Influence of plastic film mulch with biochar application on crop yield, evapotranspiration, and water use efficiency in northern China (#55313)

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Influence of plastic film mulch with biochar application on crop yield, evapotranspiration, and water use efficiency in northern China

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Background. China is the leading consumer of plastic film mulch worldwide. The significance of plastic film mulching as an efficient strategy to increase crop yields, water use efficiency (WUE), and decrease evapotranspiration (ET) has been emphasized by numerous studies. Plastic-film mulching is an efficient agricultural practice for maximizing crop yield and WUE while minimizing ET in China's rain-fed agriculture. **Methods**. A comprehensive evaluation of how co-application of plastic-film mulch and biochar in different agro-environments under varying climatic patterns influence crop yield, WUE, ET, and soil microbial activity is limited. We performed a meta-analysis according to PRISMA guideline by Moher et al., (2009) to assess the effect of plastic-film mulched ridge-furrow on yield, ET, and WUE of wheat (*Triticum aestivum* L.), potato (*Solanum tuberosum* L.), and maize (*Zea mays* L.) in China. **Results.** The use of plastic film increasedmean yields of wheat (75.7 %), potato (20.2 %), and maize (12.9 %) in Gansu, Ningxia, Shaanxi, and Shanxi provinces, respectively due to the reduction in evapotranspiration by 12.8 % in Gansu, 0.5 % in Ningxia, and 4.1 % in Shanxi, but increased in Shaanxi by 0.5 % compared to no-mulching. These changes may also be attributed to the effect of plastic film mulch application which simultaneously increased WUE by 68.5 in Gansu, 23.9 in Ningxia, 16.2 in Shaanxi, and 12.8 % in Shanxi, respectively. Compared to flat planting without mulching, in three years, the yield of maize increased with the co-application of plastic film and biochar by 22.86 % in the Shanxi and Shaanxi regions. **Conclusion.** Therefore, the co-application of plastic film with biochar may be used for improving soil and water conservation in rain-fed agriculture as an integrated practice to avert drought while simultaneously mitigating runoff and erosion.

Influence of plastic film mulch and biochar application on crop yield, evapotranspiration, and water use efficiency in northern China

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Abstract

Background. China is the leading consumer of plastic film mulch worldwide. The significance of plastic film mulching as an efficient strategy to increase crop yields, water use efficiency (WUE), and decrease evapotranspiration (ET) has been emphasized by numerous studies. Plastic-film mulching is an efficient agronomic practice for maximizing crop yield and WUE while minimizing ET in China's rain-fed agriculture.

Methods. A comprehensive evaluation of how co-application of plastic-film mulch and biochar in different agro-environments under varying climatic conditions influence crop yield, WUE, ET, and soil microbial activity were assessed. We performed a meta-analysis using the PRISMA guideline to assess the effect of plastic-film mulched ridge-furrow and biochar on yield, ET, and WUE of wheat (*Triticum aestivum* L.), potato (*Solanum tuberosum* L.), and maize (*Zea mays* L.) in China.

Results. The use of plastic film increased mean yields of wheat (75.7 %), potato (20.2 %), and maize (12.9 %) in Gansu, Ningxia, Shaanxi, and Shanxi provinces, respectively due to the reduction in ET by 12.8 % in Gansu, 0.5 % in Ningxia, and 4.1 % in Shanxi, but increased in Shaanxi by 0.5 % compared to no-mulching. These changes may also be attributed to the effect of plastic film mulch application which simultaneously increased WUE by 68.5 % in Gansu, 23.9 % in Ningxia, 16.2 % in Shaanxi, and 12.8 % in Shanxi, respectively. Compared to flat planting without mulching, in three years, the yield of maize increased with the co-application of plastic film and biochar by 22.86 % in the Shanxi and Shaanxi regions.

Conclusion. Co-application of plastic film with biochar may be used for improving soil and water conservation in rain-fed agriculture and as an integrated practice to avert drought while simultaneously mitigating runoff and erosion.

Introduction

Poor soil fertility and water scarcity pose a major threat to crop production to meet the food needs of the increasing global population (Qin et al., 2015). Soil water conservation is, therefore, an important strategy for the productivity of rain-fed agriculture (Ding et al., 2018). The amount of soil water and nutrient during the different growing seasons has a marked impact on crop yields in rain-fed agriculture, especially in semi-arid regions with changing climate (Grassini et al., 2010). Unfortunately, most of the lands in rain-fed farming areas are nutrient-deficient and susceptible to soil erosion and runoff (Liu et al., 2009). Soil is an important natural asset that should be properly managed to ensure sustainable development (Panpatte & Jhala, 2019). Hence, appropriate land and water management practices should be employed to reduce the risk of widespread water resource depletion in dry agricultural areas (Chang & Liu et al., 2014). Rain-fed crop management systems need to be optimized to provide more resilient options to cope with decreasing precipitation and extreme drought periods in these regions (Verhulst et al., 2011).

Soil water conservation by soil mulching has been proposed as a viable practice to overcome water scarcity for crop production in dry regions. Hence, local farmers practice ridge-furrowing with plastic film mulching for crop production in the semi-arid Loess Plateau of China (Eldoma et al., 2016, Pan et al., 2019, Zheng et al., 2019). Mulching offers significant agro-ecological potential (Erenstein, 2003) and thus, one of the important agronomic practices to improve moisture retention capacity of soils (Ye & Liu, 2012), crop nutrients uptake, and soil microbial activities (Chakraborty et al., 2008). Plastic film is currently and widely adopted by smallholder farmers in China for crop production and to increase yield (Yu et al., 2018, Zhang et al., 2018). Plastic film decreases soil evapotranspiration and improves the growth of crops (Qin et al., 2015, Shen et al., 2019). Plastic mulches usually leave residues in fields they have previously been applied (Jabran, 2019). The residual effect of mulching can significantly increase yields, and water use efficiency (WUE) in *Triticum aestivum* L. and *Zea mays* L. by 20 and 60 %, respectively (Qin et al., 2015) while reducing evapotranspiration (ET) (Fan et al., 2017). Additionally, in a maize field of plastic film mulched ridges and non-mulched fields, soil ET increased by 38.1 and 9.3 percent, respectively (Gong et al., 2017). In the first and second seasons under plastic film mulched and non-mulched areas, Mbah and Nwite, (2010) recorded an increase in yield from 55-78 and 108-142 percent. In two consecutive growing seasons in China, plastic film mulching with biochar modification increased the root and shoot biomass and grain yield of maize (Xiao et al., 2016). Although plastic film mulching has been the ultimate choice of mulching material in rain-fed areas, to enhance water availability in the soil for plant growth (Zhang et al., 2017), it equally poses a challenge of residual plastic film on farmlands which can impede soil structure, plant growth, nutrients and water uptake (Liu et al., 2014). Biochar applications with plastic film mulching can mitigate many negative effects of residual plastic film mulching under field conditions but the study on co-application of biochar and plastic film mulches in China is limited (Aller et al., 2018).

