Field Crops Research 163 (2014) 55–63

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Water use efficiency of dryland maize in the Loess Plateau of China in response to crop management

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ARTICLE INFO

Article history:
Received 7 March 2014
Received in revised form 3 April 2014
Accepted 3 April 2014
Available online 29 April 2014

Keywords:
Evapotranspiration
Maize
Mulching
Rainfall
Tillage
Soil water at sowing
Yield
Water use efficiency

ABSTRACT

Owing to the critical situation of water resources and demographic pressure, improvement of crop water use efficiency (WUE = grain yield per unit seasonal evapotranspiration) in the dryland area of Loess Plateau of China is crucial. The aims of this study were (i) quantifying WUE of dryland maize (*Zea mays* L.) in the Loess Plateau, and (ii) identifying management practices that improve both WUE and yield. We compiled a data base of 36 sets of experiments spanning more than 20 years, where conventional practice (CT) was compared with alternatives including RT/NT, reduced or no tillage without straw mulching; SM, straw mulching; PM, plastic film mulching 100%; RM, plastic film mulching 50% or more; RMS, ridge mulched with plastic film + furrow mulched with crop straw.

Yield ranged from 1.12 to 14.6 Mg ha^{-1} and WUE from 2.8 to 39.0 kg ha^{-1} mm^{-1}; the maximum yield and WUE were achieved under RM, PM and RMS and the minimum under CT. Practices had small and inconsistent effect on seasonal evapotranspiration, hence variation in yield and WUE were attributable to changes in both the contribution of soil evaporation to total evapotranspiration and the partitioning of seasonal water use before and after silking. The yield-evapotranspiration relationship indicated that attainable WUE was 40 kg ha^{-1} mm^{-1}. Few crops, however, reached this efficiency emphasizing the opportunities for improvement. Implications for crop management and further improvement in yield and WUE are discussed.

1. Introduction

Water stress is the main limiting factor for crop production in rainfed farming systems in arid and semi-arid areas (Debaeke and Aboudrare, 2004). In China, rainfed farming systems account for about 25 Mha, mostly located in the semi-arid Loess Plateau (from 100°54′ to 114°33′E and 33°43′ to 41°16′N) (Deng et al., 2006). Soils and climate of the region have been described in detail (Huang et al., 2011; Li and Xiao, 1992; Turner et al., 2011). Briefly, well-drained, light and medium loamy soils account for 90% of the soils in the region, with silt content (0.001–0.05 mm) around 60–75%. The climate is mostly semiarid, with long-term annual precipitation ranging from 150 to 300 mm in the north to 500–700 mm in the south but declining trends have been recorded between 1961 and 2010 (Wang et al., 2012a). Owing to population growth and scarcity of water resources, the challenge is to increase food production with less water. Technologies for improving crop water use efficiency (WUE = grain yield per unit seasonal evapotranspiration) are critical for sustainable crop production and local food security. Therefore, quantifying the attainable WUE is essential to diagnose current crop and field management and identify opportunities for improving WUE without yield penalty.

Rainfed cropping systems in the region accounts for more than 80% of the arable land (Huang et al., 2011). The limited water and frost-free window allows for a single crop per year. Family farms, typically 0.7–1 ha in size, are prevalent in the Loess Plateau (Nolan et al., 2008; Huang et al., 2011) where maize and wheat are the dominant crops (Turner et al., 2011) and input cost of production ranges from 60 to 200 $US/ha (Nolan et al., 2008). Machinery is gradually replacing animal and human labour for farm operations

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http://dx.doi.org/10.1016/j.fcr.2014.04.003
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Fig. 1. Plastic mulching in maize crops in Gansu Province, Loess Plateau of China.

such as sowing and harvesting. Crop yield is primarily driven by annual rainfall and its distribution (Huang et al., 2011). The average yield in tableland areas with higher rainfall, for example in Qingyang, are 3.5 Mg ha^{-1} for winter wheat and 6.5 Mg ha^{-1} for maize, whereas in the hilly area with lower rainfall, for example in Dingxi, is 1.0 t ha^{-1} for wheat (Nolan et al., 2008).

