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Mulching improves yield and water-use efficiency of potato cropping in China: A meta-analysis

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A R T I C L E I N F O

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Potato

A B S T R A C T

China is the world's largest producer of potato (*Solanum tuberosum* L.). Potato productivity in China is limited by water shortage. Mulching applications can effectively modify the plant hydrothermal micro-environment. However, the impacts of mulching on potato yield vary with climatic conditions and field managements. Here, we conducted a meta-analysis to evaluate the effects of plastic mulching and straw mulching on the yield and water-use efficiency (WUE) of potato cropping in China using data obtained from 131 peer-reviewed publications. The results showed that plastic mulching and straw mulching increased potato yield in average by 24.3% and 16.0%, respectively. The effects of mulching on the WUE of potato were also improved by 28.7% (plastic mulching) and 5.6% (straw mulching). At regional scale, plastic mulching performed better in Northeast China and Northwest China, while straw mulching performed better in Southwest China and South China. The yield and WUE of potato in response to mulching were affected by the mean growing season air temperature, water input, soil basic fertility and fertilizer applications. When compared to non-mulching control, the improvements of yield and WUE in potato were higher at mean air temperatures of 15–20 °C than at temperatures below 15 °C or above 20 °C during the growing season for both mulching practices. Increase in potato yield under black film was significantly higher than that under transparent film when air temperature was over 20 °C. Potato yield and WUE increases in mulching treatments were greater in areas with a water input of < 400 mm than in areas with a water input of > 400 mm. The mean effects of mulching on the yield of potato were greater at relatively low (< 100 kg ha^{-1}) or moderate (100–200 kg ha^{-1}) N rates than at high (> 200 kg ha^{-1}) N rates. Similar trends were observed for P and K rates. In conclusion, this meta-analysis demonstrated that mulching increases the yield and WUE of potato in China and that the adoption of mulching practices should be site specific.

1. Introduction

Potato (*Solanum tuberosum* L.) is currently the world's fourth-largest food crop after rice, wheat, and maize. As the world's largest producer of potatoes, China produced 95.6 million metric tons of potatoes in 2014, accounting for 25% of the world’s total production (FAO, 2014). Potato production plays an important role in ensuring food security in China. However, potato yields are limited by water shortage and sub-optimal field managements in some regions of China. Thus, adopting appropriate farming practices is necessary to enhance potato yield and meet the growing food demand in China.

Mulching is an effective method of altering the plant micro-environment to increase crop yield. According to the materials applied, mulching can be broadly divided into three main types: organic mulching (crop straw, leaves, geotextiles, etc.), inorganic mulching (pure plastic film, degradable film, etc.) and mixed mulching (plastic, straw, grass, gravel, etc.) (Kader et al., 2017). Plastic mulching and straw mulching are widely used in potato production in China. Plastic mulching was introduced to China in the 1970s and has since been widely applied, especially in the northern arid and semi-arid areas (Wang et al., 2005, 2009; Zhao et al., 2012). Straw mulching is a convenient mulching method in potato cultivation in regions where straw resources are locally available (Tang et al., 2015).

Mulching practices directly and indirectly exert positive impacts on micro-climates and crop yield. Plastic mulching influences the hydrothermal conditions of the soil by increasing soil temperature and reducing soil water evaporation (Wang et al., 2005). Mulching can protect soil from water erosion and thus reduce soil and water loss in

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arable lands (Prosdocimi et al., 2016). Mulching reduces nitrogen leaching and increases nutrient availability, thereby improving soil quality (Haraguchi et al., 2004). Plastic mulching suppresses weed growth and reduces competition with weeds for water and nutrients (Abouziena et al., 2008). As a result, mulching leads to increases in yield and water-use efficiency (WUE) (Qin et al., 2014; Zhao et al., 2014). Although mulching has many positive effects, it also has some disadvantages. Due to prolonged higher soil temperatures, applying plastic mulch over an entire growing season may reduce crop yield (Wang et al., 2009; Hou et al., 2010). Manual installation and removal of mulch materials is time consuming and labour intensive. In addition, large amounts of plastic film residue adversely affect the environment, soil structure and crop growth (Liu et al., 2014).

Field experiments are generally conducted in a single area and thus cannot evaluate the comprehensive effect of mulching on macro-scale areas. Meta-analysis is an integrated statistical method to synthesize the results of independent experiments and quantitatively evaluate treatment effects at regional or global scales (Hedges et al., 1999). In recent years, several review papers reported the effects of mulching practices on yield and WUE of particular crop species. For example, soil mulching contributed to as high as 20% and 60% of grain yield of wheat and maize, respectively (Qin et al., 2015). A study of Wang and Shangguan (Wang and Shangguan, 2015) found that on the Loess Plateau of China, plastic mulching performed better than straw mulching in improving wheat yield and WUE regardless no difference in evapotranspiration (ET).

As one of the main food crops in China, potato is widely planted under various mulching practices. However, the effects of mulching practices often differ and are in some cases contradictory in the literature, since the effects may be influenced by different climatic conditions, soil characteristics, crop species, and field managements (Belanger et al., 2000). Thus, *meta*-analysis based on peer-reviewed literature provides a useful tool to evaluate the effects of mulching practices on potato yield and WUE. The objectives of our study were (1) to quantify the effects of two major mulching practices (plastic and straw mulching) on the yield and WUE of potato in China, and (2) to investigate how the effects of mulching vary with respect to location, temperature, water input and fertilizer applications.

2. Materials and methods

2.1. Data collection

A search of the peer-reviewed published papers was performed to collect data on the effects of mulching on potato yield and WUE in China up to December 2017. Data published in English were collected from the ISI-Web of Science (http://apps.webofknowledge.com/) and Google Scholar (Google Inc., Mountain View, CA, USA), and data published in Chinese were collected from the China National Knowledge Infrastructure (http://www.cnki.net/). Data collections were restricted to field experimental studies containing at least one of the two major mulching practices (i.e. plastic and/or straw mulching) and no-mulching control. A study was included if it contained available data on potato yield and/or WUE. Based on these criteria, 131 publications (15 in English and 116 in Chinese) containing 634 side-by-side comparisons (360 for yield, 137 for WUE and ET respectively) were compiled into the dataset. As not all studies reported potato yields along with WUE and ET, the numbers of comparisons for yield, WUE and ET were not equal. Detailed information on the included publications is listed in Appendix A.

