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Reducing plastic film mulching and optimizing agronomic management can ensure food security and reduce carbon emissions in irrigated maize areas

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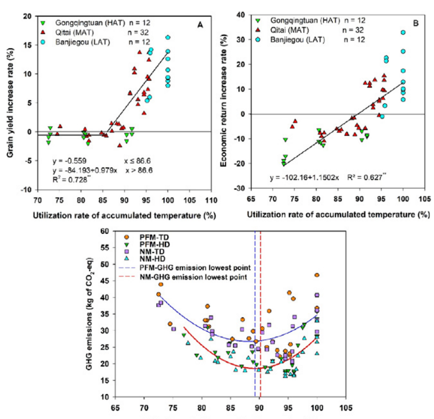
HIGHLIGHTS

- Ensuring food security while reducing environmental impacts is a challenge in China.
- Higher-density planting, no plastic mulch, integrated irrigation and fertilization increased yields and profits.
- Filmless planting reduced residual plastic pollution in irrigated maize farmlands.
- Filmless and higher-density planting reduced greenhouse gas emissions by 33.1 %.

GRAPHICAL ABSTRACT



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ABSTRACT

Increasing crop yields to ensure food security while also reducing agriculture's environmental impacts to ensure green sustainable development are great challenges for global agriculture. Plastic film, widely used to improve crop yield, also creates plastic film residue pollution and greenhouse gas emissions that restricts the development of sustainable agriculture. So, one of those challenges is to reduce plastic film use while also ensuring food security, and thus promote green and sustainable development. A field experiment was conducted during 2017–2020 at 3 farmland areas, each with different altitudes and climate conditions, in northern Xinjiang, China. We investigated the effects on maize yield, economic returns, and greenhouse gas (GHG) emissions of plastic film mulching (PFM) versus no mulching (NM) methods in drip-irrigated maize production. We also chose maize hybrids with 3 different maturation times and used 2 planting densities to further investigate how those differences more specifically affect maize yield, economic returns, and greenhouse gas (GHG) emissions under each mulching method. We found that by using maize varieties with a utilization rate of accumulated temperature (URAT) <86.6 % with NM, and increasing the planting density by 3 plants m^{-2}, yields and economic returns improved and GHG emissions reduced by 33.1 %, compared to those of PFM maize. The maize varieties with URATs between 88.2 % to 89.2 %, had the lowest GHG emissions. We discovered that by matching the required accumulated temperatures of various maize varieties to environmental accumulated temperatures, along with filmless and higher density planting, and modern irrigation and fertilization practices, yields increased and residual plastic film pollution and carbon emissions reduced. Therefore, these advances in agronomic management are important steps toward reducing pollution and achieving carbon peak and carbon neutrality goals.

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1. Introduction

Plastic film mulching (PFM) is an efficient agricultural practice that increases crop yield and it is used extensively in agricultural production worldwide (Adams, 1967; Tiwari et al., 2003; Zhang et al., 2011; Sun et al., 2020). However, since the residue of that film is an environmental pollutant, the extensive use of agricultural plastic film has been creating a serious environmental problem (Daryanto et al., 2017). A debate is currently underway that is arguing the benefits of increased crop production using plastic film versus eco-responsible, sustainable agricultural development.

PFM is widely used in arid, semi-arid, and cold areas, especially where irrigation is unavailable and temperatures are low during sowing (Zhang et al., 2005; Gao et al., 2019). Its use increases both temperature and moisture in the upper 5 cm of soil during early crop growth stages (Li et al., 1999; Zhou et al., 2009), and it can improve soil temperature, facilitate early sowing, prolong growth time, increase crop yield, promote maturity, and facilitate earlier harvests (Mahrer et al., 1984; Wang et al., 2005; Wu et al., 2017). Previous studies have shown that it increases crop yield by 20 %–50 % (Liu et al., 2014a; Liu et al., 2014b). In addition, it can effectively reduce soil water evaporation and improve water use efficiency (Sun et al., 2020; Bu et al., 2013; Yaghi et al., 2013; Qin et al., 2016; Li et al., 2018). Furthermore, it enhances crop production by suppressing weeds and improving water and nutrient use (Yan et al., 2015; Steinmetz et al., 2016). Therefore, it has contributed greatly to crop yield increases and food security. However, plastic film residues in China are nearly 2.0×10^6 t, and the recovery rate is <2/3 that amount (Wang et al., 2016). Cao et al. (2023) reported that just 1 kg ha^{-1} increase in residual plastic film content decreased maize yield by 27.67 kg ha^{-1}. Large amounts of plastic mulch film remaining in the soil destroys soil structure, reduces the quality of cultivated land and crop yields, harms crop growth, and impedes agricultural operations (Yan et al., 2006; Xie et al., 2007; Zhang et al., 2008; Yan et al., 2014). Long-term agricultural PFM has also caused serious environmental pollution because the plastic film residues increase in the soil every year, thus seriously threatening agricultural production and the environment. Therefore, the residual pollution of plastic film is a big roadblock to the sustainable development of agriculture and food security.