As the main crop, maize growing season spans from end of April to September, whereas 50–60% of annual precipitation falls as rain during the summer, from June to September. The mismatch between the rain season and maize cycle means the crop is consistently constrained by rainfall during early growth stages, whereas erratic rainfall at later stages may also reduce grain yield. Within this context, innovations in soil and crop management are sought to improve yield, water uptake and WUE. Conservation tillage and other field management practices, such as mulching with plastic film, have been extensively tested and applied to crop production. In a review of Chinese cropping systems over the past decade, Xie et al. (2008) showed that conservation tillage increased crop yield or gave similar yields to conventional tillage in 89% of studies, and decreased crop yields in the remaining 11% of studies. Plastic film mulching practices include alternating ridges and furrows, with only the ridges mulched with plastic film (Li et al., 2001; Wang et al., 2009), and a recently developed technique of double ridges and furrows mulched with plastic film. The latter technique has been reported to improve yield significantly (Liu et al., 2009; Zhou et al., 2009), and it has been applied to more than 200,000 ha in the northwest of the Loess Plateau Fig. 1.

Despite limitations that are widely acknowledged (e.g. French and Schultz, 1984), boundary functions provide a robust framework to analyze water-limited yield (French and Schultz, 1984; Angus and van Herwaarden, 2001; Sadras and Angus, 2006; Grassini et al., 2009a, 2009b). This approach was used to assess water use efficiency of wheat in low rainfall environments worldwide (Sadras and Angus, 2006), wheat in the Loess Plateau (Zhang et al., 2013), sunflower in Argentina (Grassini et al., 2009a) and maize in USA (Grassini et al., 2009b). Despite the large number of yield/evapotranspiration (ET) relationships reported for maize in the Loess Plateau, water use efficiency in this region has not been benchmarked. Importantly, this type of benchmark is useful to compare alternative management practices (Zhang et al., 2013).

In this work, we compiled yield and ET data from field-grown maize under different practices in the Loess Plateau to: (i) analyze yield, water use and WUE responses to various agronomic practices; (ii) determine boundary functions for the relationship between grain yield and seasonal ET; and (iii) discuss the agronomic factors with potential to reduce gaps of yield and WUE. By accomplishing this objective we are also making valuable information originally published in Chinese journals more broadly available.

2. Methods

Combining key words ‘maize’, ‘evapotranspiration’ and ‘Loess Plateau’, we searched for papers published between 1996 to 2012 in three data bases: Elsevier ScienceDirect, SpringerLink and China Academic Journal Network Publishing Database. Yield (with about 15% moisture content) and evapotranspiration (ET) data were taken from tables or digitized from graphs. We identified 36 studies carried out in smallholder farms and experimental stations under rain-fed conditions in the Loess Plateau (Appendix 1). The approach to data compilation and analysis has been described in Zhang et al. (2013). To avoid excessive cross-referencing, here we summarize the method. 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 crops received adequate and balanced amounts of fertilizer to ensure no nutrient-related constrain to crop growth, hence, maize yield was mainly driven by water supply and the influence of other agronomic practices on soil water balance (e.g. tillage method). Reported ET was calculated as in-season precipitation plus change in soil water content between sowing and harvest at least for a 2 m soil layer. This assumption could lead to (i) underestimation of ET and overestimation of WUE with shallower soil layer (i.e. <2 m) but this is unlikely in the deep soils of the regions, or (ii) overestimation of ET and underestimation of WUE particularly in wetter seasons were deep drainage and runoff might bias estimates (Sadras and Angus, 2006). WUE was calculated as the ratio of yield and ET.

In all these papers, local conventional tillage (CT) was compared with one or more alternative practices including: RT/NT, reduced tillage or no tillage without straw mulching; SM, no tillage or conventional tillage or subsoiling with straw mulching; PM, plastic film mulching 100% (including biodegradable film and liquid film applied in four studies, i.e. Zhang et al., 2012a; Li et al., 2012; Xiaoli et al., 2012; Wang et al., 2011); RM, plastic film mulching about 50%; RMS, ridge mulched with plastic film + furrow mulched with crop straw. The local conventional tillage was ploughed soil with no ground cover. In most studies, maize was harvested at maturity; harvest time varied between treatments thus capturing the full agronomic implications of difference practices. Plastic mulch was removed after harvest in most cases, but some experiments kept it for soil water conservation during fallow. Nevertheless, new installation is regularly made before sowing irrespective of maintenance of mulch during fallow.

Standard errors for yield and ET were not always reported so no attempt was made to account for variable errors among experiments (Hunter and Schmidt, 1990). Descriptive statistics were calculated for all three traits, i.e. yield, ET and WUE. Using local conventional tillage (CT) as reference, we calculated the percent change in yield, ET and WUE for each experiment as:

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

Where subscripts indicate conventional (CT) and alternative practices (AP) listed above. Frequency distributions of changes in yield, ET and WUE were calculated for each alternative practice except for RT/NT and RMS, as these had only 10–11 data points. Independent-samples *t*-test was used for pair-wise comparisons of CT and alternative management practices for yield, ET and WUE. The SPSS software package (v16.0) was used for all the statistical analyses.