Biochar is a carbon-rich product of the thermo-chemical conversion of organic material used as a soil amendment due to its gradual decomposition and influence on nutrient dynamics (Gao et al., 2019). The focus of biochar research has advanced from its effects on semi-arid soils to its potential as a soil management material for global agriculture (Wimmer et al., 2013). In arid areas, biochar application improves soil water adsorption capacity, fertility, microbial activity, organic matter content, soil porosity, water retention, soil quality, soil aeration, and nutrients uptake for enhanced crop production (Yang & Ali, 2018). Biochar has appreciable carbon sequestration value and may act as a modifier or carbon sink to reduce CO_2 emissions from decaying biomass, nutrient leaching, soil bulk density, erosion, or fertilizer needs (Mohan et al., 2014, Kavitha et al., 2018). The combined effects of plastic film and biochar on crop yield, ET, and WUE in a ridge-furrow rainwater harvesting system across China are currently less understood (Nelissen et al., 2012, Fischer et al., 2019).

The effects of plastic film mulched ridge-furrow with biochar on crop yield, ET, and WUE in rain-fed agro-ecological areas in China are reported with mixed results. We therefore comprehensively reviewed relevant literature using the PRISMA guideline (Moher et al., 2009) on plastic film mulching with biochar and summarized key findings. We hypothesized that the co-application of plastic film with biochar in semi-arid regions is an optimum agronomic practice for minimizing the impact of drought while simultaneously mitigating runoff and erosion. The objectives of the study were to evaluate the effects of plastic film mulched ridge-furrow with biochar on crop yield, ET, and WUE and determine how their combined effects vary with mulching management factors.

Materials & Methods

Data collection

Data from peer-reviewed publications in English investigating the effects of plastic film mulching and biochar on field crops from 1990-2020 were retrieved from online databases (*ISI Web of Science, Scopus (Elsevier), ScienceDirect, PubMed, JSTOR, and Google Scholar*). Nevertheless, publications from conference proceedings were excluded from the meta-analysis. In the databases, the terms 'yield ', 'plastic film ', 'biochar,' and 'mulching' were used as search keywords. Erastus Mak-Mensah and Dr. Eunice Essel performed the Search Strategy independently. Where there were disagreements, they were resolved by discussion between the two and any remaining disagreements were decided by Professor Qi Wang. The search produced a total of 556 publications, which were screened based on (1) On-field experimentation containing at least plastic film mulched ridges and no mulch treatments; (2) experimental sites located in rain-fed agriculture areas of China in Gansu, Ningxia, Shaanxi, and Shanxi provinces (Fig. 2); (3) colors of the plastic film were black and transparent; (4) mulching method was ridge mulching and the publication included estimates of crop yield, ET, or WUE. Data within the selected publications were categorized based on estimated biophysical parameters (Table 2). Farming provinces and locations of field experiments for all the crops in this study are shown in

Table 1 and Figure 2. The process of screening of publications for the meta-analysis is depicted in a flowchart (Figure 1); which was adapted from the PRISMA protocol (Moher et al., 2009).

Data analysis

Meta-analysis allows the quantitative analysis and estimation of the effect sizes of other authors' reported experimental results. Meta-analysis enhances the statistical capacity available for testing the hypotheses and the reaction variations between treatments in different environments. Unbiased estimation of the underlying true effect size, subject to random variance, can be assumed to be the effect size observed in each sample. If the outcome of each study is statistically important or not, both studies lead to the overall calculation of the impact of a treatment. More weight is given to data from experiments with more reliable measurements because they have a larger effect on the overall calculation (Yu et al., 2018).

We used construction confidence interval analysis to compare the magnitude of the response ratio between the plastic film mulching and no mulching treatments. The effect size was computed as the natural log (ln R) of the response ratio (R) (Gao et al., 2019; Qin et al., 2015), which reflects the severity of the effect of plastic film mulch on yield, ET, and WUE in this meta-analysis (Hedges, Gurevitch & Curtis, 1999), equation 1:

$$R = \frac{\hat{\mathrm{I}}\text{¸}t}{\hat{\mathrm{I}}\text{¸}c} \qquad (1)$$

$$\mathrm{In\ R} = \mathrm{In}\left(\frac{\hat{\mathrm{I}}\text{¸}t}{\hat{\mathrm{I}}\text{¸}c}\right) = \mathrm{In}\ \theta t - \mathrm{In}\ \theta c \qquad (2)$$

where θt and θc equates the mean values of yield, ET, and WUE in plastic film mulch and no mulching, respectively. To further confirm the results from the study, the percentage of change (Z) in yield, ET, and WUE were computed according to Li et al. (2018) as:

$$Z = (R - 1) \times 100\ \% \qquad (3)$$

Where a negative value for percentage change shows a decline in the variable with plastic film mulching relative to no mulching and a positive value for percentage change, indicates an enhancement in the matching variable for plastic film mulching relative to no-mulching. Conversely, the sample sizes of the variables and standard deviation (SD) involved were obtained in addition to the means from the articles or computed using the following equation (Yu et al., 2018):

$$SD = SE \times \sqrt{n} \qquad (4)$$

For studies which did not report the SD; the average coefficient of variation (CV) within each data was computed and then approximated the unavailable SD using the following equation (Yu et al., 2018):

$$SD = CV\ \text{Ã—}\ \theta \qquad (5)$$

Where θ equals the mean of plastic film with biochar or no mulching. The effect sizes of plastic film with biochar mulching and no-mulching for crop yield, ET, and WUE were continuous variables, hence were calculated by random-effects models using Review Manager (RevMan) (version 5.3, Nordic Cochrane Centre, Denmark). Random-effects models were implemented in cases of mild to high heterogeneity, indicated by a Chi-square P-value $<$ 0.05

and $X^2 > 50$ %. The RevMan program weighed the mean differences of the plastic film with biochar and no-mulching groups according to their SE and sample sizes, and their confidence intervals (CI) were computed from their weighted effect sizes. If there was no zero in the 95 % CIs of the effect size for that variable, the effect of a treatment on the variable was significant. Conversely, when the 95 percent CIs comprise zero, the treatment effect was considered not to be significant. Similarly, a general linear model in SPSS statistical software (version 26.0, SPSS Inc., Chicago, USA) was used to compute the effect of location, crop type, and rainfall on crop yield, ET, and WUE. The frequency distribution of effect sizes (Odds ratio) was computed using Excel 2016 software to illustrate the distribution regularities of the individual studies.

