Agricultural Water Management 190 (2017) 1–5

Contents lists available at ScienceDirect

Agricultural Water Management

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

Short communication

Can ridge-furrow plastic mulching replace irrigation in dryland wheat and maize cropping systems?

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ARTICLE INFO

Article history:
Received 24 August 2016
Received in revised form 18 April 2017
Accepted 13 May 2017

Keywords:
Agricultural production
China
Evaporation
Meta analysis
Transpiration
Water use efficiency

ABSTRACT

Dryland crop production requires significant water investments, but problems associated with irrigation have been observed in many dryland regions (e.g., China, Australia and the Mediterranean basin). A key strategy for maintaining crop yields without over-exploiting the scarce water resource is by increasing water use efficiency (WUE). Plastic mulching technology for wheat and maize has been commonly used in China, but their effect on yield, soil water content, evapotranspiration (ET), and WUE has not been compared with traditional irrigation. Using a meta-analysis approach, we quantitatively examined the efficacy of plastic mulching in comparison with traditional irrigation in the same region. By covering the ridges with plastic and channeling rainwater into a very narrow planting zone (furrow), our results showed that plastic mulching resulted in a yield increase comparable to irrigated crops but used 24% less water in comparison with irrigation due primarily to a much greater WUE and better retention of soil water. The higher WUE in plastic-mulched croplands was likely a result of a greater proportion of available water being used for transpiration (T) than evaporation (E). Currently production costs and residual plastic pollution hinder worldwide adoption of the technique, despite being a promising strategy for dryland cropping systems.

1. Introduction

Dryland crop production remains the primary source of staple food production for the majority of densely-populated regions such as China, sub-Saharan Africa, India, and the Mediterranean. With aridity index (i.e., ratio between precipitation and potential evapotranspiration (ET_0)) ≤ 0.65 (Wang et al., 2012), crop production in drylands is a continuous exercise to allocate the limited rainwater supply to meet the ET demand of growing crops. Therefore, increasing water use efficiency (WUE; crop yield per unit of available water) in dryland cropping systems is essential in order to maximize productivity (Bennie and Hensley, 2001; Lu et al., 2016a).

The challenges facing dryland crop production are further amplified with a changing climate (i.e., more frequent drought) as most climate models suggest that climate change will be more detrimental towards dryland (i.e., rainfed) than to fully irrigated crop production systems (Piao et al., 2010). In countries like China where dryland regions account for 65% of the total arable land and contribute the majority of the nation's food production (Deng et al., 2006), supplementary irrigation is necessary to ensure food security. Low WUE associated with irrigation in the dry regions, however, has caused severe environmental problems, including groundwater decline and drying rivers (Deng et al., 2006), seawater intrusion and soil salinization (Cudennec et al., 2007; Lambers, 2003; Narayan et al., 2007) as reported in China, Australia and the Mediterranean.

The use of water-saving strategies is therefore critical for dryland cropping systems considering that rainfall is not only low in absolute amount but is also unevenly distributed. During the last five decades (1950–2000), grain production has increased dramatically from about 113×10^6 tons to 512×10^6 tons in China (~3% increase annually) (Cui et al., 2010). Currently, China is the largest producer of wheat and only second after the United States (US) in terms of global maize production (Daryanto et al., 2016). One water-saving strategy that may have contributed to the increase is the adoption of plastic mulching technology that is most commonly used in northern China for maize and wheat production. Nationwide, plastic mulching has increased maize and wheat grain production by 33.7% and 33.2%, respectively (Liu et al., 2014). Food security and the growth of grain production have been an ongoing priority for the Chinese government, who have provided farmers with a guaranteed amount of plastic mulch at low, subsidized prices since the agricultural reform initiated in 1979 (Colby et al., 1991; Ni, 2013). The technique, introduced in 1978, has gained popularity

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http://dx.doi.org/10.1016/j.agwat.2017.05.005
0378-3774/

ever since (Zhou et al., 2009) and, over the past two decades, the use of plastic mulch has increased in all provinces and regions of China. Between 1990 and 2000 alone, 80% of the world's plastic-mulched surface was found in China with 25% annual growth rate (Espi et al., 2006). While the lowest estimated increase rate of cultivation area covered by plastic mulch would be about 5% over the next ten years if the covered crop area increased from the current 20×10^6 ha to 30×10^6 ha, the number could be higher (8–10%) if the increasing covered crop area went above 30×10^6 ha (Liu et al., 2014).

Plastic mulch conserves water in areas where irrigation is limited or not available, and protects emerging crops from low spring soil temperature (Zhou et al., 2009). The use of organic mulch (e.g., straw mulch), on the other hand, has been limited due to its rapid decomposition and its adverse effects on soil temperature (i.e., too cold during winter or spring) (Chen et al., 2015). In general, the plastic mulching technology is deployed in a ridge-furrow system; the plastic mulch is placed on top of the ridge to concentrate the flow of water from the ridge to the furrow where the crops are planted. From now on, the term 'plastic mulching' will be used to refer to the aforementioned description. The use of plastic mulching, however, requires larger input of money and labor on an annual basis, and may result in reduced subsoil water with increasing plant growth and transpiration rate compared to traditional irrigation (Li et al., 1999; Liu et al., 2009). The effectiveness of plastic mulching also varies, depending on the type of surface cover on the furrow, climate and soil conditions, as well as their interactions (Han et al., 2014), highlighting the importance of quantitatively examining the efficacy of this water-saving strategy.