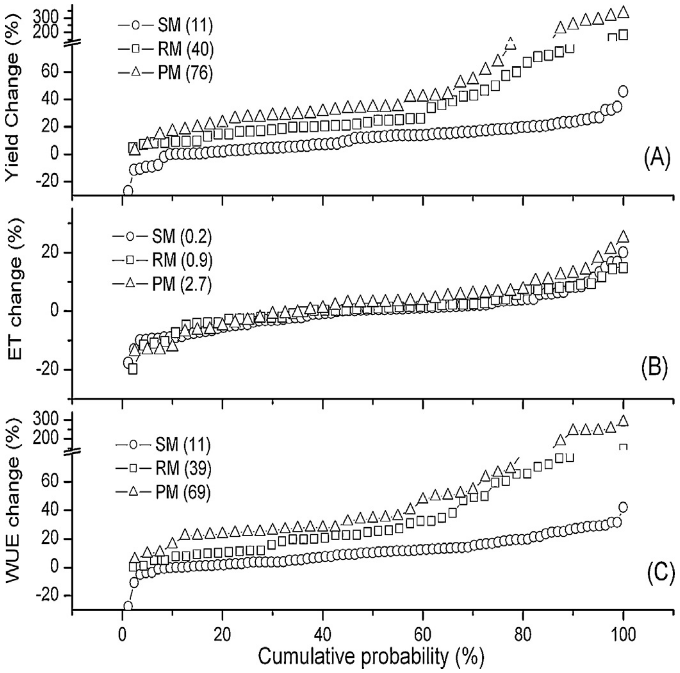

Fig. 2. Frequency distribution of change in (A) yield, (B) evapotranspiration and (C) water use efficiency of maize in the Loess Plateau. Changes are the value of the variable under alternative practice relative to local conventional tillage. Alternative practices SM, no tillage or subsoiling or conventional tillage with straw mulching; PM, plastic film (or biodegradable or liquid film) mulching 100%; RM, plastic film mulching about 50%; Numbers between brackets are average percent change in yield, ET and WUE.

Boundary function analysis followed the approach of French and Schultz (1984). Yield is plotted against seasonal crop ET, and a linear function is fitted to those data that delimit the upper frontier for yield. This linear frontier has agronomically meaningful parameters, i.e. the slope represents the seasonal transpiration-efficiency (TE) and the *x*-intercept is usually interpreted to be the (minimum) amount of seasonal soil evaporation (Sinclair et al., 1984).

3. Results

3.1. Yield

Grain yield ranged from 1.12 to 14.6 Mg ha^{-1} across soils, seasons, and treatments (Table 1). The average for each practice ranged from 5.96 Mg ha^{-1} for CT$_{SM}$ to approximately 9.8 Mg ha^{-1} for RM and PM. On average, alternative practices increased yield relative to conventional by 11% under SM to 76% under PM (Fig. 2A). 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 are presented for SM, RM and PM treatments (Fig. 2A); small sample size precluded analysis for RMS. The results further highlighted the spread of yield responses. Yield responses under stubble mulch (SM) were largely neutral to positive, with yield increase up to 45%. The RM and PM practices had neutral to large positive effects on yield, with 20–30% records of improvement larger than 50% (Fig. 2A). Yield change under RMS was 35% on average, and varied from 12% to 73%.

3.2. Seasonal crop evapotranspiration

Seasonal ET ranged from 253 to 706 mm, but means for different practices showed a relatively narrow range, from 380 to 398 mm (Table 1). Frequency distributions of changes in ET also showed an overall neutral effect, with few cases where alternative practices increased or decreased ET more than 10% (Fig. 2B). In addition, RMS generally had neutral effect on ET relative to CT (data not shown).

Analysis of a subset of studies reporting soil water content at sowing showed consistent gains for SM, PM, RM, and RMS in relation to conventional tillage except one year at one site (Table 2). On average, SM increased initial soil water over CT from 16 to 27 mm, and RM increased it from 9 to 53 mm. A consistent benefit of PM in increasing soil water over CT during fallow was apparent, from 18 to 65 mm. Overall, PM was superior to other practices in terms of capturing water during fallow.