According to diverse geographic, climatic conditions and natural cultivated regions of potato in China (Zongfan et al., 1989; Zhao et al., 2016; Xu et al., 2017), the study areas were grouped into seven geographic regions: North-central China, Northeast China, Northwest China, Qinghai and Tibet, The Middle and Lower reaches of Yangtze River, Southwest China and South China. 1) Northwest China: This area accounts for 36% of China's total potato acreage. The potatoes produced in this area are mainly used for seed potatoes, direct consumption and processing. Potatoes in this zone are usually planted in late April to early May and harvested from September through October. This zone includes Inner Mongolia, Gansu, Xinjiang, Ningxia and Shaanxi provinces. 2) North-central China: This area accounts for 6% of China's total potato acreage. The potatoes produced in this area are mainly used for processing and direct consumption. Potatoes in this zone are usually planted in May and harvested from September through October. This zone includes Hebei, Beijing, Tianjin, Shanxi, Shandong and Henan provinces. 3) Northeast China: This area accounts for 8% of China's total potato acreage. The potatoes produced in this area are mainly used for processing and direct consumption. Potatoes in this zone are usually planted in May and harvested in September. This zone includes Heilongjiang, Jilin and Liaoning provinces. 4) Qinghai and Tibet: This area accounts for 2% of China's total potato acreage. The potatoes produced in this area are mainly used for processing and direct consumption. Potatoes in this zone are usually planted in May and harvested in September. 5) Southwest China: This area accounts for 35% of China's total potato acreage. The potatoes produced in this area are mainly used for processing and direct consumption. Potatoes in this zone are usually planted in September through November and harvested from February through April. This zone includes Guizhou, Yunnan, Chongqing and Sichuan provinces. 6) The Middle and Lower reaches of Yangtze River: This area accounts for 8% of total acreage. Spring potatoes are planted in February through March and harvested during May or June. Autumn potatoes are planted in July-August and harvested in October-November. The potatoes produced in this area are mainly for export and direct consumption. This zone includes Jiangxi, Jiangsu, Zhejiang, Anhui, Hunan and Hubei provinces. 7) South China: This area accounts for 5% of total acreage. Potatoes in this zone are planted in October–November and harvested in February–March. The potatoes produced in this area are mainly for export and direct consumption. This zone includes Guangdong, Fujian, Guangxi, and Hainan provinces. Some general climatic information and crop system of each potato-cultivating region is shown in Table 1 (Zongfan et al., 1989; Cui et al.,

Table 1
General climate information of experimental sites in potato-cultivating regions and common cropping systems.

Region	Annual mean temperature (°C)	Accumulated temperature above 10 °C (°C)	Annual sunshine time (hour)	Annual mean precipitation (mm)	Cropping system
Northeast China	−4 to 12	1600–3800	2200–2900	400–1000	Single cropping
North-central China	6–15	3000–5000	2000–2800	400–1000	Single or double cropping
Northwest China	−4 to 14	2500–5000	2000–3300	50–800	Single cropping
Qinghai and Tibet	−4 to 8	500–2100	3000–4000	50–1000	Single cropping
The Middle and Lower reaches of Yangtze River	10–18	4500–6000	1100–2500	800–1750	Double cropping
South China	18–24	6500–9500	1200–2500	1000–2500	Double cropping
Southwest China	−4 to 20	2000–8000	900–2500	500–1500	Single or double cropping

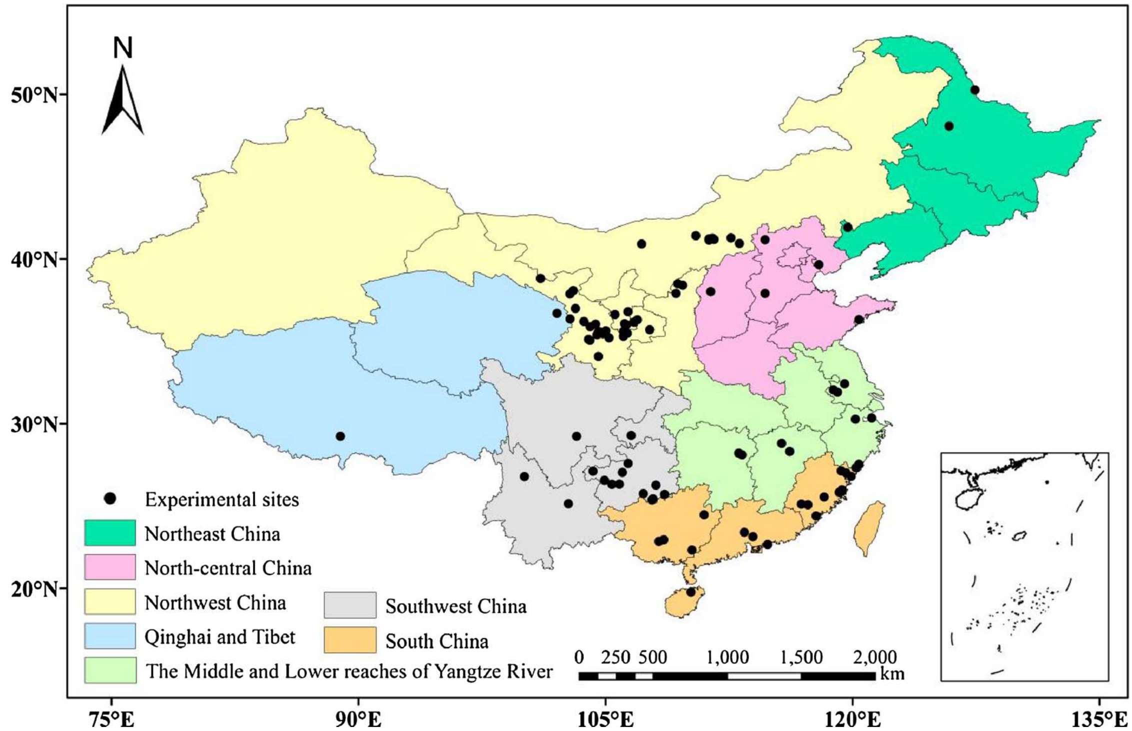

Fig. 1. Geographic regions of potato cropping in China and locations of field experiments in the literature included in this *meta*-analysis.

2016). The geographic distribution of experimental sites is indicated in Fig. 1.

Based on the classification of different mulching materials (Kader et al., 2017) and the main mulching practices applied in China, the mulching methods were subject to two main categories: (1) plastic film mulching, and (2) straw mulching. Plastic mulching materials included black plastic film and transparent plastic film. The straw materials in the literature comprised rice, wheat and maize residues. To explain variations in the responses of potato yield, WUE and ET to climate conditions, the mean air temperature during the potato growing season was divided into three categories: < 15 °C, 15–20 °C, and > 20 °C. Water input (sum of rainfall and irrigation during potato growing season) levels during the growing season were partitioned into two groups: low (< 400 mm) and high (> 400 mm). According to basic soil fertility, soil available N was divided into two groups: < 50 mg kg^{-1} and > 50 mg kg^{-1}; soil available P was divided into two groups: < 20 mg kg^{-1} and > 20 mg kg^{-1}; soil available K was divided into two groups: < 100 mg kg^{-1} and > 100 mg kg^{-1}. According to N, P and K fertilizer application rates, the dataset was divided into three sub-datasets (< 100 kg ha^{-1}, 100–200 kg ha^{-1} and > 200 kg ha^{-1}). As only some of the included studies reported soil basic fertility along with fertilizer application rates, therefore only the effects of mulching on potato yield were assessed.

