Suitability of Mulch and Ridge-furrow Techniques for Maize across the Precipitation Gradient on the Chinese Loess Plateau

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Abstract

Mulch and ridge-furrow are effective techniques to improve water harvest, reduce evaporation and increase crop productivity in dry rainfed areas. We collected grain yield data of maize (*Zea mays L.*) across the precipitation gradient on the Loess Plateau under three treatments: (1) CK, flat plot without mulch; (2) HM, half-mulch flat plot, i.e. alternating mulched row and bare row without ridge-furrow; and (3) DRM, double ridges and the furrow fully mulched with plastic film. Maize grain yields were highest in the DRM treatment and lowest in the CK treatment. Mulch or ridge-furrow with mulch have increased maize grain yield significantly. The highest increase was found in low growing season precipitation regimes. Grain yields of the three treatments trended to converge in high growing season precipitation regimes. Regressions between grain yields and growing season precipitation for the three treatments showed that maize yields increased linearly with precipitation for CK; statistically significant quadratic models were found for HM and DRM treatments. The economic net incomes were calculated based on yields and inputs of capital and labor for the three treatments. Considering both water resource and economic outcome, we recommend that a precipitation range of 196-532 mm is most suitable for mulch and ridge-furrow techniques for maize on the Loess Plateau. Spatially, CK and HM treatment were most suitable for small parts of the southeast part of the plateau and DRM was suitable for most of (87%) the plateau.

Keywords: precipitation, maize, plastic film mulch, ridge, furrow

1. Introduction

Agricultural productivity in semi-arid area is highly dependent on water availability (Li et al., 1999; Ye et al., 2010; Zhao, 1996). The Loess Plateau in northwest of China (Figure 1), covering an areas of 640,000 km^2 or about 6.7% of the total land area of China (Zhang & Liu, 2010), is mainly characterized by a semiarid monsoon climate (also includes a small part of arid and sub-humid areas). Lacking other water resources for irrigation, precipitation is the only water resource for agriculture production. Low and variable precipitation combined with high evaporation (annual free water evaporation can be three times higher than annual precipitation) often lead to low crop yields on the Loess Plateau (Li et al., 2001; Liu et al., 2009; Wang et al., 2004). Therefore, rainwater harvesting and soil moisture conservation play an important role in agricultural production (Li et al., 1999; Liu et al., 2009; Zhao, 1996).

Mulches have long been used in agriculture to reduce water loss through evaporation, (Li et al., 1999). The technique has been successfully applied to a number of crops including wheat (*Triticum aestivum*) (Chakraborty et al., 2008; Li et al., 1999) and maize (*Zea mays L.*) (Wang et al., 2011a; Zhou et al., 2012). Straw is an effective mulch material (Langdale et al., 1992), but the application of straw mulch is restricted on the Loess Plateau because grain yield may be decreased due to lower soil surface temperature (Gao & Zhao, 1995). To address this problem, plastic (polyethylene) film mulch was introduced to China in 1978, and the technique has since been adopted widely (Luo, 1982). The conventional plastic film mulch technique for maize is called "half-mulch flat-plot (HM)" i.e. alternating plastic film mulched row and bare row without ridge (Liu et al., 1989). Ridge and furrow have been developed to harvest rainwater after that, and a new mulching pattern-double