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. 3. In some cases, change in ET correlated with change in initial soil water, but the slopes are lower than 1 thus indicating that for 1 mm increase in initial soil water, ET increased by 0.6–0.9 mm (Fig. 3A and B). In other cases, changes in evapotranspiration were unrelated to changes in initial soil water content (Fig. 3C and D).

3.3. Relationships between yield and water use

Fig. 4 shows grain yield as a function of evapotranspiration for the pooled data. A boundary line with slope 40 kg grain ha^{-1} mm^{-1} (a proxy to attainable transpiration efficiency, TE) and *x*-intercept = 40 mm provided an upper limit for all the data. Crop WUE ranged from 2.8 to 39.0 kg ha^{-1} mm^{-1} across soils, seasons, and treatments, whereas averages for each practice ranged from 15.6 to 26.2 kg ha^{-1} mm^{-1} (Table 1), which accounted for 39–66% of attainable TE. Water use efficiency improved an average of 11% with SM, 35% with RMS, 39 with RM and 69% with PM (Fig. 2C).

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

Practices	No. of data (n)	Grain yield (Mg ha^{-1})		ET (mm)		WUE (kg ha^{-1} mm^{-1})	
		Mean	Range	Mean	Range	Mean	Range
SM	84	6.48 a	3.1–11.7	390 a	253–691	17.4 a	8.2–29.2
CT$_{SM}$		5.96 a	2.6–11.4	396 a	253–706	15.6 a	6.3–27.1
RM	47	9.89 a	4.83–14.6	380 a	282–554	26.2 a	14.0–39.0
CT$_{RM}$		7.50 b	2.16–12.2	387 a	261–582	18.0 b	7.8–30.3
PM	40	9.70 a	5.5–14.33	398 a	278–545	24.6 a	17.4–36.9
CT$_{PM}$		6.21 b	2.05–8.89	380 a	280–582	15.8 b	6.5–29.4
RMS	11	9.59 a	4.98–11.52	394 a	277–538	24.5 a	17.4–31.6
CT$_{RMS}$		7.25 b	4.1–8.84	398 a	261–582	18.6 b	14.7–27.1

Note: SM, no tillage or subsoiling or conventional tillage with straw mulching; RM, plastic film mulching 50% or more; PM, plastic film mulching 100%; RMS, ridge mulched with plastic film + furrow mulched with crop straw; CT, conventional tillage, the subscripts indicate corresponding CT of alternative practices listed in the first column. Different lower case letters in the same column mean significant difference between alternative practice and its corresponding CT tested by t-test ($P < 0.05$).

Table 2
Change in water content in soil profile (0–200 cm) at maize sowing under various management practices compared with conventional tillage.

Practice	Location	Min.–Max (mm)	Average (mm)	Experimental years	Reference
SM	Heyang, Shaanxi	13–38	23	2007–2009	Cai et al., 2011
	Heyang, Shaanxi	16–33	26	2007–2009	Shang et al., 2010
	Pengyang, Ningxia	6–32	18	2007–2010	Gao et al., 2012
	Shouyang, Shanxi	−2–40	27	2003–2008	Wang X., et al., 2011
RM	Heyang, Shaanxi	7–14	9	2007–2010	Li et al., 2012
	Heyang, Shaanxi	11–47	27	2009–2010	Zhang et al., 2012
	Zhenyuan, Gansu	–	53	1998–2000	Wang, 2001
	Zhenyuan, Gansu	–	36	1999–2002	Fan et al., 2005
	Zhenyuan, Gansu	11–34	20	1999–2010	Wang et al., 2012a,b
PM	Xifeng, Gansu	36–46	42	2002–2004	Li et al., 2006
	Jingyuan, Gansu	34–46	40	2006–2008	Yang et al., 2010
	Yuzhong, Gansu	40–55	47	2006–2008	Yang et al., 2010
	Zhuanglang, Gansu	52–68	60	2006–2008	Yang et al., 2010
	Qinzhou, Gansu	58–72	65	2006–2008	Yang et al., 2010
	Anding, Gansu	39–58	49	2005–2007	Liu et al., 2008
	Zhenyuan, Gansu	46–61	53	2005–2007	Liu et al., 2008
	Yuzhong, Gansu	15–60	38	2007–2009	Zhang et al., 2010
	Zhuanglang, Gansu	24–60	42	2008–2010	Liu et al., 2012
	Heyang, Shaanxi	16–21	18	2007–2010	Li et al., 2012
	Xixian, Shanxi	56–65	61	–	Dang et al., 2006
	Pengyang, Ningxia	33–77	55	–	Ma et al., 2011

Note: SM, no tillage, subsoiling or conventional tillage with straw mulching; PM, plastic film (or biodegradable or liquid film) mulching 100%; RM, plastic film mulching 50% or more.