2.2. Data analysis

The natural log (lnR) of the response ratio (R) was calculated as the effect size in this *meta*-analysis (Hedges et al., 1999), representing the effects of mulching, using the following equations:

$$R = \frac{X_T}{X_C}$$

$$lnR = \ln\left(\frac{X_T}{X_C}\right) = lnX_T - lnX_C$$

where X_T is the mean value of potato yield, WUE or ET in mulching treatments and X_C is the mean value of potato yield, WUE or ET in no-mulching controls. As most of the studies included in this study did not provide variance, an un-weighted method (Chen et al., 2013) was adopted using MetaWin 2.1 software (Rosenberg et al., 2000). Mean effect sizes and bias-corrected 95% confidence intervals (CIs) were generated using a bootstrapping procedure (4999 iterations). Groups with fewer than two valid comparisons were excluded from the *meta*-analysis. To facilitate interpretation, the percentages of changes in potato yield, WUE and ET were calculated by (R−1) × 100%. A positive percentage change indicated an increase in the respective variable under mulching relative to no-mulching, while a negative value indicated a decrease. The mean percentage change was considered significantly positive or negative when 95% CI did not overlap with zero (Hedges et al., 1999).

In addition, the frequency distribution of effect size was plotted to reflect the distribution regularities of individual studies. The frequency of effect size was also fitted to a Gaussian distribution function to test the homogeneity of observations. These procedures were performed using SigmaPlot v. 10.0 software. The general linear model (GLM) was performed to determine the effects of each variable and their interactions on yield, WUE and ET of potato using SPSS statistical software (Version 20.0 for Windows, SPSS, Chicago, USA).

3. Results

3.1. Overview of the dataset

Our dataset consisted of 634 comparisons (360 for yield, 137 for WUE and ET respectively) from 131 studies (15 published in English and 116 in Chinese). There were 517 comparisons for plastic mulching (275 for yield, 121 for WUE and ET respectively) and 117 for straw mulching (85 for yield, 16 for WUE and ET respectively). The frequency distributions of effect sizes were found to follow Gaussian normal distributions for the yield, WUE and ET of potato, indicating that the datasets were homogeneous (Fig. 2) (Shan and Yan, 2013).

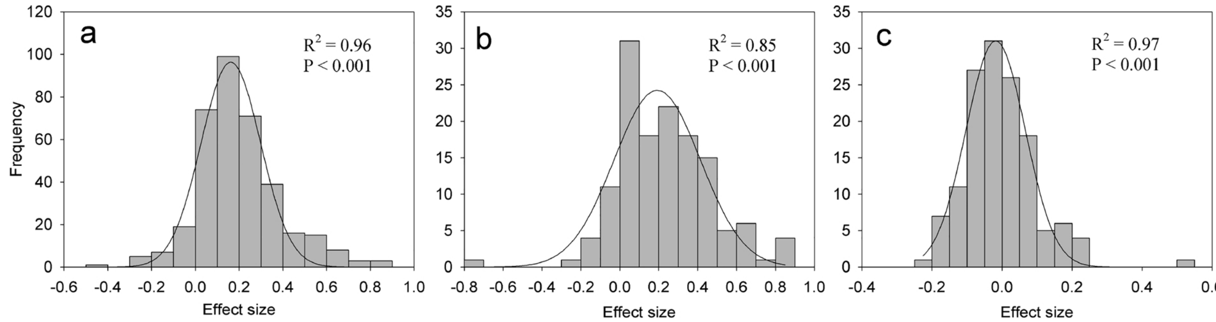

Fig. 2. Frequency distribution of effect sizes for potato yield (a), WUE (b) and ET (c) responding to mulching compared to no-mulching. Solid lines are fitted normal (Gaussian) distributions of frequency data sets.

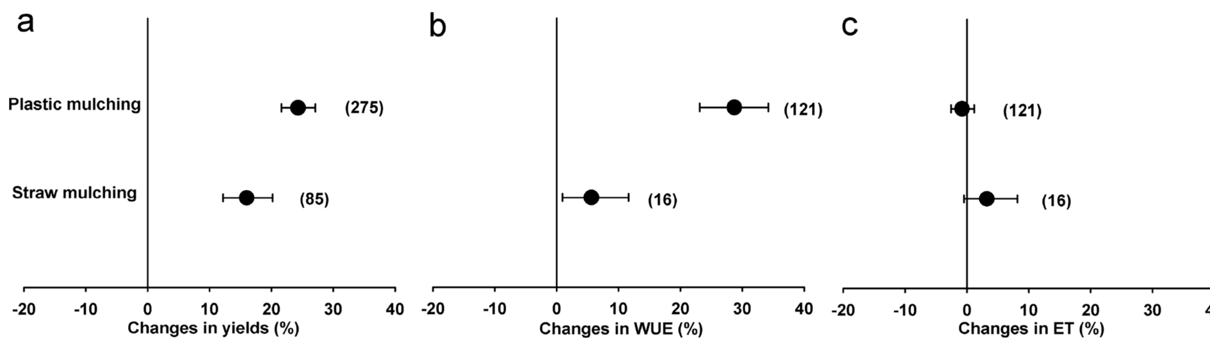

Fig. 3. Overall effects of mulching on yields (a), WUE (b) and ET (c) of potato. Error bars represent 95% confidence intervals. The numbers of comparisons are indicated in parentheses.

3.2. Overall effects of mulching on potato yield and WUE

The yield and WUE of potato were significantly increased by both plastic mulching and straw mulching compared to the no-mulching control (Fig. 3). On average, the increase in potato yield with plastic mulching was 24.3%, significantly higher than that of straw mulching (16.0%) (Fig. 3a). Similarly, the mean effect of plastic mulching on potato WUE (28.7%) was also significantly higher than that of straw mulching (5.6%) (Fig. 3b). Compared to control, plastic mulching decreased ET by 0.8%, while straw mulching increased ET by 3.2%, but the effects were not significant (Fig. 3c).

3.3. Yield and WUE of potato in response to mulching in different regions

The yield, WUE and ET of potato in response to mulching varied with regions in China (Fig. 4). For plastic mulching, the highest increase in potato yield was found in Northeast China (27.7%), followed by Northwest China (27.0%), South China (22.1%), The Middle and Lower reaches of Yangtze River (21.5%), Qinghai and Tibet (17.4%), North-central China (14.9%)and Southwest China (14.7%) (Fig. 4a). However, the effects of straw mulching on potato yield in different regions were ranked in the order of Southwest China (20.6%), South China (17.4%), Northwest China (15.2%) and The Middle and Lower reaches of Yangtze River (4.5%) (Fig. 4b).