ridges and the furrow fully mulched with plastic film (DRM)-has been developed for maize since 2007 and achieved a significant improvement in grain and forage production (Zhou et al., 2012). The new planting and mulching pattern has been wieldy adopted. For example, land area using this pattern reached 1.93×10^5 ha in Gansu Province in northwest of China during 2008, which occupied about 7% of the total cropland and contributed 20% to the total grain production (Wang, 2009) (http://www.gs.xinhuanet.com/news/2009-01/17/content_15482691.htm, access 8 June 2012). In 2012, this pattern is expected to be adopted over 1×10^6 ha land areas in four major dryland farming provinces (whole Shanxi and Ningxia provinces and a large part of Gansu and Shaanxi provinces belong to the Loess Plateau) in China, the grain yield of maize is expected to be 3.21×10^5 ton (http://xbkf.chinawestnews.net/system/2010/06/25/010283475.shtml, access 8 June 2012).
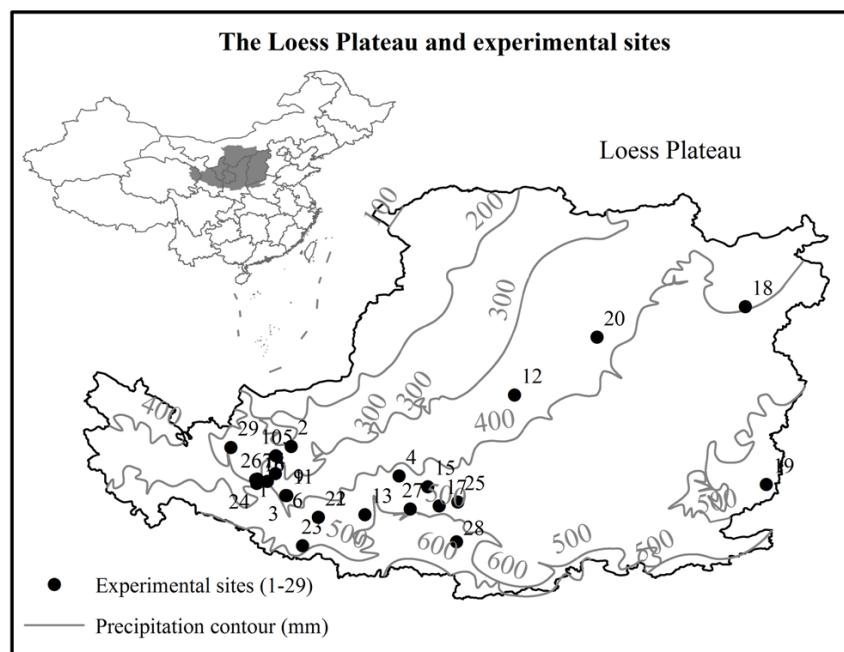

Figure 1. Location of the Loess Plateau in China and the experimental sites considered from literature review

The objectives of this study were to (i) analyze effect of plastic film mulch and ridge-furrow techniques on maize grain yield across the precipitation gradient; (ii) map the spatial distribution of grain yield potential on the Loess Plateau under recent (1950-2000) climate. Agriculture is not only influenced by climate but also by economic and technological factors (Li et al., 2011).While plastic film mulch and ridge-furrow techniques can increase grain yield and economic benefit compared to conventional cultivation, it requires significant inputs as capital and labor (Liu et al., 2009). Therefore, it is also meaningful to (iii) delineate potential areas that will benefit from using the techniques or suitable areas for adopting the techniques on the plateau.

2. Materials and Methods

2.1 Site Based Grain Yield and Precipitation Data

Grain yields of maize with three treatments were compiled across the Loess Plateau through a comprehensive literature review (Figure 1 and Table 1). The three treatments considered were (1) flat-plot sowing without ridge-furrow mulching (CK, Figure 2a), (2) half-mulched flat-plot, i.e. alternating plastic film mulched row and bare row on flat plots (HM, Figure 2b), (3) double ridges and the furrow fully mulched with plastic film, maize is sown in the furrow (DRM, Figure 2c). Most of the studies provided grain yields and the corresponding growing season (from April to September) precipitation data. For studies only have yield data, we obtained precipitation data from the nearest meteorological station for the same year. Regressions were conducted between grain yields and growing season precipitation.