Significant correlations were found between yield and both soil water at sowing (Fig. 5) and pre-silking water use (Fig. 6). No association was found between yield and post-silking water use (data not shown). As the benchmark in Fig. 4 is based on seasonal evapotranspiration, the association between yield and water use before silking in a subset of data (Fig. 6) suggests seasonal distribution of water supply could explain part of the gaps between boundary line and data points below it.

4. Discussion

4.1. *Yield responses to alternative practices*

Owing to the spatial and temporal variation in weather, differences in soils and crop management practices such as sowing date and sowing density, there was a large variation in yield for a given target practice, i.e. CT and alternatives. The neutral or adverse effect

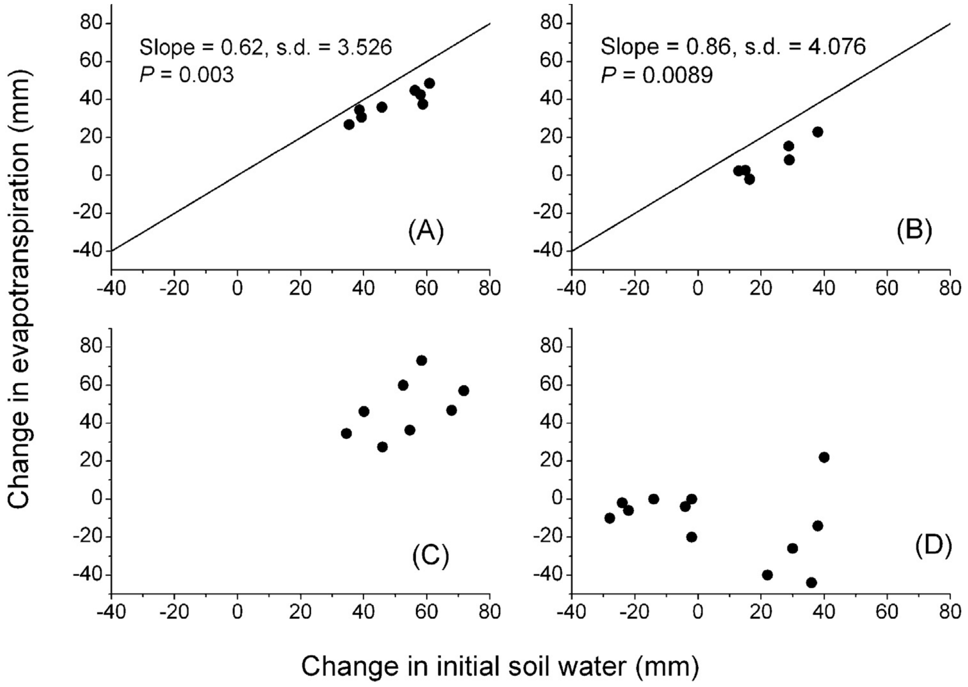

Fig. 3. Relationship between change in seasonal evapotranspiration of maize and change in soil water content at sowing in the Loess Plateau. Changes refer to values measured under alternative management relative to conventional practice. In (A and B) the lines are $y = x$. Alternative practices are: (A) PM, (B) SM, (C) PM, and (D) RT, SM; where PM is plastic film mulching 100% during certain time of fallow before sowing; SM is straw mulching during fallow; RT is reduced tillage without straw mulching. Sources: (A) Liu et al. (2008), (B) Cai et al. (2011), (C) Yang et al. (2010), (D) Wang X., et al. (2011). The slopes are indicated increments of evapotranspiration contributed by per mm increase in presowing soil water.