Cuello et al. (2015) reported that PFM significantly decreased soil organic matter content and largely increased the CH_4 and N_2O gas emissions. Nan et al. (2016) suggested that PFM significantly increased the potential of CO_2 and N_2O emissions from the soil. In addition, He et al. (2018) suggested that PFM increased GHG emissions countrywide by an average of 32 % for wheat and 10 % for maize. Also, Lee et al. (2019) showed that under the same fertilization, PFM increased seasonal N_2O and CH_4 emissions by 5.0 %–10.0 % and 130.0–260.0 %, respectively, over those emissions with no mulching (NM). A meta-analysis found that compared with no mulching, PFM significantly increased N_2O emission by 18.6 % and CO_2 emission also increased significantly, while CH_4 uptake was significantly inhibited (Wang et al., 2021a). These studies highlight how PFM systems negatively impact the environment. However, some studies that independently examined the effect of PFM on GHG emissions found opposite results (Chen et al., 2017; Wei et al., 2022; Zhang et al., 2022). These contradictions could be due to the crop, climate conditions, mulching methods, soil properties, tillage patterns, fertilization methods, and different field management practices (Snyder et al., 2009; Wei et al., 2022). However, few studies have assessed GHG emissions from PFM combined with agronomic variables and under drip irrigation.

Searching to find ways to effectively reduce residual plastic film pollution, some studies have shown that improved plastic film quality and mechanized residual film recovery, economical mulch application to reduce mulch use, and replacement of plastic with biodegradable film can effectively reduce mulch residue (Gao et al., 2019; He et al., 2009; Yan et al., 2014; Zhao et al., 2017; Yin et al., 2019). To some extent, some of those measures have reduced plastic film residue in the soil. However, hampered by unavoidable factors in agricultural production, positive effects of residual film recovery, have not proved satisfactory, and a lack of technical agricultural support to reduce PFM often leads to crop reduction. In current agricultural production, the plastic film mechanical recovery rate is generally low, and that recovered plastic is still a problem. The usual method of treating recovered residual film, incineration, causes serious secondary environmental pollution (e.g., organic pollutants and GHG emissions) (Jayasekara et al., 2005). Additionally, plastic film production itself consumes significant energy resources and produces greenhouse gas (GHG) emissions (Rahim and Abdul Raman, 2017). That leaves biodegradable plastic film as a good choice to replace plastic film, but it has not been applied on a large-scale because problems, such as uncontrollable degradation time and comparatively high cost, hinder its adoption (Yan et al., 2016). Therefore, plastic film use should be based on managing the tradeoffs among yield, economic returns and ecological benefits.