Table 1. Experimental sites across the growing season precipitation gradient on the Loess Plateau

Experimental sites	Precipitation (mm)	Experimental year	Source[§]
1	180	2004	1
2	197	2007	2
3	197	2009	3
4	209	2008	4
5	213	2007	5
6	229	2010	6
7	274	2009	7
8	283	2004	8
9	284	2009	9
10	287	2006	9
11	293	2008-2010	9
12	294	2010	9
13	294	2009	10
14	308	2008-2010	10
15	310	2009	11
16	314	2007-2009	12
17	328	2007-2009	13
18	333	2009	13
19	373	2009	14
20	401	2006	15
21	406	2007	13
22	436	2005	16
23	436	2007	16
24	447	2007	16
25	449	2008-2010	16
26	455	2007	16
27	461	2008-2010	17
28	462	2009	17
29	560	2007	18

[§]1 = (Zhang et al., 2005); 2= (ATESGS, 2009); 3 = (Wang et al., 2011b); 4 = (Ma et al., 2011); 5 = (Zhou et al., 2009); 6 = (Liu et al., 2008); 7 = (Zhao, 2005); 8 = (Huang et al., 2010a); 9 = (Huang et al., 2010b); 10 = (Hai, 2011); 11 = (Zhang et al., 2010); 12 = (Zhang et al., 2011); 13 = (Zhi et al., 2011); 14 = (Yan et al., 2010); 15 = (Shi et al., 2008); 16 = (Ji, 2006); 17 = (Zhen, 2008); 18 = (Wang, 2010)
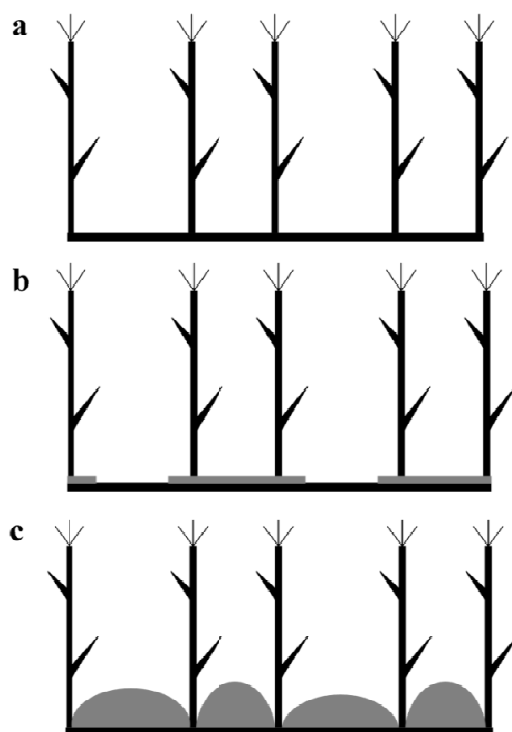
Figure 2. Maize planted using three methods. (a) flat-plot sowing without ridge-furrow mulching (CK), (b) half-mulched flat-plot, i.e. alternating plastic film mulched row and bare row on flat plot (HM), (c) double ridges and the furrow fully mulched with plastic film, maize is sown in the furrow (DRM)

2.2 Gridded Precipitation Data

To analyze the spatial distribution of grain yields, growing season precipitation data (average of 1950-2000) were obtained from WorldClim (Hijmans et al., 2005) (available at http://www.worldclim.org/), a publicly available global database of climate surfaces at 30 arc-second spatial resolution (~1km at the Equator). Tuner et al. (2011) compared the data against the observation from the Chinese Meteorological Administration (CMA) in the period from 1980 to 2008 for 10 stations across the Loess Plateau and found good agreement.

3. Results

3.1 Grain Yields across the Precipitation Gradient

An experimental dataset was collected by comprehensive literature review (Figure 1, Table 1). Maize grain yields were highest in the DRM treatment and lowest in the CK treatment. Mulch or ridge-furrow with mulch have increased maize grain yield significantly (ANOVA test). The highest increase was found in low growing season precipitation regimes. Grain yields of the three treatments trended to converge in high growing season precipitation regimes. Regressions between grain yields and growing season precipitation for the three treatments showed that maize yields increased linearly with precipitation for CK; statistically significant quadratic models were found for HM and DRM treatments (Figure 3).