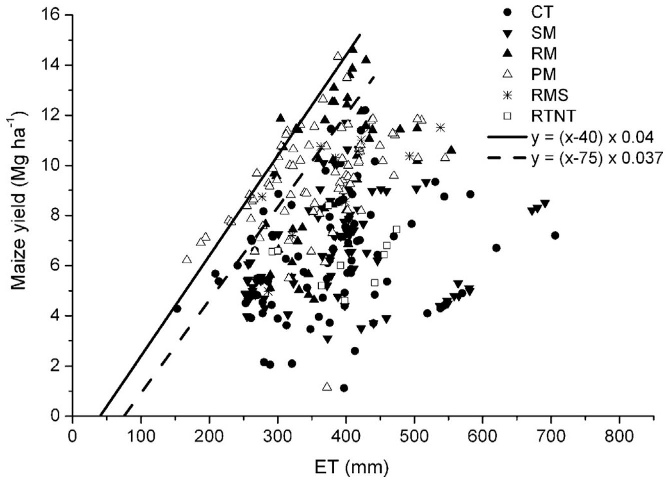

Fig. 4. Relationship between maize grain and evaportranspiration (ET) in the Loess Plateau of China ($n = 314$). The solid line is based on French and Schultze (1984) frontier concept, with x-intercept = 40 mm and slope = 40 kg grain ha^{-1} mm^{-1}. For comparison we included the dashed line with slope of 37 kg grain ha^{-1} mm^{-1} reported for maize in the Western Corn-Belt by Grassini et al. (2009b).

of straw mulching on yield, observed in approximately 45% of cases, can be attributed to low soil temperature, which slows down maize development (Dam et al., 2005; Zhang et al., 2011). Hence, application of straw mulching in the region needs to consider its impact on soil thermal condition and consequences for crop development.

In contrast to the inconsistent effects of stubble on yield, alternative practices using plastic film mulching (RM, PM and RMS) significantly increased maize yield by more than three tons per hectare (Table 1, Fig. 2A). This could be attributed to a combination of factors including higher soil temperature that accelerated maize development (Liu et al., 2010b; Li et al., 2013a), higher available soil water (Liu et al., 2010c; Li et al., 2013b; Zhang et al., 2011), lower soil evaporation (Li et al., 2013b), improved capture of radiation (Liu et al., 2010b), enhanced nutrient uptake and reduced weed pressure (Kasirajan and Ngouajio, 2012). However, due to depletion of soil water and fertility derived from RM and PM practices (Li et al., 2007; Zhang et al., 2011), the RMS might be a sustainable means of increasing crop yield and WUE in the region.

4.2. Water use and water-yield relationships

Despite improvement on initial soil water content (Table 2), alternative practices generally had small impact on seasonal water use (Table 1, Fig. 2B and Fig. 3) except for PM, for which about 20% of cases showed gains in ET. This indicates that alternative practices mainly change the ratio between soil evaporation and maize transpiration (Li et al., 2013b). The attainable maize yield in the Loess Plateau was bounded by a line with slope representing transpiration efficiency = 40 kg grain ha^{-1} mm^{-1}, and x-intercept representing soil evaporation = 40 mm. For maize in the western USA Corn Belt, the boundary transpiration efficiency was 37 ± 1.3 kg grain ha^{-1} mm^{-1} and the soil-evaporation parameter 75 mm (Grassini et al., 2009b). Of interest, the boundary transpiration efficiency of 37 kg grain ha^{-1} mm^{-1} estimated by Grassini et al. (2009b) applies to our data, except where crops were grown with plastic mulch. The higher transpiration efficiency and lower soil evaporation in our data set compared with the parameters for maize in USA were therefore mostly associated with crops under plastic mulch (triangles in Fig. 4), reinforcing the gain in efficiency and reduced soil evaporation under this practice. Part of the increased transpiration efficiency maybe explained by higher radiation use efficiency (RUE) under this practice; this is supported by both local experiments (Liu et al., 2010b) and theory on the link between RUE and TE (Stockle and Kemanian, 2009). Early studies reported correlations between RUE and TE in sunflower (Sadras et al., 1991).

Among various practices in the region, the highest WUE was achieved under RM, PM and RMS and the lowest was under CT. Small variation in ET indicated that increase in WUE under alternative practices was attributable to differences in yield (Table 1), which in turn relates to variation in soil evaporation/transpiration ratio (Li et al., 2013b) and pre-silking water use (Fig. 5).