In addition to yield data, studies conducted in North-central China, Northwest China and Southwest China also reported potato WUE and ET values, which were not reported in studies from other regions. Therefore the effects of mulching on WUE and ET were assessed based on studies in these three regions only. Since there was only one pair of observations (mulching treatment and control) included in subgroup of Southwest China, this subgroup was excluded from the *meta*-analysis of straw mulching. Plastic mulching and straw mulching significantly increased potato WUE in North-central China by 30.2% and 6.4%, respectively (Fig. 4c and d). However, plastic mulching had no significant effect on potato WUE in North-central China and Southwest China (Fig. 4c). Plastic mulching decreased potato ET in North-central China and Northwest China and increased potato ET in Southwest China, and straw mulching had a positive effect in Northwest China; however, neither difference was significant (Fig. 4e and f).

3.4. Yield and WUE of potato in response to mulching at different temperatures

The effects of mulching on potato yield and WUE varied with the mean air temperature during the potato growing season (Fig. 5). Plastic mulching increased the yield of potato crops grown at mean air temperatures of < 15 °C, 15–20 °C and > 20 °C during the growing season by 21.2%, 25.5% and 20.1%, respectively (Fig. 5a). Growth temperature had the similar influence on potato yield under straw mulching practices with the most significant increase at air temperatures ranging from 15 to 20 °C (18.9%), followed by < 15 °C (13.3%) and > 20 °C (11.5%), respectively (Fig. 5b).

For plastic mulching, enhancement in potato WUE was higher at air temperatures ranging from 15 to 20 °C than that at air temperatures of > 20 °C (Fig. 5c). Straw mulching significantly increased potato WUE by 7.7% at air temperatures ranging from 15 to 20 °C, and no significant effect when mean growth temperatures > 20 °C (Fig. 5d). Plastic mulching had no significant effect on ET regardless mean growth temperatures (Fig. 5e). However, straw mulching significantly increased potato ET by 11.4% when mean growth temperatures > 20 °C (Fig. 5f).

3.5. Yield of potato in response to plastic mulching with different film colors

Since there were relatively few papers reporting black film mulch, the effects of different film colors on potato yield were assessed only. The effects of plastic mulching were affected by the color of the plastic film. In China, the overall increase in potato yield with black film mulching was 25.8%, higher than that of transparent film mulching (23.7%) (Fig. 6a). The effects of black and transparent film on potato yield varied with regions (Fig. 6b). In Northeast China and Northwest China, enhancements in potato yields under transparent film were a

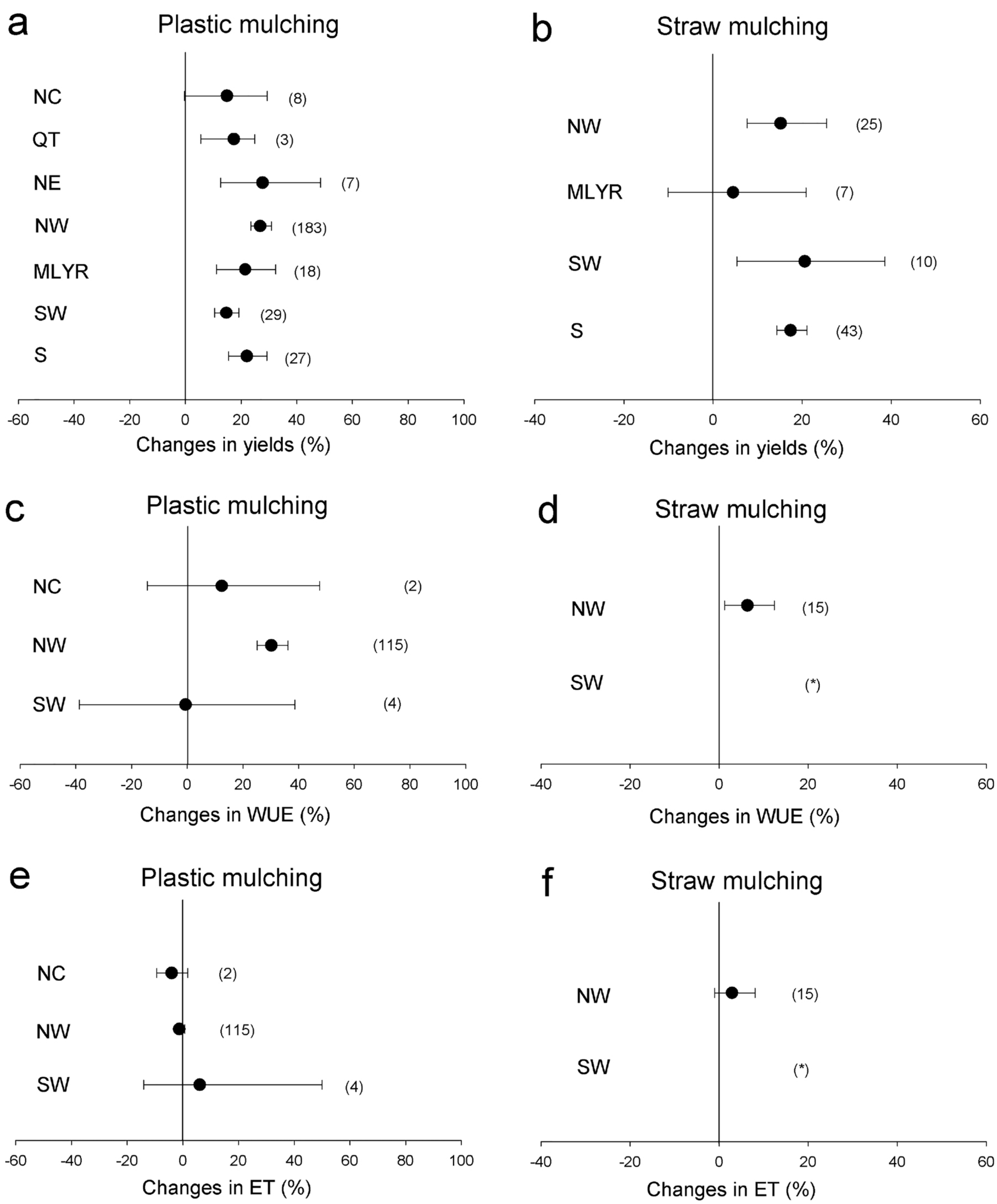

Fig. 4. Effects of two common mulching practices on yields (a and b), WUE (c and d) and ET (e and f) of potato in different regions of China (plastic mulching, left side; straw mulching, right side). Error bars represent 95% confidence intervals. The numbers of comparisons are indicated in parentheses. Asterisks (*) represent only one comparison in this subgroup. NC, QT, NE, NW, MLYR, SW and S represent North-central China, Qinghai and Tibet, Northeast China, Northwest China, The Middle and Lower reaches of Yangtze River, Southwest China and South China respectively.

little higher than those under black film. However, black film performed better than transparent film in The Middle and Lower reaches of Yangtze River, Southwest China and South China. In South China, increase in potato yield under black film was significantly higher than that under transparent film. The effects of black and transparent film on potato yield varied with the mean air temperature during the potato growing season (Fig. 6c). Both transparent film and black film had significantly positive effects on potato yield at mean air temperatures of < 15 °C and 15–20 °C. However, increase in potato yield under black film was significantly higher than that under transparent film when air temperature was above 20 °C.