Results

Yield response of wheat, maize, and potato in different locations and climate

Considering both climate variables (precipitation and air temperature), the meta-analysis indicated that both growing-season precipitation and air temperature had no significant effects on maize, wheat, and potato yields in the plastic film mulched ridge-furrow treatment (Fig. 1). The meta-analysis dataset had pH in all the areas of study as slightly alkaline (>7) hence no comparison was made in that regard. Therefore, we evaluated the impacts on maize, wheat, and potato yields of plastic film mulching and ridge-furrow in three categorized soil types, i.e., light, medium, and heavy (Table 3B). In the plastic film mulched ridge-furrow treatment, the mean effect size for the light soil type (1.68 [0.38, 2.99]) was significant as compared to the other medium and heavy soil types (Figure 3). The mean effect size was not significantly different among the medium and heavy soil types in the plastic film mulched ridge-furrow treatment. Maize yields in Shanxi ranged from 11290 to 11527 kg ha^{-1} in the plastic film mulched ridge-furrow treatment was significantly higher than for Ningxia which ranged from 12779 to 13073 kg ha^{-1} in our meta-analysis dataset (Table 3A). The effects of the mulched ridge-furrow plastic film on yield varied with the density of soil bulk (Table 4B). Plastic film mulched ridge-furrow significantly increased yield in light categorized soils by 43% compared with flat planting without mulching in regions with a soil bulk density of >1.3 g cm^{-3} (Fig. 3). In areas of > 9 g / kg in the plastic film, mulched ridge-furrow treatment, the soil organic carbon (SOC) content of the 0-10 cm soil layer was increased (27.8 percent) compared to flat planting without mulching. With high soil available N (> 50 mg kg^{-1}), plastic mulching exerted a greater effect on maize, wheat, and potato yield with high soil available P (>20 mg kg^{-1}) and low soil available K (<150 mg kg^{-1}).

ET and water use efficiency of wheat, maize, and potato in different locations

Compared with flat planting without mulching, plastic film mulched ridge-furrow significantly increased WUE (16.1 %) in regions with an air temperature > 9 °C, but, had no significant impact on ET (0.46 %) (Fig. 4). This increase in WUE was significant in regions with heavy soil categorized type of soil texture (20.68 %), soil organic carbon content of > 9 g/kg

(22.2 %), and soil available N of > 50 mg kg−1 (22 %) (Fig. 5). In contrast, plastic film mulched ridge-furrow had no significant effects on ET in heavy soil categorized type (0.99 %), soil organic carbon content of > 9 g/kg (1.67 %) and soil available N of > 50 mg kg−1 (0.51 %) (Fig. 4). The average WUE of maize in Ningxia was significantly increased by 33.9 % with plastic film mulched ridge-furrow higher than in Shaanxi which was 16.2 % compared to flat planting without mulching (Fig. 5). The increase in WUE under plastic film mulched ridge-furrow was attributed to the increase in yield and the decrease in ET, as these results suggested.

Influence of co-application of plastic film mulched ridge-furrow and biochar on yield

In three years, the yield of maize increased with the co-application of plastic film and biochar by 22.86 % compared with flat planting without mulching in the Shanxi and Shaanxi regions. Although, in the plastic film mulched ridge-furrow and biochar co-application treatment, the mean effect size for maize (0.79 [-0.92, 2.50]) was not significant as compared to the flat planting without mulching in these regions, mean yields ranged from 10.43 - 14.7 (t/ha) which is 10430 -14700 kg/ha in the plastic film mulched ridge-furrow and biochar co-application treatment as compared to 9.11 - 9.99 (t/ha) (9110 - 9990 kg/ha) in the flat planting without mulching (Table 3C).

Discussion

In the Loess Plateau, variability in the amount and distribution of seasonal precipitation is a major source of variation in ET, which includes evaporation from the soil surface and crop transpiration (Lu et al., 2014) and WUE. Our meta-analysis showed that the yield of wheat, maize, and potato was increased with plastic film mulch compared to the no-mulch in Gansu, Ningxia, Shaanxi, and Shanxi provinces. This could probably be due to the increase in WUE and decreased in ET in the treatment fields. This is consistent with Mbah and Nwite, (2010), who reported plastic film mulch boosts maize yield (55-78 %) in the first and second seasons (108-142 %) of maize production. Ding et al. (2019) found that improved soil hydrothermal conditions under plastic film mulching effectively accelerated the emergence of wheat leaves and tiller development, resulting in increased spike number and grain yield. Again, yield affected by plastic film mulch (Zhou et al., 2009), decreased soil evaporation (Zribi et al., 2015), and ET (Zhou et al., 2009) in maize fields. Thus, plastic film mulching significantly improves crop production and increases resource use efficiency, as a potential soil amendment for sustainable dryland farming (Ding et al., 2019).

Several studies have subsequently shown that plastic film use increases yield and WUE in various crops (Anikwe et al., 2007). In this study, plastic film mulch significantly increased WUE and decreased ET in the low and high areas of rainfall in Gansu, Ningxia, Shaanxi, and Shanxi provinces. In these areas, the reduction in ET increases the availability of soil water content that contributes to plant growth. This finding is consistent with a study by Liu et al. (2014), who suggested double ridge–furrow and whole-year plastic film mulching could bolster grain yields in maize (110 kg N ha^{-1}) and maintain soil water balance during drought periods.

Simulation of soil water and heat flow in ridge cultivation with plastic film mulching on the Chinese Loess Plateau decreased ET where plastic film mulching was less efficient practice for increasing WUE in dryland agriculture (Zhao et al., 2018). Plastic film mulching can provide advantageous environments for achieving high potato yield (Wang et al., 2019) and facilitating maize grain filling hence maximizing yield (Liu et al., 2016). Therefore, ridge planting with plastic mulching may serve as a promising agronomic practice for improving potato productivity (Qin et al., 2016).