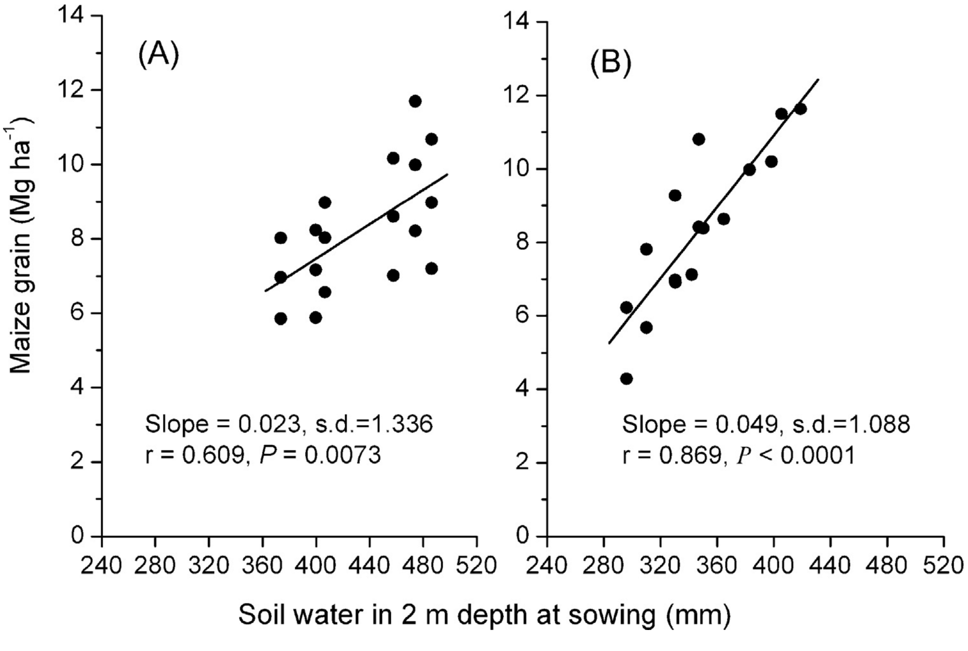

Fig. 5. Soil water content and maize yield relationship. Practices are: (A) CT, SM and (B) CT, PM; where SM is straw mulching during fallow and crop season; PM is plastic film mulching 100% during fallow and crop season. Source: (A) Shang et al., 2010; (B) Yang et al., 2010.

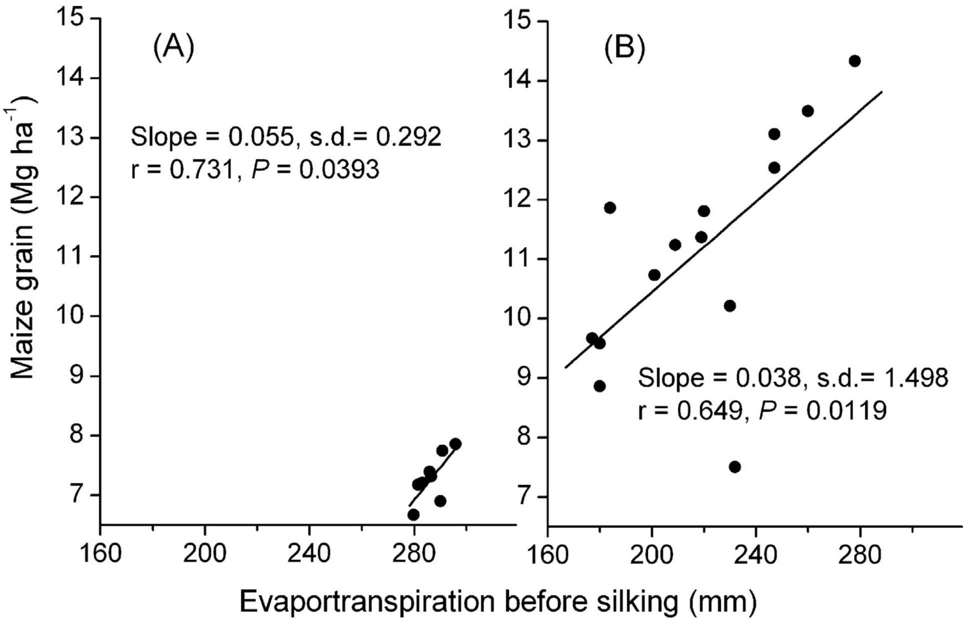

Fig. 6. Correlation between evapotranspiration before silking with maize yield. Source: (A) Cai et al., 2011; (B) Li et al., 2010.

The average WUE across all practices was 21.5 kg ha^{-1} mm^{-1}, which compares well with global measured average WUE of 18.0 kg ha^{-1} mm^{-1} for irrigated maize (Zwart and Bastiaanssen, 2004), again reinforcing the effective use of agricultural practices in the region. Nonetheless, large and frequent yield gaps (i.e. the points under the boundary line in Fig. 4) may result from environmental (e.g. rainfall pattern) and management factors (e.g. sowing date). For example, rainfall close to the critical period of kernel number determination would increase yield and WUE compared to rainfall concentrated in earlier or later parts of the season (Otegui et al., 1995; Passioura and Angus, 2010). A large proportion of small rainfall events favours soil evaporation losses, as documented elsewhere (Sadras, 2003). Then, mismatch between plant population density and rainfall could also contribute to the gap (Barbieri et al., 2012; Grassini et al., 2011a). In addition, different varieties might also contribute to the scatter of yield vs. ET data (Liu et al., 2010a).