3.6. Yield and WUE of potato in response to mulching at different water input levels

The effects of mulching were also affected by different water input levels during the potato growing season (Fig. 7). For plastic mulching, increases in potato yield were greater in areas with low water input (26.0%) than in areas with high water input (19.4%) (Fig. 6a). Similarly, the mean effect of straw mulching on potato yield was 17.4% in areas with low water input and 12.3% in areas with high water input (Fig. 7b). Plastic mulching showed the similar trend as straw mulching (Fig. 7c).

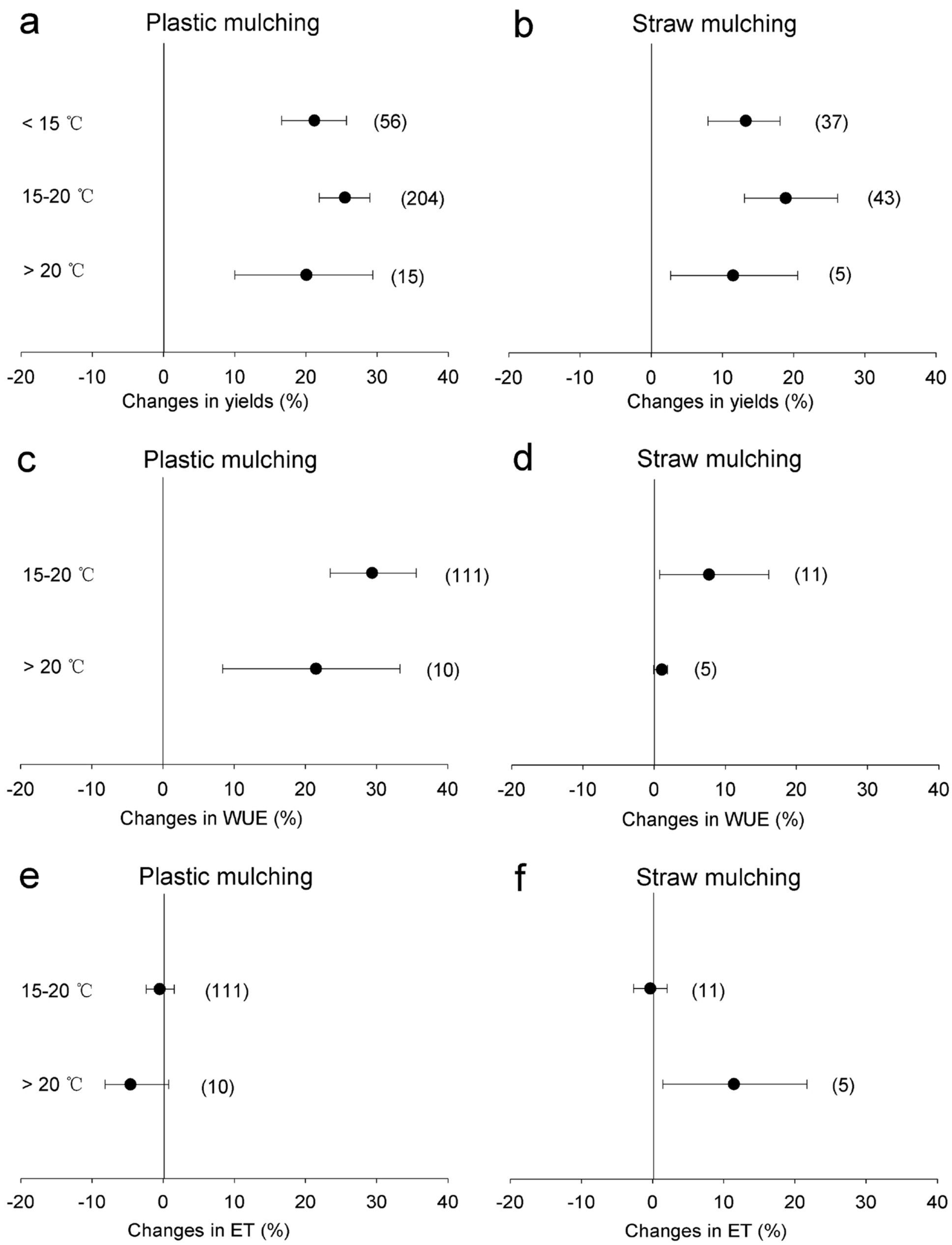

Fig. 5. Effects of two common mulching practices on yields (a and b), WUE (c and d) and ET (e and f) of potato at different mean temperatures during the potato growing season (plastic mulching, left side; straw mulching, right side). Error bars represent 95% confidence intervals. The numbers of comparisons are indicated in parentheses.

Straw mulching significantly increased potato WUE by 8.3% in areas with low water input, but had no significant effect in areas with high water input (Fig. 7d). Plastic mulching significantly decreased potato ET by 1.8% at low water input level (Fig. 7e). The effects of straw mulching on potato ET were positive but not significant under either water input categories (Fig. 7f).

3.7. Yield of potato in response to mulching at different soil fertility and fertilizer application rates

Mulching effects were also influenced by soil fertility and inorganic fertilizer application rates. Plastic mulching performed better at relatively low (< 100 kg ha^{-1}) or moderate (100–200 kg ha^{-1}) NPK rates (Fig. 8). Specifically, increase in potato yield was higher at moderate N rate (100–200 kg ha^{-1}) when soil available N was below 50 mg kg^{-1}. With high soil available N (> 50 mg kg^{-1}), plastic mulching exerted greater effect on potato yield at N rate of < 100 kg ha^{-1} (Fig. 8a). Plastic mulching performed better at low P rate (< 100 kg ha^{-1}) with low basic soil P fertility (< 20 mg kg^{-1}) and at moderate P rate (100–200 kg ha^{-1}) with high basic soil P fertility (> 20 mg kg^{-1}), respectively (Fig. 8b). Increases in potato yield were higher at relatively low K application rate (< 100 kg ha^{-1}) (Fig. 8c). Similarly, straw mulching performed better at relatively low (< 100 kg ha^{-1}) or moderate (100–200 kg ha^{-1}) NPK rates with different soil basic fertility (Figs. 8d–f).