According to Xiao et al. (2016), yields of 20 t ha-1 biochar without mulching treatment plot and 30 t ha-1 biochar without mulching treatment plot increased by 9 percent and 13 percent in 2012 and by 11 percent and 14 percent in 2013, respectively, compared to no biochar or mulching treatment. Grain yield was significantly higher without mulching in 30 t ha-1 biochar than in 2013 without mulching in 10 t ha-1 biochar. Grain yield markedly increased by 6% and 9% in 2012 and 2013, respectively, in plastic film mulched ridge-furrow with 20 t ha–1 biochar treatment relative to plastic film mulched ridge-furrow without biochar treatment (Xiao et al., 2016). In addition, Jeffery et al. (2011) in a statistical meta-analysis indicated that biochar-treated soils increased crop productivity by a mean of 10 % (a range from –28% to 39%) relative to plots without mulching. As a result of the rise in soil fertility due to biochar, an increase in crop yield in the co-application of plastic film mulched ridge-furrow with biochar treatment occurs (Rehman & Razzaq, 2017).

Conclusions

In regions where rainfall is minimal during the cultivation periods, the mulching of the land with the plastic film resulted in improved WUE and crop yields. The co-application of plastic film mulched ridge-furrow with biochar will potentially mitigate the adverse effects of plastic film application including greenhouse gas emissions, and plastic film residue buildup in soils. Our analysis indicates that WUE and yield of maize, wheat, and potato in Gansu, Ningxia, Shaanxi, and Shanxi provinces were significantly influenced by the plastic film mulch application compared to no mulching. Compared with no mulching, ET was greatly reduced during the rising seasons. The co-application of plastic film with biochar in semi-arid regions is an optimum agronomic practice that may be employed by smallholder farmers in crop production in Gansu, Ningxia, Shaanxi, and Shanxi provinces of the Loess Plateau of China. The practice may equally serve as a potential soil and water conservation practice in rain-fed agriculture especially in areas with changing climate to minimize the effect of drought while mitigating runoff and erosion. We, therefore, recommend a future study on plastic film mulched ridge-furrow rainwater harvesting system with biochar assesses and provides detailed information on the combined effect of biochar with plastic film on soil physicochemical properties under field conditions.

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Table 1(on next page)

Study areas, crops and literature sources used in this meta-analysis

Table 1. Study areas, crops and literature sources used in this meta-analysis

Province	Study areas	Geo-coordinate (N, E, m a.s.l)	Crop	Reference
Gansu	Qingyang	35°42′, 107°20′	Wheat	Gao et al., 2014
	Tangjiabu, Dingxi	35°57′, 104°59′, 1970		Li et al., 2004
	Dingxi	35°33′, 104°35′, 1896.7	Potato	Zhao et al., 2012
		35°33′, 104°35′, 1896.7		Zhao et al., 2014
		35°33′, 104°35′, 1874		Qin et al., 2014
		36°02′, 104°25′, 2400		Zhou et al., 2015
	Zhonglianchuan, Yuzhong	36°02′, 104°25′, 2400		Liu and Siddique, 2015
		36°2′, 104°25′, 2400	Maize	Eldoma et al., 2016
		36°02′, 104°25′, 2400		Zhou et al., 2009
	Gaolan	36°2′, 103°7′, 1780	Potato	Wang et al., 2005
	Yuzhong	35°9′, 104°1′, 1800		
Ningxia	Pengyang	35°51′, 106°48′, 1658		Wu et al., 2017
		106°45′, 35°79′, 1800		Zhang et al., 2017
Shaanxi	Changwu	34°59′, 107°38′, 1220	Maize	Lu et al., 2020
		35°14′, 107°41′, 1206		Zhang et al., 2011
		35°14′, 107°41′, 1200 - 1206		Lin et al., 2019
		35°14′, 107°42′, /	Wheat	Qin et al., 2018
		35°12′, 107°45′, 12000		He et al., 2016
	Heyang	35°15′, 110°18′, 910		Li et al., 2012
		35°15′, 110°18′, 910	Maize	HAN et al., 2013
Shanxi	Shouyang	37°54′, 113°09′, 1273		Gaimei et al., 2017
		37°45′58″, 113°12′9″, 1202		Gong et al., 2017

Table 2(on next page)

Categorization of data within the selected publications

Table 2. Categorization of data within the selected publications

Annual mean precipitation	Annual air temperature	Organic C content	Soil bulk density (0-20 cm)	Soil texture (0-20 cm)	pH	Soil available N	Soil available P	Soil available K
< 400 mm	< 9 °C	< 9 g/kg	< 1.3 g cm^{-3}	Light: sandy and sandy loam soils	Very acidic: pH < 5	< 50 mg kg^{-1}	< 20 mg kg^{-1}	< 150 mg kg^{-1}
> 400 mm	> 9 °C	> 9 g/kg	> 1.3 g cm^{-3}	Medium: loamy sand and loam soils	Acidic: pH 5-6	> 50 mg kg^{-1}	> 20 mg kg^{-1}	> 150 mg kg^{-1}
				Heavy: clay loam, silty clay, and clay soils	Neutral: pH 6-7			
					Slightly alkaline: > 7			

[a] < 400 (low mean precipitation); > 400 mm (high mean precipitation);
[b] < 9 °C (low mean temperature); > 9 °C (high mean temperature);
[c] < 9 g/kg (low organic C content); > 9 g/kg (high organic C content);
[d] < 1.3 (low soil bulk density) g cm^{-3}; > 1.3 g cm^{-3} (high soil bulk density);
[e] < 50 (low soil available N) mg kg^{-1}; > 50 mg kg^{-1} (high soil available N);
[f] < 20 (low soil available P) mg kg^{-1} ; > 20 mg kg^{-1}(high soil available P);
[g] < 150 (low soil available K) mg kg^{-1}; > 150 mg kg^{-1}(high soil available K)

Table 3 (on next page)

Variations in yield, evapotranspiration (ET), and water use efficiency (WUE) of wheat, maize, and potato under plastic film and no-mulching application.

Table 3. Variations in yield, evapotranspiration (ET), and water use efficiency (WUE) of wheat, maize, and potato under plastic film and no-mulching application.