3.2 Economic Benefit across a Precipitation Gradient

It is important to analyze how farmers will benefit from using mulch and ridge-furrow techniques since they need inputs of capital and labor (Table 2). Input was highest in DRM treatment, followed by HM treatment and CK. Maize price was around 0.24 USD kg^{-1} (1.5 CNY kg^{-1}) during recent years (Liu et al., 2009; Liu et al., 2008).

Based on the yield-growing season precipitation regression models (Figure 3a) and economic inputs (Table 2), the net income across the precipitation gradient were estimated by subtracting inputs from outputs for the three treatments. Farmers will benefit most by using DRM treatment where growing season precipitation is < 532 mm, HM treatment where growing season precipitation is between 534 and 584, and CK where growing season precipitation is > 584 mm (Figure 3b).
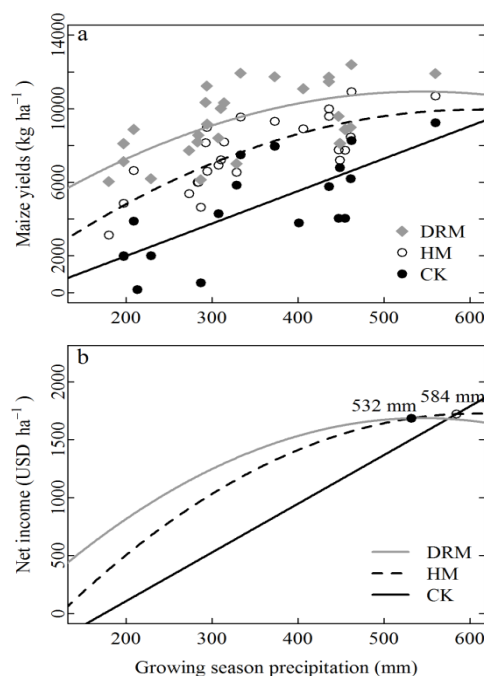
Figure 3. Maize grain yields (a) and net income (b) under the three treatments (see Figure 2 for description of the three treatments) across the growing season precipitation gradient on the Loess Plateau. Regressing grain yield against growing season precipitation, linear model is found for CK (y = 18x – 1538, r^2 = 0.55, p < 0.001) and quadratic models are found for HM (y = -0.031x^2 + 38x - 1494, r^2 = 0.60, p < 0.001) and DRM (y = -0.031x^2 + 34x + 1793, r^2 = 0.39, p < 0.00). In Figure 3b, the black dot is the intersection (precipitation is 532 mm) of HM and DRM lines, and the hollow dot is the intersection (precipitation is 584 mm) of CK and HM lines

Table 2. Economic inputs (USD ha^{-1}) of maize in three treatments (see Figure 2 for description of the three treatments) on the Loess Plateau

	CK	HM	DRM
Seed	25.0	25.0	25.0
Phosphate fertilizer	47.6	47.6	47.6
Farmyard manure	47.6	47.6	47.6
Nitrogen fertilizer	152.4	152.4	152.4
Plastic film	0.0	83.3	166.7
Plough	95.2	95.2	95.2
Labor cost for mulching and making ridge-furrow	0.0	190.5	381.0
Total	367.9	641.7	915.5

Notice that net incomes under DRM treatments are still higher than that of CK in low growing season precipitation regimes such as those < 100 mm (Figure 3b). We assumed that farmers will adopt the mulch and furrow-ridge only if net income is ≥ 790 USD ha^{-1} (or 5000 CNY ha^{-1}, the average net income per ha farmland on the Loess Plateau), the minimum precipitation needed is about 196 mm. Therefore, the growing season precipitation range suitable for the mulch and ridge-furrow techniques (DRM) is 196-532 mm.