3.8. Interactions of multiple variables in yield, WUE and ET of potato

Results of the statistical analysis of the effects of mulching methods, geographic regions, mean growth air temperatures, water inputs, and N, P and K application rates and their interactions on the yield, WUE and ET of potato crops are summarized in Table 2. Mulching methods, geographic regions, mean growth air temperature and water input had significant effects on potato yield, respectively (Table 2). In addition,

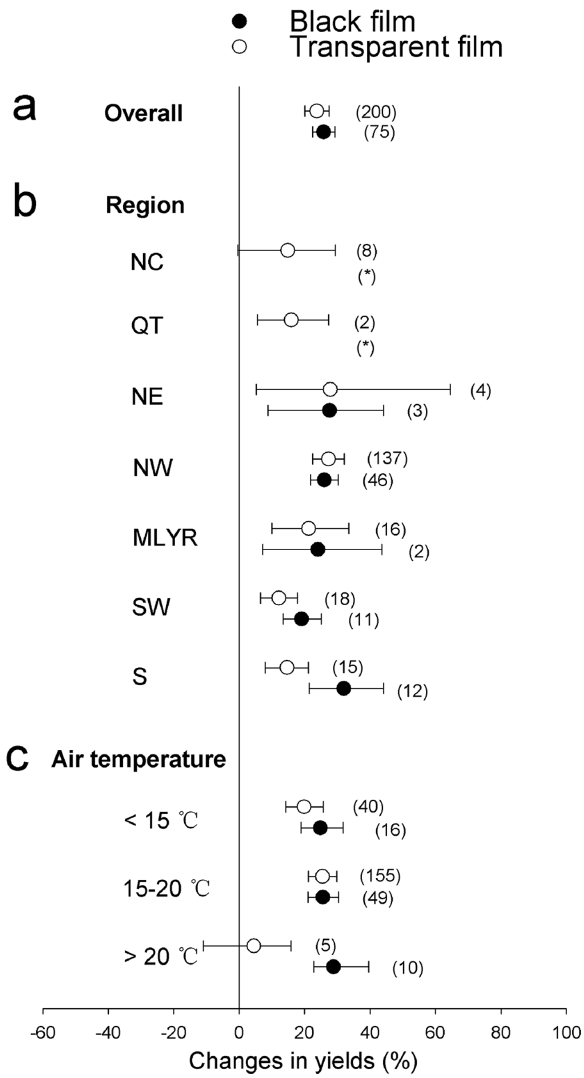

Fig. 6. Effects of black and transparent film on potato yield (a, overall; b, region; c, air temperature) during the potato growing season. Error bars represent 95% confidence intervals. The numbers of comparisons are indicated in parentheses. Asterisks (*) represent insufficient comparison (zero or one) in this subgroup. NC, QT, NE, NW, MLYR, SW and S represent North-central China, Qinghai and Tibet, Northeast China, Northwest China, The Middle and Lower reaches of Yangtze River, Southwest China and South China respectively.

potato yield significantly responded to N and K inputs. There were significant interactions between temperature and water input in potato yield during growing season. The interactions between water and N input, water and P input, N and K input, water, N, P and K input were also significant.

WUE of potato significantly responded to mulching methods, water and P input (Table 2). There were significant interactions between temperature and water inputs in WUE of potato. In addition, the interactions between water and P input, N and P input, P and K input, N, P and K input, water, N, P and K input were also significant.

ET of potato was significantly responded to geographic regions (Table 2). There were significant interactions between water and P input, water, N, P and K input.

4. Discussion

Our study provides a systematic and quantitative analysis on the impacts of two common mulching practices (plastic mulching and straw mulching) on the yield and WUE of potato based on literature search. This study focused on plastic mulching and straw mulching because of their widespread adoption in potato production in China.

4.1. Effects of different mulching methods on yield and WUE of potato

In this study, data showed that increases in the yield and WUE of potato under plastic mulching were significantly larger than those under straw mulching (Fig. 3a and b). Plastic mulching decreased potato ET, but straw mulching increased potato ET (Fig. 3c). Qin et al. (2015) reported that plastic mulching exerted a much greater effects than straw mulching on the yield and WUE of maize, whereas the effects of the two mulching methods were similar for the yield and WUE of wheat. Wang and Shangguan (Wang and Shangguan, 2015) studied the effects of five different mulching practices on the yield and WUE of wheat and reported that plastic mulching was more effective on the Loess Plateau than other mulching methods.

4.2. Effects of mulching on yield and WUE of potato in different regions

At the regional scale, plastic mulching in Northeast China and Northwest China showed higher increases in the yield and WUE of potato compared to other regions. The regional variations in yield and WUE in response to plastic mulching might be attributed to differences in climatic conditions and cropping systems. Northwest China is the major potato production region (Zhao et al., 2016). Cool climate, large diurnal temperature range, and abundant sunlight make this region highly suitable for potato cultivation. Typically, local potatoes are sown in spring (April–May) and harvested in autumn (September-October), with only one planting season per year. However, most arable land in this region is rain-fed agricultural land, and water resources are a key factor limiting potato production. In Northeast China, spring drought postpones sowing date, delays seedling emergence and limits crop yields due to the shorter growing period (Jia et al., 2017). Irregular emergence due to drought also decreases yield. Plastic mulching can decrease soil evaporation, retain soil water content and enable the full utilization of limited rainfall, thereby relieving water shortage to some degree (Li et al., 2004). In addition, plastic mulching can increase the temperature of the topsoil, and thus accelerate the speed of germination and emergence in the early growing stage at relatively low temperatures (Wang et al., 2005; Zhao et al., 2012). Therefore, plastic mulching has great potential for increasing potato yield and WUE in Northeast China and Northwest China (Fig. 4). In Southwest China and South China, where crop rotation is practised, straw resources are abundant (Fan et al., 2005). Thus, straw mulching is more prevalent in these regions. In addition, straw mulching maintains topsoil structure and encouraged rainwater infiltration, thus decreases runoff and erosion rates in these regions (Barton et al., 2004). Fan et al. found that the water utilization coefficient of straw mulching was higher than for plastic film and paper film in South China (Fan et al., 2002).

4.3. Effects of mulching on yield and WUE of potato at different temperatures

Potato is a shallow-rooted, cool-season crop, and lower night temperatures are favourable for the accumulation of dry matter and carbohydrates in the tubers (Belanger et al., 2000). Plastic mulching accelerated the speed of germination and emergence of potato by increasing the topsoil temperature. Potato tuberization occurs at low temperatures and is delayed or even inhibited at higher temperatures, and tubers rarely form when air temperature is above 30 °C (Kar and Kumar, 2007). Therefore, potatoes are often grown in regions where the prevailing mean air temperature is approximately 15–18 °C during the growing season (Marinus and Bodlaender, 1975; Hay and Allen, 1978; Caldiz et al., 2001). Previous studies showed that plastic mulching and straw mulching performed better for maize at relatively low temperatures (Shan and Yan, 2013; Qin et al., 2015). Similarly, our study