			Yield				ET				WUE			
Treatments	**Parameters**	**Variable**	**n**	**Mean**	**Range**	**CV**	**n**	**Mean**	**Range**	**CV**	**n**	**Mean**	**Range**	**CV**
Plastic film	Location	Gansu	10	8821.6	2162.3 - 45882	151	7	279	215.4 - 386.5	22	7	33.3	0.8 - 129.95	138
		Ningxia	2	12926	12779.3 - 13072.5	1.6	2	435	375.5 - 494.3	19	2	30.4	26.8 - 34.1	17
		Shaanxi	7	9313.1	4931.8 - 13079.3	32.6	3	367	300 - 409.5	16	3	25.5	22 - 32.1	22.2
		Shanxi	2	11408	11290 - 11526.7	1.47	2	391	345.4 - 435.7	16	2	14.9	3.4 - 26.5	110
	Crop type	Maize	13	9813.4	2420 - 13079.3	32.8	8	392	300 - 494.3	15	7	23.9	3.4 - 34.1	42.3
		Wheat	2	3547.1	2162.3 - 4931.8	55.2	1	273	-	-	1	0.75	-	-
		Potato	6	11235	2359.3 - 45882	152	5	259	215.4 - 333.7	18	6	38.7	6.4 - 129.95	123
	Rainfall	<400	8	9532.4	2359.3 - 45882	156	6	281	215.4 - 386.5	23	6	38.7	6.4 - 129.96	123
		>400	13	9678.2	2162.3 - 13079.3	35.3	8	378	272.5 - 494.3	19	8	21	0.8 - 34.1	59.2
	Temperature	<9	13	9776.2	2162.3 - 45882	119	11	328	215.4 - 494.3	27	11	29.4	0.75 - 129.95	125
		>9	8	9660.8	4931.8 - 13079.3	28.7	3	367	300 - 409.5	16	3	25.5	22 - 32.07	22.2
No mulching	Location	Gansu	10	5021.3	353 - 27385.5	162	7	320	253.5 - 461.1	26	7	19.7	0.6 - 79.6	144
		Ningxia	2	10755	9978.3 - 11532	10.2	2	437	400 - 473.99	12	2	24.6	24.2 - 24.9	1.93
		Shaanxi	7	8249.1	4650.4 - 10422.3	27.5	3	365	289.7 - 404	18	3	22	19.5 - 26	16.2
		Shanxi	2	10116	9988.3 - 10243.3	1.78	2	407	380.6 - 433.3	9.2	2	13.2	2.7 - 23.7	113
	Crop type	Maize	13	7896.5	353 - 11532	44	8	398	289.7 - 473.99	13	8	17.8	0.9 - 26	57
		Wheat	2	2639.8	629.1 - 4650.4	108	1	273	-	-	1	0.56	-	-
		Potato	6	6960.7	833 - 27385.5	147	5	313	253.5 - 461.1	29	5	27.4	3.6 - 79.6	113
	Rainfall	<400	8	5537.7	353 - 27385.5	163	6	328	253.5 - 461.1	27	6	22.9	0.9 - 79.6	129
		>400	13	8107.4	629.1 - 11532	38.7	8	382	273.1 - 473.99	18	8	17.8	0.6 - 26	57.5
	Temperature	<9	9	7069.7	353 - 27385.5	122	11	357	253.5 - 474	24	11	19.4	0.56 - 79.6	117
		>9	8	7590.7	4650.4 -10422.3	28.3	3	365	289.7 - 404	18	3	22	19.5 - 26.03	16.2

Table 4(on next page)

Mean, range, and coefficient of variation (CV) of yield, evapotranspiration (ET), and water use efficiency (WUE) of wheat, maize, and potato under plastic film mulching and no mulching in different locations and precipitations in northern China

Table 4. Mean, range, and coefficient of variation (CV) of yield, evapotranspiration (ET), and water use efficiency (WUE) of wheat, maize, and potato under plastic film mulching and no mulching in different locations and precipitations in northern China

			Yield				ET				WUE			
Treatments	**Parameters**	**Variables**	**n**	**Mean**	**Range**	**CV**	**n**	**Mean**	**Range**	**CV**	**n**	**Mean**	**Range**	**CV**
Plastic film	Organic C content	<9	8	10504	2162.3 - 45882	140	6	334	215.4 - 494.3	29	6	32.9	0.75 - 129.95	147
		>9	7	11369	9260 - 13079.3	13.2	4	403	375.5 - 435.7	6.4	4	28.8	22.5 - 34.07	18.3
	Bulk density	<1.3	8	11190	2162.3 - 45882	129	6	327	230.9 - 435.7	23	5	47.5	6.35 - 129.95	103
		>1.3	9	9399.7	4255.75 - 13072.5	36.6	6	379	259.2 - 494.3	20	6	22.5	3.36 - 34.07	50.4
	pH	>7	11	11729	2420 - 45882	102	7	381	215.4 - 494.3	23	7	36.5	6.35 - 129.95	115
	Soil texture	Light	5	16667	2549.8 - 45882	101	4	340	215.4 - 435.7	27	4	50.5	11.7 - 129.95	106
		Medium	5	7571.2	2162.3 - 13079.3	57.8	3	254	230.9 - 272.5	8.4	3	23.4	0.75 - 52.85	114
		Heavy	10	7938.6	2359.3 - 13072.5	50.1	6	388	300 - 494.3	17	6	18.8	3.36 - 32.07	60.8
	N	<50	4	7221.3	2420 - 13079.3	76.8	2	301	215.4 - 386.5	40	2	8.98	6.35 - 11.62	41.5
		>50	6	9935.7	2162.3 - 13072.5	41.7	5	388	272.5 - 494.3	20	5	23.2	0.75 - 34.07	57.5
		<20	8	9775.4	2420 - 13079.3	40.9	4	423	375.5 - 494.3	13	4	23.4	6.35 - 34.07	50.9
	P	>20	4	7636.7	2162.3 - 12545.3	57.5	4	343	272.5 - 409.5	20	4	19.3	0.75 - 32.07	68.4
		<150	7	9788.8	4931.8 - 13079.3	31.2	4	384	300 - 435.7	15	5	20.8	0.75 - 32.07	57.3
	K	>150	4	20382	9794.5 - 45882	83.7	3	401	333.7 - 494.3	21	3	63.6	26.8 - 129.95	90.5
No mulching	Organic C content	<9	8	6676.5	353 - 27385.5	137	6	374	273.1 - 473.99	23	6	21.5	0.56 - 79.6	140
		>9	7	8891	5282 - 10422.3	20.6	4	410	400 - 433	3.9	4	23.5	19.5 - 26.03	12.1
	Bulk density	<1.3	8	7499.1	353 - 27385.5	118	6	332	253.5 - 433.3	22	5	31.1	0.85 - 79.6	94.3
		>1.3	9	7215.8	2184.5 - 11532	49.2	6	386	253.8 - 473.99	19	6	18.1	2.7 - 26.03	51.3
	pH	>7	11	8213.5	353 - 27385.5	91.4	7	417	344.1 - 473.99	10	7	25.4	0.85 - 79.6	102
	Soil texture	Light	5	11622	833 - 27385.5	83.1	4	410	344.1 - 461.1	12	4	33	3.6 - 79.6	98.9
		Medium	5	4872.7	629 - 8848.5	66.2	3	260	253.5 - 273.1	4.3	3	14.3	0.56 - 30.9	108
		Heavy	10	6206.8	353 - 11532	65.2	6	392	289.7 - 473.99	15	6	15.6	0.85 - 26.03	70.5
	N	<50	4	4989.9	353 - 9925.2	102	2	431	400 - 461.05	10	2	2.23	0.85 - 3.6	87.4
		>50	6	7606	629.1 - 11532	53.6	5	390	273.1 - 473.99	19	5	19	0.56 - 26.03	55.8
		<20	8	7569.7	353 - 11532	50	4	427	400 - 473.99	8.2	4	18.4	0.85 - 24.9	63.6
	P	>20	4	6172.1	629.1 - 10422.3	67.1	4	342	273.1 - 404	21	4	16.6	0.56 - 26.03	66.7
	K	<150	7	8210.3	4650.4 - 10422.3	27.2	4	382	289.67 - 433.3	17	5	18	0.56 - 26.03	56.1

