.1	CT, CTS, RM, RMS	Winter	2007–2010	Chen et al. (2010a) and Liu et al. (2012)
Changwu, Shaanxi	35°12′	1220	584	9.1	CT, PM	Winter	2008–2009	Chen et al. (2010b)
Changwu, Shaanxi	35°12′	1220	584	9.1	CT, RM	Winter	2009–2010	Xue et al. (2011)
Fuping, Shaanxi	34°52′	500	533	12.6	CT, PM	Winter	1998–1999	Wang and Zhang (1999)
Heyang, Shaanxi	35°19′	910	582	10.5	CT, NTS	Winter	2001–2004	Zhang et al. (2007)
Heyang, Shaanxi	35°19′	910	582	10.5	CT, NTS, SS	Winter	2008–2009	Mao et al. (2010)
Heyang, Shaanxi	35°19′	910	582	10.5	CT, CTS	Winter	2007–2009	Liu et al. (2010)
Heyang, Shaanxi	35°19′	910	582	10.5	CT, RM, RMS	Winter	2008–2010	Li et al. (2011a)
Heyang, Shaanxi	35°19′	910	582	10.5	CT, RM	Winter	2007–2010	Bai et al. (2010) and Yang et al. (2011)
Qianxian, Shaanxi	34°31′	900	584	10.9	CT, PM	Winter	1997–1998	Han and Wang (2001)
Yangling, Shaanxi	34°17′	525	550	13.0	CT, RM	Winter	2000–2001	Wang et al. (2004)
Yangling, Shaanxi	34°17′	525	550	13.0	CT, CTS, RM	Winter	2003–2005	Wang et al. (2012a)
Dingxi, Gansu	35°33′	1895	426	6.3	CT, CTS	Spring	1997–1998	Huang et al. (2005)
Dingxi, Gansu	35°57′	1970	420	6.2	CT, PM	Spring	1999–2000	Li et al. (2004a)
Dingxi, Gansu	35°57′	1970	420	6.2	CT, PM	Spring	1999–2000	Li et al. (2004b)
Anding, Gansu	35°28′	1971	391	6.2	CT, NT, NTS, PM	Spring	2002–2005	Huang et al. (2008)
Dingxi, Gansu	35°57′	1970	420	6.2	CT, PM	Spring	2008	Hou et al. (2010)
Dingxi, Gansu	35°28′	1971	391	6.2	CT, NT, NTS	Spring	2008	Wang et al. (2010)
Dingxi, Gansu	35°28′	1971	391	6.2	CT, PM	Winter	2009	Zhang et al. (2011)
Qingyang, Gansu	35°40′	1298	548/562	8.3	CT, NT, NTS, CTS	Winter	2001–2005	Zhou et al. (2008)
Zhenyuan, Gansu	35°30′	1290	542	8.3	CT, PM	Winter	1997–2003	Fan et al. (2005)
Zhenyuan, Gansu	35°30′	1290	542	8.3	CT, NT	Winter	2005–2008	Zhang et al. (2010)
Luoyang, Henan	34°30′	324	614	13.7	CT, RT, NTS, SS	Winter	1999–2005	Su et al. (2007)
Luoyang, Henan	34°30′	324	575	13.7	CT, RT, NTS, SS	Winter	2000–2005	Jin et al. (2007)
Luoyang, Henan	34°30′	324	643	13.7	CT, CTS, PM	Winter	2004–2005	Zhang et al. (2008)
Luoyang, Henan	34°30′	324	600	14	CT, RM	Winter	2007–2008	Wang et al. (2011)
Linfen, Shanxi	36°5′	420	450	10–12	CT, NTS, SS	Winter	1992–1995	Wang et al. (2012b)
Tunliu, Shanxi	36°18′	945	550	10	CT, NT	Winter	1987–1990	Wang et al. (2012b)
Linfen, Shanxi	36°4′	420	500	10–12	CT, CTS, NTS	Winter	1999–2005	Wang et al. (2009)
Linfen, Shanxi	36°4′	458	468	12.2	CT, RM	Winter	2008–2009	Kang et al. (2010)
Tunliu, Shanxi	36°18′	945	550	10	CT, CTS	Winter	1989–1992	Zhao et al. (1996)
Wenxi, Shanxi	35°21′	700	430	12.5	CT, RM, PM	Winter	2011–2012	Zhao et al. (2012)
Pengyang, Ningxia	35°79′	1800	435	8.1	CT, SS	Winter	2007–2010	Hou et al. (2012)

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