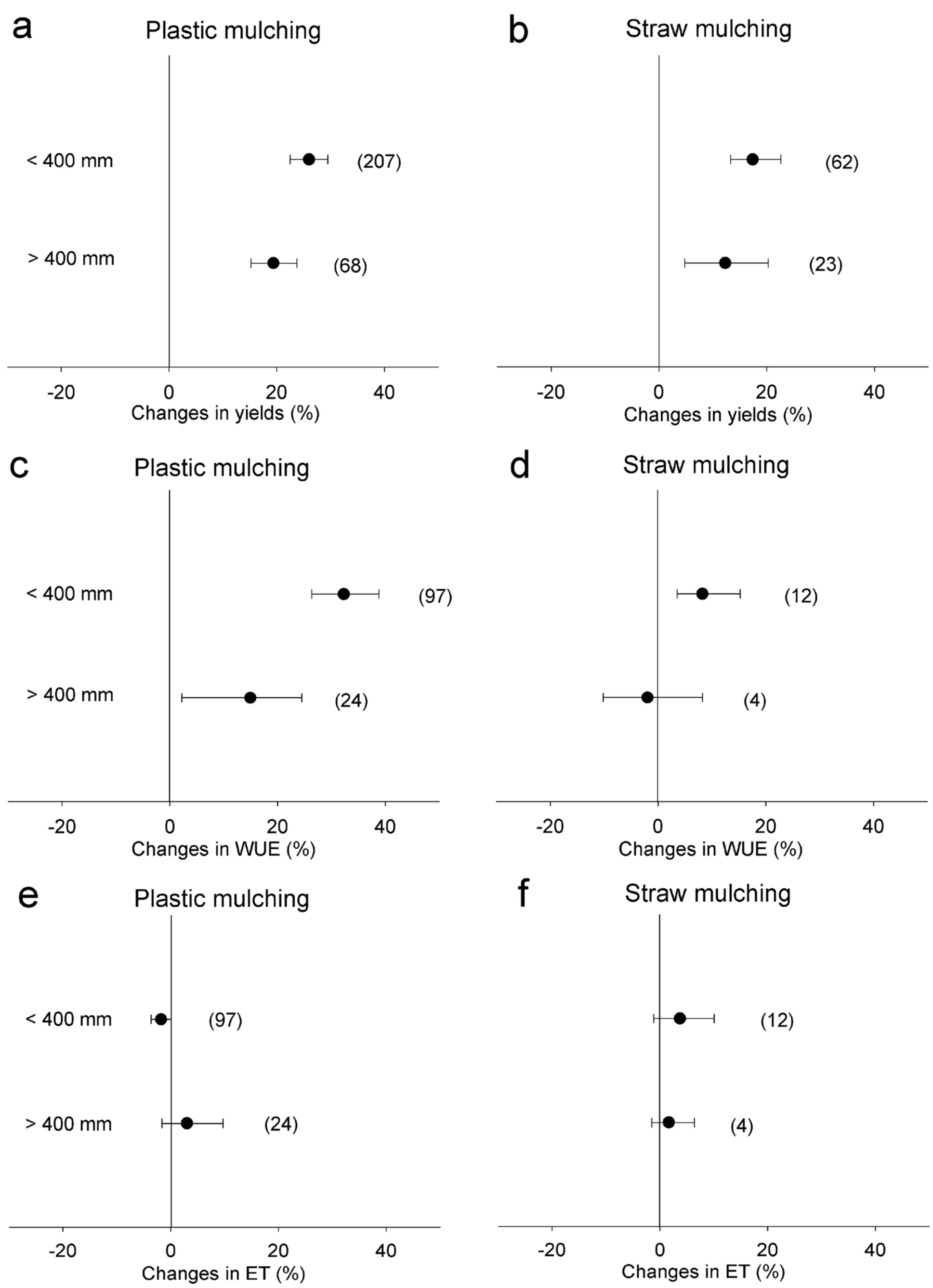

Fig. 7. Effects of two common mulching practices on yields (a and b), WUE (c and d) and ET (e and f) of potato at different water input levels during the potato growing season (plastic mulching, left side; straw mulching, right side). Error bars represent 95% confidence intervals. The numbers of comparisons are indicated in parentheses.

indicated that the effects of mulching on the yield and WUE of potato were greater when mean air temperature was moderate (15–20 °C) during the growing season (Fig. 6). The appropriate temperature not only leads to early emergence but also increases emergence rate (Zhao et al., 2012), whereas low soil temperature can extend the time of crop emergence (Gan et al., 2013). Thus, appropriate temperature is crucial to increase potato yield under mulching conditions.

4.4. Effects of plastic mulching with different colors of plastic film

In this study, transparent film performed slightly better in northern regions of China, while black film performed better in southern regions of China particularly in South China. In addition, increase in potato yield under black film was significantly higher than that under transparent film when air temperature exceeded 20 °C. Transparent film has good light transmittance, thus, most of the solar radiation can pass through film, be directly absorbed by the soil. Transparent film is more effective in increasing the topsoil temperature in the early growing season of potato when temperatures are low in spring in northern regions of China (Jia et al., 2017). The improvement of topsoil temperature create favorable conditions for seed germination and seedling growth (Zhao et al., 2014). Increased emergence rates and strong seedling establishment result in vigorous growth and high potato yields. In regions with mean air temperature above 20 °C, the maximum air temperature of late growth stage usually exceed 30 °C, topsoil temperature under transparent film is too high for potato tuberization. Black film mulch can reduce the diurnal amplitude of soil temperature, and always reduce the radiant heat gain by the soil (Liakatas et al., 1986). Thus, black film performed relatively better in regions with growing season air temperature above 20 °C.

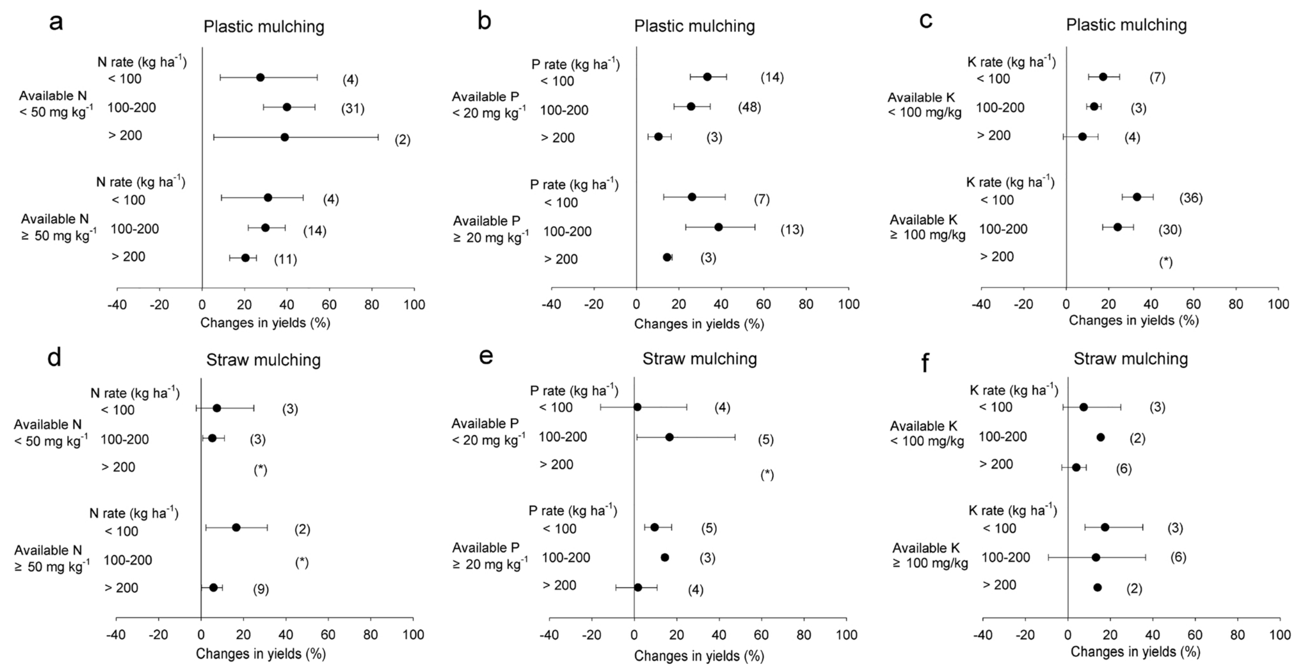

Fig. 8. Effects of two common mulching practices on yields of potato at different soil basic fertility and fertilizer application rates (plastic mulching, upper graphs; straw mulching, lower graphs). Error bars represent 95% confidence intervals. The numbers of comparisons are indicated in parentheses. Asterisks (*) represent insufficient comparison (zero or one) in this subgroup.