>150	4	13544	5282 - 27385.5	70.9	3	406	344.1 - 473.99	16	3	42.9	24.23 - 79.6	74.1

3

Table 5(on next page)

Mean, range, and coefficient of variation (CV) of yield of maize for plastic film mulched ridge-furrow and no mulching in Shanxi and Shaanxi provinces in China

Table 5. Mean, range, and coefficient of variation (CV) of yield of maize for plastic film mulched ridge-furrow and no mulching in Shanxi and Shaanxi provinces in China

Treatments	Crop	n	Mean	Range	CV
Plastic film + biochar mulching	Maize	3	11.913	10.43 - 14.7	20.3
No mulching	Maize	3	9.6967	9.11 - 9.99	5.24

Table 6(on next page)

Heterogeneity analysis on yield, evapotranspiration (ET), and water use efficiency (WUE) of wheat, maize, and potato under plastic film and no-mulching treatments using random-effects models.

Table 6. Heterogeneity analysis on yield, evapotranspiration (ET), and water use efficiency (WUE) of wheat, maize, and potato under plastic film and no-mulching treatments using random-effects models.

Items	Parameters	Categories	n	Heterogeneity			
				df	P	Chi2	I2 (%)
Yield	Location	Gansu	22	9	1	0.68	0
		Ningxia	5	1	0.37	0.82	0
		Shaanxi	27	6	0.59	4.67	0
		Shanxi	5	1	0.9	0.01	0
	Crop type	Maize	39	12	0.2	15.72	24
		Wheat	7	1	0.79	0.07	0
		Potato	14	5	0.99	0.44	0
	Rainfall	<400	18	7	1	0.55	0
		>400	43	13	0.92	6.66	0
ET	Location	Gansu	14	6	1	0.3	0
		Ningxia	5	1	0.53	0.4	0
		Shaanxi	10	2	0.71	0.68	0
		Shanxi	6	1	0.35	0.87	0
	Crop type	Maize	23	7	0.88	3.05	0
		Wheat	2	-	-	-	-
		Potato	10	4	0.99	0.22	0
	Rainfall	<400	12	5	1	0.29	0
		>400	23	7	0.89	2.99	0
WUE	Location	Gansu	14	6	1	0.37	0
		Ningxia	5	1	0.19	1.71	41
		Shaanxi	10	2	0.33	2.19	9
		Shanxi	6	1	0.5	0.46	0
	Crop type	Maize	23	7	0.69	4.79	0
		Wheat	2	-	-	-	-
		Potato	10	4	0.99	0.35	0
	Rainfall	<400	12	5	1	0.37	0
		>400	23	7	0.68	4.87	0

Table 7(on next page)

Heterogeneity analysis on yield, evapotranspiration (ET), and water use efficiency (WUE) of wheat, maize, and potato under plastic film and no-mulching treatments using random-effects models.

1 **Table 7.** Heterogeneity analysis on yield, evapotranspiration (ET), and water use efficiency
2 (WUE) of wheat, maize, and potato under plastic film and no-mulching treatments using
3 random-effects models.

Items	Parameters	Categories	n	Heterogeneity			
				df	P	Chi2	I2 (%)
Yield	Organc C content	<9	20	7	1	0.45	0
		>9	20	6	1	0.28	0
	Bulk density	<1.3	25	7	0.97	1.78	0
		>1.3	25	8	0.9	3.43	0
	pH	>7	30	10	0.97	3.51	0
	Soil texture	Light	13	4	0.99	0.25	0
		Medium	10	4	0.99	0.32	0
		Heavy	34	9	0.93	3.68	0
	N	<50	9	3	0.99	0.09	0
		>50	16	5	0.96	1.04	0
	P	<20	22	7	0.87	3.2	0
		>20	12	3	0.78	1.11	0
	K	<150	23	6	0.76	3.4	0
		>150	9	3	0.8	1.01	0
ET	Organc C content	<9	13	5	0.99	0.48	0
		>9	13	3	0.69	1.48	0
	Bulk density	<1.3	14	5	1	0.33	0
		>1.3	17	5	0.74	2.74	0
	pH	>7	18	6	0.98	1.14	0
	Soil texture	Light	10	3	0.92	0.5	0
		Medium	6	2	0.99	0.02	0
		Heavy	17	5	0.78	2.46	0
	N	<50	4	1	0.99	0	0
		>50	14	4	0.81	1.57	0
	P	<20	10	3	0.89	0.65	0
		>20	12	3	0.87	0.72	0
	K	<150	13	3	0.87	0.72	0
		>150	7	2	0.8	0.45	0
WUE	Organc C content	<9	13	5	1	0.25	0
		>9	13	3	0.33	3.41	12
	Bulk density	<1.3	12	4	1	0.17	0
		>1.3	17	5	0.8	2.38	0
	pH	>7	18	6	0.91	2.09	0
	Soil texture	Light	10	3	0.48	2.47	0
		Medium	6	2	0.95	0.11	0
		Heavy	17	5	0.95	2.41	0

	N	<50	4	1	0.86	0	0
		>50	14	4	0.62	2.66	0
	P	<20	10	3	0.49	2.43	0
		>20	12	3	0.52	2.28	0
	K	<150	15	4	0.62	2.61	0
		>150	7	2	0.42	1.75	0

Figure 1

Flowchart of literature identification, and screening for use in this study. Adapted from PRISMA (Moher et al., 2009)