Grassini et al. (2011b) found a ceiling for yield of 15 Mg ha^{-1} when seasonal water supply reached about 650 mm for irrigated maize in USA. In comparison, our data set suggests a ceiling of yield of 14.4 Mg ha^{-1} for ET => 400 mm (Fig. 4). This can be related to direct effects of excess water, or indirect effects such as lower temperature and less radiation during critical reproductive stages in extremely wet seasons (Cirilo and Andrade, 1994). Other reasons may contribute further to the apparent discrepancy. For example, in the present study the residual soil moisture at maturity has been subtracted from the ET estimate, while Grassini et al. (2011b) have not. Also, lower vapor pressure deficit in the Loess Plateau compared to the western US Corn Belt (Sadras and Angus, 2006) accounts for part of the difference in TE between regions.

4.3. Implications for management

4.3.1. Increasing water availability and reducing water loss

The relationship between maize yield and soil water at sowing highlighted the importance of water supply for guaranteeing crop growth at early stages, when rainfall is scarce in the Loess Plateau. A larger benefit of PM in increasing soil water over CT during fallow was apparent (Table 2). This was because the PM blocks soil evaporation (Li et al., 2001), and increases harvesting of small rainfall events (<5 mm) (Zhu et al., 2004). Greater amounts of stored soil water at sowing could support higher plant population density conducive to greater biomass accumulation and ultimately greater yield (Nielson et al., 2010). Hence, encouraging farmers to apply PM and adjusting other practices such as sowing density would be important to improve maize production and WUE in this region.

4.3.2. Modulating the partitioning of water use before and after flowering

Crop water use depends on water availability, population density and structure and nutrient supply, as these factors modulate the rate of canopy and root expansion. Based on relationship in Fig. 6, previous studies have shown that higher population density increased crop ET during the initial stages of maize growth (Barbieri et al., 2012) or before silking (Alessi and Power, 1974, 1976). In the Loess Plateau, soil water availability increased under PM (Table 2) thus providing the opportunity for increased population density leading to higher yield (Liu et al., 2014), and WUE. Nevertheless, further studies are needed to define plant population density according to pre-sowing stored water.

There are also opportunities to tailor nitrogen fertilization to soil management, site and rainfall. A 10-year field experiment under conventional practice showed that in dry seasons maize yields decreased with increasing N rate above 120 kg ha^{-1}, and in normal or wet seasons, maize yields increased with increasing N to 240 kg ha^{-1} (Zhou et al., 2004). Under plastic film mulching, Zhang et al. (2012b) reported the optimum N fertilization rates were lower in dry season or with low available soil water at sowing (150 kg N ha^{-1}), compared with normal season and high available soil water at sowing (>300 kg N ha^{-1}). Furthermore, Wang et al. (2012b) documented that split application of nitrogen contributed both high maize yield and better grain quality compared with single application under plastic film mulching in both fallow and growing season period. In addition, N rate of 200 to 250 kg N ha^{-1} with split application favoured water use and biomass accumulation before silking which could increase yield closer to potential (13.1 to 15.1 Mg ha^{-1}) from dry to wet seasons under PM (Liu et al., 2014).

Therefore, PM during fallow and growing season would buffer dry spells, and allowing for a refined N management determined by local yield target based on cultivar and sowing density.

In conclusion, soil and crop management offer a range of solutions to increase maize yield and WUE in water-limited Loess Plateau. To improve dryland maize production and close yield and WUE gaps, strategies include (i) increase the capture and retention of fallow rain through mulching, especially plastic cover; (ii) increase the proportion of water productively transpired by the crop in-season through mulching, especially plastic cover combined with crop residue and (iii) increase ET before silking by adjusting population density and fertilizer N management.

Acknowledgements

This study was financially supported by the Special Fund for Agro-scientific Research in the Public Interest of China (201103003) and Agricultural Scientific Research Talent and Team Program of China. Fu Li is greatly acknowledged for providing the photograph of plastic mulching. The support of Northwest A & F University for VS work in the Loess Plateau is gratefully acknowledged.

Appendix A. References for appendix

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