Table 2
Probability values (*P*) for Yield, WUE and ET, respectively, based upon a GLM analysis of experimental data from studies in literature.

Factors	Yield	WUE	ET
Mulching method	0.002**	0.000**	0.265
Region	0.035*	0.278	0.007**
Temperature	0.015*	0.247	0.115
Water	0.000**	0.016*	0.139
N	0.011*	0.119	0.563
P	0.093	0.012*	0.061
K	0.007**	0.678	0.691
Temperature × Water	0.000**	0.031*	0.207
Water × N	0.007**	0.375	0.462
Water × P	0.004**	0.047*	0.027*
Water × K	0.620	0.434	0.064
N × P	0.598	0.006**	0.238
N × K	0.003**	0.062	0.438
P × K	0.076	0.008**	0.076
N × P × K	0.227	0.012*	0.133
Water × N × P × K	0.003**	0.020*	0.004**

* ($P \leq 0.01$), * ($0.01 < P \leq 0.05$), ns ($P > 0.05$).

4.5. Effects of mulching on yield and WUE of potato at different water input levels

The effects of mulching were affected by water input levels during the potato growing season. In this study, the effects of both plastic mulching and straw mulching on yield and WUE of potato tended to decrease when water input level increased (Fig. 7). Qin et al. (2015) summarized published data regarding water input levels and found that the enhancement of plastic mulching on maize yield was 60% with low water input (< 370 mm) and 40% with high water input (> 370 mm), and the mean increment of plastic mulching on maize WUE was 70% with low water input and 40% with high water input; however, the effects of straw mulching on yield were much lower than those of plastic mulching. Zhou et al. (2009) found that plastic mulching exhibited great potential to increase potato production when rainfall was limited. Similarly, maize yield was significantly increased by 15–26% under plastic mulching in dry years, whereas no significant increase in yield was observed in rainy years in northeast China (Xu et al., 2015). As mulching practice can retain and utilize water more effectively, increases in yield and WUE are greater with low water input level (Liu and Siddique, 2015).

4.6. Effects of mulching on yield and WUE of potato at different soil fertility and fertilizer application rates

Responses to mulching in potato yield and WUE also varied with different soil basic fertility and inorganic fertilizer application rates. In this study, mulching effects on the yield of potato were higher at relatively low or moderate fertilizer rates (Fig. 8). Qin et al. (2015) reported that the mean effects of straw mulching on wheat yield and WUE were higher at low N input than those at high N input. Compared with no-mulching, the average rice grain yields under plastic mulching increased by 14% with lower N levels (0 and 75 kg N ha^{-1}) and 2% with higher levels (150 and 225 kg N ha^{-1}); while those under straw mulching decreased by 16% and 4.7%, respectively (Fan et al., 2005). Higher soil temperatures caused by plastic mulching are favourable for N mineralization and enhanced plant N uptake (Wilson and Jefferies, 1996). Singh et al. (2015) showed that residue mulching benefits were also greater at low N rates. These benefits can be attributed to better utilization of applied N due to a more favourable hydrothermal regime. In addition, mulching can improve P and K availability to plants (Kaya et al., 2005; Henry and Chinedu, 2014). Tang et al. (2013) found that straw mulching improved soil available N, P and K contents at major growth stages of wheat on the Chengdu Plain of China.

4.7. Interactions of multiple variables in yield and WUE of potato

In our study, effects of mulching practices on potato yield and WUE had significant interactions between multiple variables (Table 2). Significant interactions between temperature and water input in potato yield and WUE indicated that mulching effects strongly depended on environmental conditions. In addition, there were significant interactions between water and N input, water and P input, water, N, P and K input in potato yield during growing season. Effects of water and N on crop yield are not independent of each other, and they usually interact.

Water shortage can limit N uptake as a result of the decreased water uptake and transpiration rate. N deficit decreases root hydraulic conductivity, thereby affecting leaf water status and leaf growth (Sadras et al., 2016). In addition, binary combination of water and P also affect crop productivity (Gutierrez-Boem and Thomas, 1998). Mulching retains soil moisture and improves soil water condition, so the effect of water input correspondingly decreases and the effects of fertilizer application rate stand out. Similarly, Ram et al. (2006) showed that interaction effect of moisture regimes and nitrogen rates improved yield of menthol mint under sugarcane trash mulch. Thus, for regions with irrigation conditions, improving soil fertility is an effective way to obtain sustainable agriculture. For rainfed agriculture, based on mulching and rainfall harvesting measures, appropriate increment of fertilizer rate is also important to enhance utilization efficiency of limited water resources. K application is often necessary to obtain optimum potato yield because of a relatively high K requirement compared with other crops. Consistent with previous study (Zhang et al., 2010), our result also showed that interaction between N and K in potato yield was significant under mulching condition. Fertilizer can be effectively utilized by crops under mulching, lower or higher application rate of a single fertilizer is not conducive to the formation of crop yield. Therefore, the rational combined application rate of NPK has a great influence on the improvement of potato yield.

5. Conclusions

Our analyses based on reported studies conducted in China showed that mulching significantly increased the yield and WUE of potato compared with no-mulching practices. The mean effects of plastic mulching on the yield and WUE of potato were generally greater than those of straw mulching. Plastic mulching performed better in Northeast China and Northwest China, while straw mulching performed better in Southwest China and South China. The effects of mulching varied with different growing season air temperatures, water inputs, soil basic fertility and fertilizer application rates. In addition, black film performed better than transparent film in regions with mean air temperature above 20 °C during potato growing season. Considering the environmental side-effect of plastic mulching, and fact that straw materials are not always available in some regions, other mulching methods such as biodegradable film mulching may be used (Bourtoom and Chinnan, 2008). Using a combination of integrated farm managements such as non-till, fertilization, intercropping and crop rotation, crop yield and WUE under mulching practices is expected further improvement in the future. Thus, the adoption of promising mulching practices for potato production should be site specific and consider field management practices in China.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.fcr.2018.02.017.

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