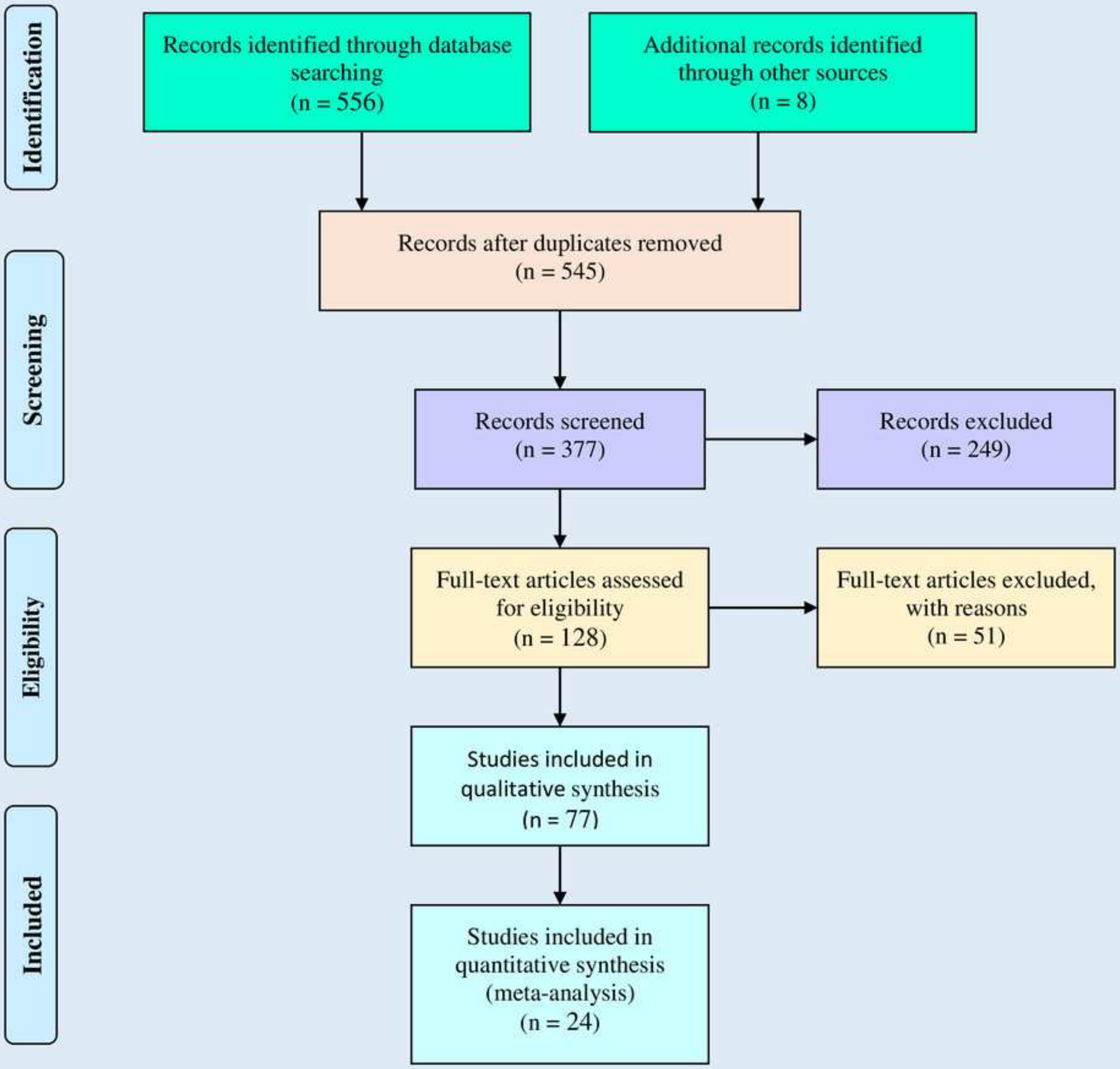

Figure 1. Flowchart of literature identification, and screening for use in this study. Adapted from PRISMA (Moher et al., 2009).

Figure 2

Experimental locations from the peer-reviewed publications for the meta-analysis.
ArcGIS 10.6 software (ESRI, Redlands, California) was used to produce the map.

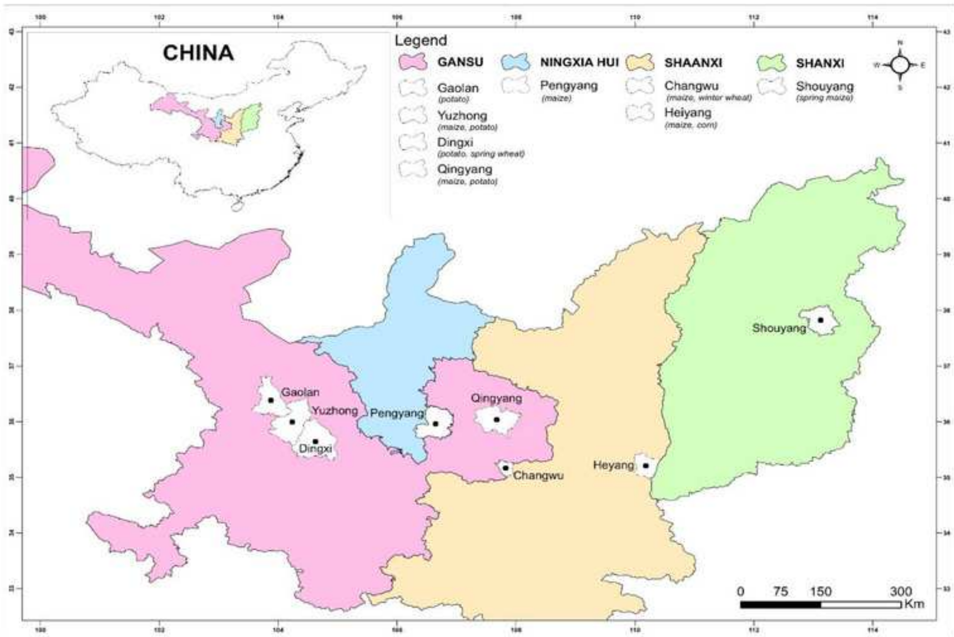

Figure 2. Experimental locations from the peer-reviewed publications for the meta-analysis. ArcGIS 10.6 software (ESRI, Redlands, California) was used to produce the map.

Figure 3

A. Odds ratios of crop yields in different locations and climate. B. Odds ratios of yield in different soil properties. The error bars signify 95% confidence intervals, and the values above the bars indicate the number of observations (n).

