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Benefits and limitations to straw- and plastic-film mulch on maize yield and water use efficiency: A meta-analysis across hydrothermal gradients

Yue-Yuan Yu[a], Neil C. Turner[b], Yan-Hong Gong[a], Feng-Min Li[a], Chao Fang[a], Li-Juan Ge[a], Jian-Sheng Ye[a,*]

[a] State Key Laboratory of Grassland Agro-ecosystems, Institute of Arid Agroecology, School of Life Sciences, Lanzhou University, No. 222, South Tianshui Road, Lanzhou, 730000, China

[b] The UWA Institute of Agriculture and UWA School of Agriculture and Environment, The University of Western Australia, M082, Locked Bag 5005, Perth, WA, 6001, Australia

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ABSTRACT

Ridge-furrow mulching can reduce soil evaporation and conserve rainfall, thereby increasing crop yield and water use efficiency (WUE) in dryland cropping systems. In this study, we collected 837 observations from 50 published papers and used meta-analysis to investigate whether ridge-furrow and mulching practices are equally effective on maize yield, WUE and evapotranspiration (ET) across a range of precipitation and temperature gradients and soil types in China. Five practices were included: (i) straw mulch on flat plots (SMF), (ii) straw mulch on ridge-furrow plots (SMR), (iii) plastic mulch on flat plots (PMF), (iv) plastic mulch on ridge-furrow plots (PMR), and (v) flat plots without mulch, which was used as a control (CK). The meta-analysis showed that both straw mulch and plastic mulch significantly increased maize yields and WUE (except for SMR), and that plastic mulch was more effective than straw mulch in increasing yields, particularly in cold and dry environments. PMR has the highest yields and is more effective in clay loam than in silt loam soils. Straw mulch, but particularly plastic mulch, increased the soil moisture compared to the CK, while plastic mulch increased soil temperature, mainly in spring. However, the positive effect of plastic mulch on maize yield diminished with increasing mean growing-season temperature and precipitation, reaching zero (similar to the CK of no mulch and flat plots) when the growing-season precipitation was greater than 770 mm and the mean growing-season air temperature exceeded 24 °C. The small benefit of straw mulch (on average about 12%) was similar across the precipitation and temperature gradients, including when the benefits of plastic mulch reached zero. While our analysis has shown the benefits of ridge-furrow plastic mulch on yield and water-use efficiency, it has also highlighted the limitations of the benefits. The results provide a guide to the regions where plastic-film mulch and ridge-furrow planting are likely to improve maize yields and regions where the benefits are likely to be limited.

1. Introduction

Global food demand is projected to double by 2050 compared to that at the beginning of this century (Tilman et al., 2011), but there will be limited or no increase in the area of arable land or water for irrigation. The situation is very severe in China due to its large population; the available cropland is only 0.1 ha per capita (Wu, 2001) and the available water per capita is only one quarter the world average (Shan et al., 2000). Water shortage is even more severe in northern China, which has 65% of the total arable land, but less than 20% of total national available water resources (Deng et al., 2006). Because of the lack of water resources for irrigation in northern China, precipitation is the main source of water for crop growth (Ye and Liu, 2012). To support the large and growing population in China, the increase of food production must be based on improving crop yields and water use efficiency of existing cropping systems (Deng et al., 2006; Godfray et al., 2010).

Maize has become China's largest crop; the area and yield reached 38 million hectares and 224 million tons in 2015 (Li et al., 2017). It is mainly grown in semi-arid and arid regions, both rainfed and with irrigation. In semi-arid and arid areas, the precipitation is mainly concentrated in July to September, that is in the mid- to late growth period. Water deficits and cold temperatures in the early stages of growth affect the emergence and early growth of maize, thereby affecting the crop

* Corresponding author.
E-mail address: yejiansheng30@gmail.com (J.-S. Ye).

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yield (Wang et al., 2010). Different *in situ* soil and water management practices, such as mulching and ridge-furrow tillage, have been developed and shown to be effective in increasing crop yields and water use efficiency (WUE) in water-limited environments of China (Gan et al., 2013; Wang et al., 2015; Wang and Shangguan, 2015; Wang et al., 2016a). For maize (*Zea mays* L.), these practices include alternating ridges and furrows with only the ridges covered with plastic film (Li et al., 2001; Wang et al., 2010), alternating mulched and bare rows without ridges (Liu et al., 1989), flat plots all mulched with plastic film (Zhang et al., 2004), straw mulching, and in recent decades the commonly used technique of double ridges and furrows mulched with plastic film (Zhang et al., 2011). Both straw and plastic mulch have been shown to reduce soil evaporation and improve water use efficiency, while plastic mulch can also improve the soil temperature in spring, allowing earlier planting and quicker development (Sui et al., 1992; Chen et al., 2007; Liu et al., 2014; Wang et al., 2016a).