3.3 Spatial Distribution of Grain Yield Potential

In recent history (1950-2000), growing season precipitation tended to decrease gradually from southeast to northwest of the Loess Plateau (Figure 1). Based on the regression models and gridded precipitation data, the spatial distributions of grain yield potentials were estimated for the three treatments (Figure 4). Without mulch and ridge-furrow (i.e. CK), grain yields were highest in the south and southeast of the Loess Plateau where precipitation was also highest (Figure 4a). The average grain yield was 5142 kg ha^{-1} for the whole plateau. Generally, grain yields under HM treatment were higher (2820 kg ha^{-1} in average or about 55%) than those of

CK, however, negative effects are found in a small part of the south of Loess Plateau where precipitation was the highest (Figure 4b). Spatial distribution of grain yields under DRM treatment was very similar to that under HM treatment (Figure 4c); yields were higher (4569 kg ha⁻¹ or 89%) than those of CK in average.
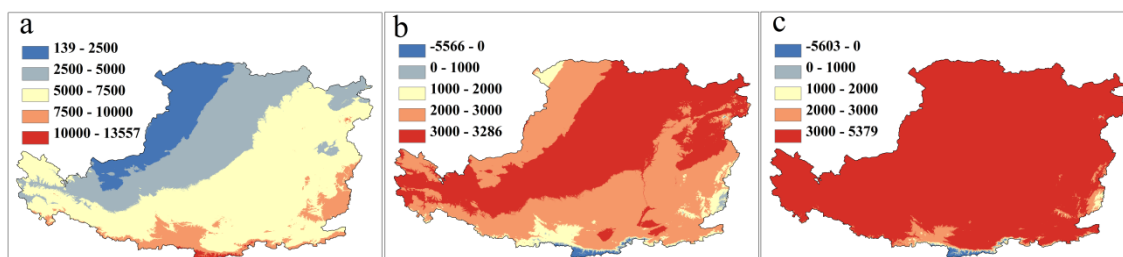

Figure 4. Maize grain yield potentials (kg ha⁻¹) under three treatments (see Figure 2 for description of the three treatments) on the Loess Plateau. (**a**) Yields of CK treatment; (**b**) yields difference between HM and CK treatments (HM-CK); (**c**) yields difference between DRM and CK treatments (DRM-CK)

3.4 Suitable Areas of Mulch and Ridge-furrow Techniques for Maize

Spatial distributions of net income potential for the three treatments were estimated. For each grid, the maximum net income was calculated for the three treatments and only grids with net incomes ≥ 790 USD ha⁻¹ were regarded as suitable for maize cultivation. CK and HM treatments were most suitable for small parts of the south and east of the Loess Plateau (Figure 5a-b), they occupied 5% of the land areas in total. DRM treatment was suitable for most land areas (87%) of the plateau (Figure 5c). 8 % of the land areas were not suitable for maize.
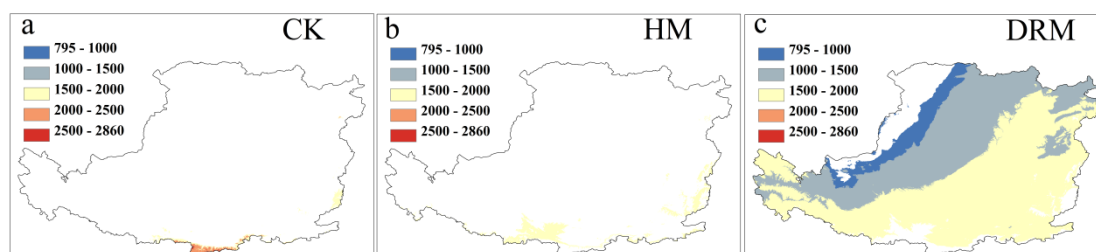

Figure 5. Maximum net income potentials (USD ha⁻¹) and the corresponding treatment (see Figure 2 for description of the three treatments) on the Loess Plateau. (a) Areas suitable for CK and the corresponding net income potential; (b) areas suitable for HM and the corresponding net income potential; (c) areas suitable for DRM and the corresponding net income potential