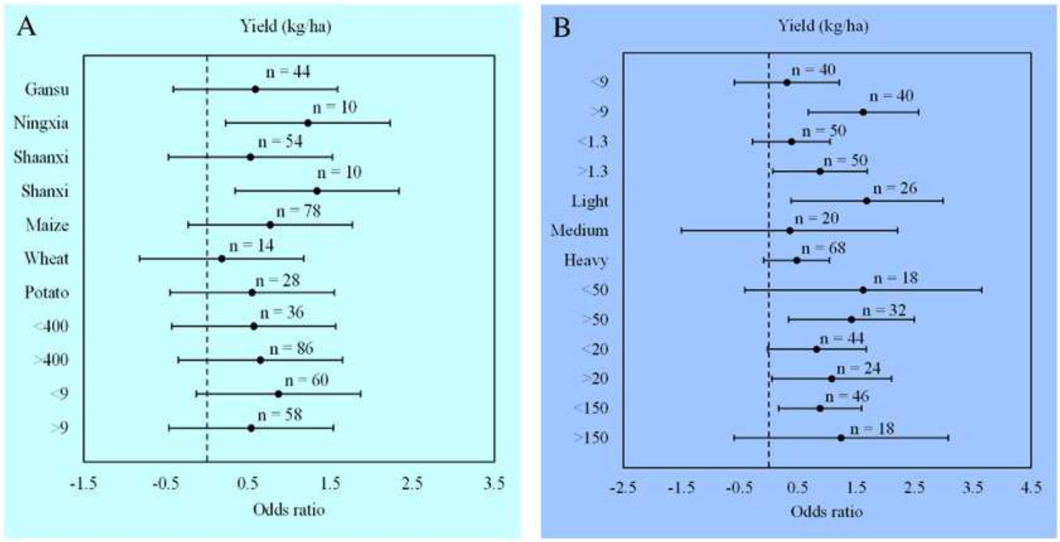

Figure 3. A. Odds ratios of crop yields in different locations and climate. B. Odds ratios of yield in different soil properties. The error bars signify 95% confidence intervals, and the values above the bars indicate the number of observations (n).

Figure 4

A. Odds ratios of evapotranspiration (ET) in different locations and climate. B. Odds ratios of evapotranspiration (ET) in different soil properties. The error bars signify 95% confidence intervals, and the values above the bars indicate the number of obs

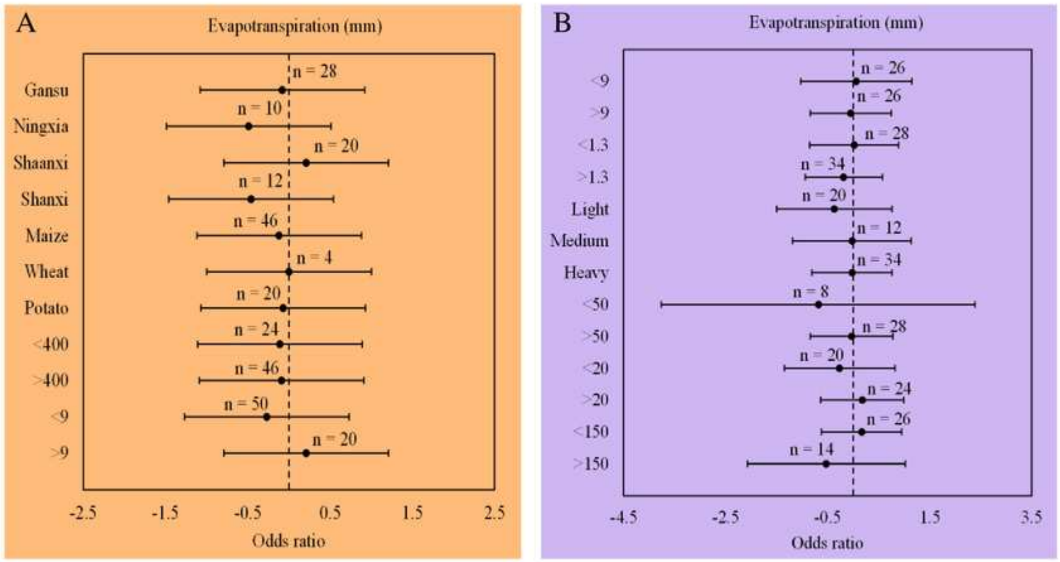

Figure 4. A. Odds ratios of evapotranspiration (ET) in different locations and climate. B. Odds ratios of evapotranspiration (ET) in different soil properties. The error bars signify 95% confidence intervals, and the values above the bars indicate the number of observations (n).

Figure 5

A. The odds ratios of water use efficiency (WUE) for plastic film relative to no mulching in different locations and climate. B. The odds ratios of water use efficiency (WUE) for plastic film relative to no mulching in different soil properties. The error

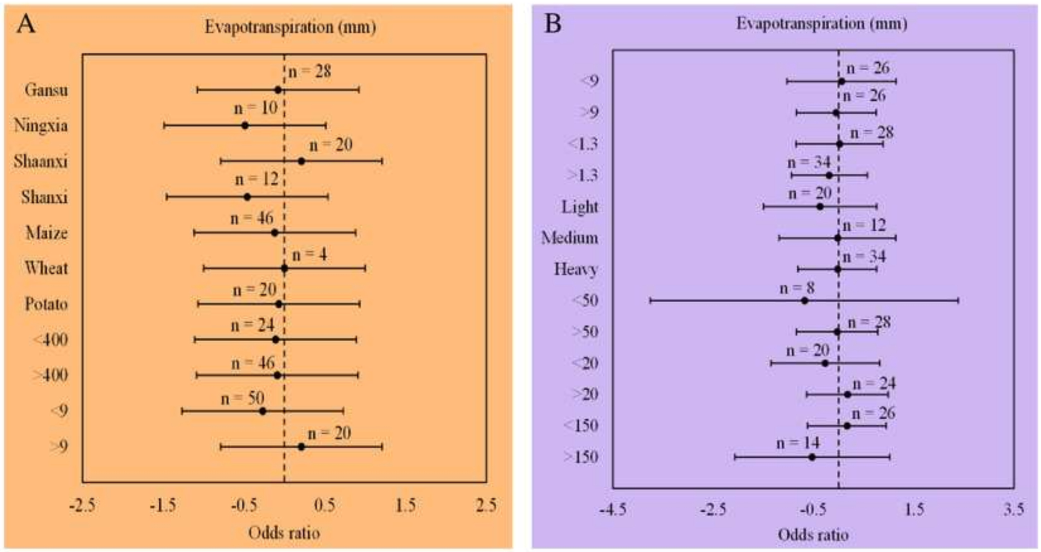

Figure 5. A. The odds ratios of water use efficiency (WUE) for plastic film relative to no mulching in different locations and climate. B. The odds ratios of water use efficiency (WUE) for plastic film relative to no mulching in different soil properties. The error bars show the 95% confidence intervals, and the values above the bars indicate the number of observations.