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

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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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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:

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

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