4. Discussion

The mulch and ridge-furrow techniques greatly increased the grain yield of maize, which is mainly due to the effect of plastic film on reducing water evaporation from soil (Li et al., 2004; Liu et al., 2009) and ridge-furrow on increasing rainwater harvesting (Li et al., 2001; Wang et al., 2005). Therefore, the techniques reduced the sensitivity of maize yield to change in precipitation. The benefit of mulch and ridge-furrow decreased as precipitation increased. There is less or even no need to reduce evaporation and harvest rainwater because precipitation is enough for crop growth in humid region.

Rainwater harvesting has been an effective technique for improving productivity and thus livelihoods of residents in the vast dryland worldwide (Ngigi, 2003). Generally speaking, rainwater harvesting is suitable for arid and semi-arid region where no irrigation is available or the cost of irrigation is too high (Tian et al., 2003). In regions with annual precipitation ranging from 100 to 700 mm, low cost water harvesting might provide an promising alternative if irrigation water from other sources is not readily available or too costly (Prinz, 1996). Others suggested that areas with precipitation large than 250 mm is most suitable for rainwater harvesting agriculture on dryland (Boers et al., 1986; Li, 1998). Zhang et al. (2010) suggested that mulch and ridge-furrow techniques were most suitable for regions with annual precipitation between 300~500 mm. Pacey and Cullis (1986) gave a more conservative range of annual rainfall, 500–600 mm. However, the application potential for

the mulch and ridge-furrow techniques are not only dependent on climate (especially precipitation) but also on labor and capital factors (Ali and Yazar, 2007; Liu et al., 2009). Based on multiple experimental sites across the precipitation gradient on the Loess Plateau, we recommend that a growing season precipitation range of 196-532 mm was suitable for mulch and ridge-furrow techniques for maize in this region, considering both water resource and economic outcome. The lower end of the precipitation range is in between 100 mm suggested by Prinz (1996) and 250 mm suggested by Boers et al. (1986) and Li (1998), the higher end of range is in between 500 mm suggested by Zhang et al. (2010) and 600 mm suggested by Pacey and Cullis (1986). Although this range did not include impact of other environmental factors, it is still useful because farmers are able to easily decide what treatment to use in different precipitation regimes.

Some studies used multi-criteria evaluation or other methods to delineate suitable areas for agriculture or specific crop based on climate, relief and soil factors (Ceballos-Silva & López-Blanco, 2003; Reshmidevi et al., 2009; Ye et al., 2010). The unique feature of the present study is inclusion of social economic variables to assess the suitability of different techniques across the precipitation gradient. We only considered the economic inputs of materials and labor force for the three techniques in the current study (Table 2). The ecological aspect such as negative effect of plastic residue in soil and the fate of breakdown products are unclear and are recently being measured (Turner et al., 2011; Yan et al., 2006). Four major dryland farming provinces in China plan to allocate more land areas to adopting plastic film much and ridge-furrow techniques in the near future. The results of the study are useful for governments and farmers to decide what land to adopt the techniques in this region and in similar regions of the world.

5. Conclusions

In this study, grain yields data of maize in three treatments (CK, HM and DRM) on the Loess Plateau were compiled from comprehensive literature review. Grain yield of maize was highest in DRM treatment and lowest in CK. The difference of grain yields among the three treatments were highest in low growing season precipitation regime, they trended to converge in high growing season precipitation regime. The benefit of mulch and ridge-furrow decreased as precipitation increased. The economic net incomes were calculated based on yields and inputs of capital and labor for the three treatments. Considering both water resource and economic outcome, we recommend that a growing season precipitation range of 196-532 mm as most suitable for mulch and ridge-furrow techniques for maize on the Loess Plateau. Spatially, CK and HM treatments were most suitable for small parts of the south and east of the plateau where precipitation was highest. DRM treatment was suitable for most land areas (87%) on the Loess Plateau.

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