In this communication, we compare plastic mulching and traditional irrigation in terms of improving wheat and maize yield, as well as relevant crop and soil parameters (e.g., ET, WUE, and soil water content). We used a meta-analysis approach to summarize the results from independent experiments (Hedges et al., 1999) across different climatic zones and soil types. Using China's dryland crop production as an example, our results can help to quantitatively evaluate plastic mulching and develop water-saving strategies in other semi-arid regions that are severely affected by drought and water shortages.

2. Methods

Peer-reviewed journal articles published in English from 1985 to 2016 were collected to build the database based on Web of Science search using the following sets of keywords: (i) wheat or maize; (ii) film mulch or plastic mulch or plastic cover; and (iii) water stress or water deficit or drought or irrigation deficit. We replaced the phrases 'film mulch'; 'plastic mulch' and 'plastic cover' with 'irrigation' and 'China' to search for articles discussing supplementary irrigation specific to the region. The search for mulching and irrigation articles resulted in 78 and 394 articles; respectively; but only articles from China that met the following criteria were included in the database: (i) the experiments were conducted under field conditions where the effect of irrigation or plastic mulching was compared with flat (even or level topography); rainfed conditions; (ii) the reported plants were monoculture cereals of maize (*Zea mays*) and wheat (i.e.; bread wheat; *Triticum aestivum*); and (iii) the articles reported crop response as grain yield. This resulted in 49 articles (see list in the Supplementary Information) that all came from regions with similar agro-ecological features. If the articles reported a combination with other treatments (e.g.; addition of fertilizer; cultivar; or spacing width); the effects of these treatments were averaged across the mulching or irrigated condition. By averaging the response; we avoided over-representation of a study; reduced publication bias; increased the reliability of our results; and ensured the independence of each data entry (Lu et al., 2016b). We did not differentiate among irrigation methods and only recorded the amount of water applied; since there have been many studies showing that the type of irrigation was not significant in comparison to the amount of water in determining yield including in the drylands (Erdem et al., 2006; Onder et al., 2005; Sammis, 1980; Shalhevet et al., 1983; Ünlü et al., 2006). We also recorded the amount of rainfall received during the growing season to understand the extent of irrigation relative to the rainfall. The ratio between irrigation and rainfall ranged between 0.3 and 4.9. If a study was conducted across different years or study sites with similar agro-ecological features; or reported more than one amount of irrigation; all observations were considered independent and included in the database (Daryanto et al., 2016).

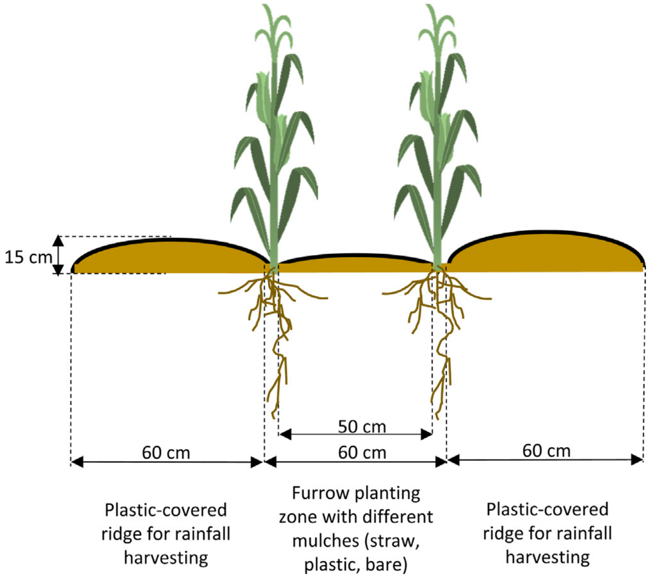

Fig. 1. Schematic diagram of the water harvesting strategy of ridge-furrow plastic mulching (i.e., plastic-covered ridge with different furrow cover).

The magnitude of yield, total ET, WUE, and average soil water content (0–20 cm) responses throughout the crop growing season were examined based on four treatments: (i) irrigation and three different types of mulch that covered the furrow: (ii) plastic, (iii) straw, and (iv) no cover or bare (Fig. 1). No additional irrigation was provided for each of the mulching treatments. The number of observations (samples) for each treatment are available in the corresponding figure of the Results section. To compare the differences in crop or soil response ratio between each treatment, meta-analysis was used to construct the confidence intervals. In order to include those studies that did not adequately report sample size or standard deviation, we performed an unweighted analysis using the log response ratio (lnR) to calculate bootstrapped confidence limits using the statistical software MetaWin 2.0 (Rosenberg et al., 2000). The response ratio is the ratio between the outcome of treatment group (i.e., irrigation or mulched) to that of the control group (i.e., flat, rainfed condition) to estimate the proportional change resulting from irrigation or mulching. We performed a simple diagnostic test using the formula following Lajeunesse (2015) to improve the reliability of lnR in estimating the effect size. The results of the calculation are provided in Supplementary Table S1. Bootstrapping was also iterated 9999 times to improve the probability that the confidence interval was calculated around the cumulative mean effect size for each categorical variable. The difference between the control and irrigated or mulched condition was considered significant if the bootstrap confidence intervals did not overlap with zero, while the difference among treatments was