Since the main effects of plastic mulch are to reduce soil evaporation and increase soil temperature, it is likely that the positive effects of plastic mulch will diminish as precipitation and temperature increase. A few studies have shown that plastic-film mulch increased maize yield and its stability more as the hydrothermal conditions became more severe (Qin et al., 2015; Wang et al., 2016a). Several recent meta-analyses have focused on which mulch and tillage practices have the greatest effect on crop yield, water use efficiency and nitrogen use efficiency. The analyses showed that plastic mulch is more effective than straw mulch (Qin et al., 2015), and ridge-furrow plastic mulch most consistently increases crop yields and WUE (Wang and Shangguan, 2015; Zhang et al., 2017). Our meta-analysis aimed to quantify the effects of different mulch and tillage practices on maize yields, WUE and evapotranspiration across a series of hydrothermal gradients. Compared to the previous studies, our meta-analysis is novel in that it (1) includes a vast region of China and evaluates the effects of both mulching (straw vs. plastic film) and tillage practices (flat vs. ridge furrow plots); (2) estimates not only the benefits, but also the limitations to plastic mulching by rainfall and temperature, i.e., under which precipitation and temperature conditions do the positive effects of plastic mulching and ridge-furrow tillage on maize disappear; and (3) evaluates the effects of mulching and ridge-furrow tillage in different soil types and different nutrients levels. As much of the literature on mulching and tillage are published in Chinese, their inclusion in our analysis extends the scope of the previous analyses that focused mainly on studies published in English.

2. Methods

2.1. Data search and collection

Relevant literature of the grain yield of maize with different mulching and tillage practices was searched using the online databases of the Chinese Academy of Sciences (http://www.isiknowledge.com/ and http://www.cnki.net/) and Google Scholar (http://scholar.google.com/). The search terms were 'mulch' or 'mulching', 'maize' and 'yield' in the article title, abstract, and keywords. Publications in both Chinese and English were included. To be considered, the publications had to fit the following criteria: (1) the studies had to be conducted in the field and include both control (no mulch and flat plots, CK) and treatments (either flat or ridge-and-furrow tillage and/or straw or plastic-film mulch) (Table 1); (2) the maize was not be irrigated at any time within the growing season; (3) the location and year of the experiment were provided; (4) for factorial experiments, only data from non-mulched and mulched treatments were used and data from interactions among treatments, such as fertilization × straw mulch or plastic-film mulch, were excluded; (5) data without a control treatment, that is sown on flat plots without mulch, were only used for regression analysis, not in the meta-analysis.

The mean, standard deviation (*SD*) or standard error (*SE*), and the number of replicates of the treatments were directly acquired from the publication or calculated using the following formula (Rusinamhodzi et al., 2011):

$$SD = SE \times \sqrt{n} \quad (1)$$

As some studies did not report the *SD*, we calculated the average coefficient of variation (*CV*) within each dataset and then estimated the missing *SD* via the following equation (Wang et al., 2015):

$$SD = \overline{X} \times CV \quad (2)$$

where $\overline{X}$ is the mean of the treatment (mulch and/or tillage treatments) and control group (CK, no mulch and flat plots).

In addition, the site mean growing-season temperature and precipitation were also obtained from the publication. If no meteorological information was given in the publication, we obtained the mean growing-season temperature and precipitation from the nearest meteorological station (the Chinese meteorological data network, http://data.cma.cn/user/toLogin.html). In total, 963 observations of the five management practices were obtained from 90 published papers (Tables S1 and S2, Supplementary Information). Of these, 837 observations from 50 field experiment studies that included both CK (no mulch and flat plot) and treatments (mulch and tillage) were used in the meta-analysis (Table 2). The other 126 observations from 40 field experiments did not include CK and were not used in the meta-analysis, but the data were used for analyzing the relationships between yield and temperature, and yield and precipitation. In summary, all data in Table S1 were used to analyze the relationships between yield and temperature/precipitation; only data in Table 2 (a subset of Table S1) were used for meta-analysis. In the meta-analysis, each treatment was compared to its corresponding CK. For example, yield data of the straw mulch planted in flat plots (SMF) were compared to CK data obtained from the same studies. CK data obtained from studies without SMF treatment were excluded because these studies may be located in areas with very different growing-season precipitation or/and temperatures (thus falsely increasing or decreasing the average values of CK). In some studies, several levels of a single treatment such as 1–9 t dry mass of straw ha^{-1} were applied (Table 1). Therefore, the number of observations (*n*) shown in Table 2 may be different for each treatment and its corresponding CK.

Soil type, soil organic matter, nitrogen, phosphorus and potassium contents were collected for sites for which this information was available (Table 3 and Table S3). Data shown in Table S3 are for all datasets used for regression analyses, while only the subset used in the meta-analysis is shown in Table 3. Three soil types, namely clay loam, silt loam and clay were identified at the study sites. Most of the sites (96.6%) have a loam soil type which drains well, but relatively poor soil nutrient content (Gong, 1999).

The ET, WUE, soil water content (gravimetric water content in % measured at 0–0.2 m soil depth), and soil temperature (measured at 0–0.2 m soil depth) data under different treatments were also collected from individual studies where these data were available. Soil water data were available for all five practices, while soil temperature data were not available in the straw-mulch treatments. The field sites used in the meta-analysis were generally in central and northern China (Fig. 1), characterized by arid and semiarid climates.

2.2. Meta-analysis

Meta-analysis is a formal quantitative statistical method to summarize results from independent experimental studies (Hedges et al., 1999). In this study, we used the effect size (*R*) to quantify the effect of mulch and ridge-furrow treatments on maize yield, WUE and ET:

$$R = \overline{X}e / \overline{X}c \quad (3)$$

where $\overline{X}e$ is the mean of the treatment group (mulch and/or tillage