PFM has been widely used in the production of major crops, (i.e. maize, wheat, rice and potato). However, the most widely grown crop in the world, maize (*Zea mays* L.), is also the crop that uses the largest area of PFM in China (Sun et al., 2020). Many studies have shown that PFM has significantly increased maize yields in semiarid regions (Zhang et al., 2011; Zhou et al., 2009). However, Zhang et al. (2008) showed that PFM decreased maize yield in dryland. Furthermore, Ma et al. (2007) reported that production and profit increases due to PFM are not realized in areas with >10 °C average daily temperatures and accumulated temperatures (*Ta*) higher than 3000 °C in northeast China. In the West Liaohe River Basin, the grain yield and economic return of plastic film mulching maize under drip irrigation did not increase compared with non-mulching (Mei et al., 2018). Moreover, Qi et al. (2022) reported that plastic film mulching does not increase the seed cotton yield due to the accelerated late-season leaf senescence of short-season cotton compared with non-mulching. Therefore, whether PFM increases crop yields is conditional on the circumstances and the crop. Furthermore, the advancement of crop breeding and cultivation management technology has expanded the zoning of planted crops and increased yields, and it provides favorable conditions for reducing or even canceling the use of plastic film (Yu, 2019). So, can the new cultivation and management technology replace the yield increasing effect of plastic film? Under what conditions can we use new technology to replace plastic film. That is a problem that needs to be solved urgently. Here, we used maize grown in irrigated areas of China as our study subject. The objectives of this study were to (1) clarify the effects of no-mulch planting on maize yield and the economies in arid, irrigated areas and (2) determine how to effectively reduce PFM through agronomic technology, while increasing maize yield and reducing GHG emissions. Our results provide new insights that can help reduce plastic film pollution and increase agricultural production and efficiency in arid regions, with the ultimate goals of promoting green production and sustainable agricultural development.

2. Materials and methods

2.1. Experimental region and site

We set our experiment in 3 irrigated areas with different altitudes and climate conditions in northern Xinjiang, China (Gongqingtuan, Qitai, Banjiegou). Meteorological data for the 2017 to 2020 maize growing seasons were obtained from meteorological stations (WatchDog 2900ET, Spectrum Technologies, Aurora, IL) located at the experimental sites (Table 1). These areas have a temperate arid climate characterized by abundant sunshine during the maize growing season and a large diurnal temperature range. The soils were sandy loam.

2.2. Experimental design

Field experiments were conducted from 2017 to 2020. For a pilot study, in 2017 we explored whether filmless planting in an irrigated maize area would affect yield. Those experiments were conducted in a middle *Ta* area (MAT) in northern Xinjiang (Qitai). Throughout the entire study, *Ta* was measured at air temperature ≥10 °C. We employed either PFM or NM methods with 4 commonly grown maize hybrids: early maturing (EM) KWS2030 (*Ta* ≤ 2300 °C), medium maturing (MM) KWS9384

(2300 °C ≤ Ta ≤ 2700 °C), and late maturing (LM) Xianyu335 (XY335) and Xinyu77 (XY77) (Ta ≥ 3000 °C). We used 2 planting densities: the locally used, traditional density (TD, 9.0 plants m^{-2}) and a newer high-density (HD, 12.0 plants m^{-2}) (Xu et al., 2017; Zhang et al., 2020; Liu et al., 2020). To clarify both the Ta conditions for filmless planting and the measures needed to further increase maize yield and economic returns, we conducted our 2018 and 2019 field experiments in 3 altitudinally different irrigated areas: Gongqingtuan, Qitai, and Banjiegou. Gongqingtuan was the high accumulated temperature area (HAT); Qitai, the middle accumulated temperature area (MAT); and Banjiegou, the low accumulated temperature area (LAT). We employed either PFM or NM methods and planted KWS2030 (EM), KWS9384 (MM), and KWS3564 (LM, Ta ≥ 3000 °C) at both TD and HD at all 3 sites. XY77 (LM) was also planted at both densities at Qitai. Then, in 2020, we verified the filmless cultivation technology effect in the MAT area (Qitai) by replicating the 2017 treatments. For each experimental site, we set up a split block design in which the main factor, side factor, and accessory factor were cultivar, planting density, and mulching methods, respectively. Each experimental plot was 88 m^2 (10 m × 8.8 m) and each plot was replicated 3 times.

2.3. Agronomic practices

Maize sowing and harvesting dates were based on local, traditional tillage dates. Plants were seeded in alternating wide-narrow row patterns (alternating row spaces of 70 and 40 cm, respectively) in all 4 years (Zhang et al., 2017). In both the PFM and NM treatments, all of the following procedures were identical and an integrated water – fertilizer technology was used for irrigation and fertilization. One day after sowing, 20–30 mm of water (amount based on soil moisture) was applied to assure uniform, rapid germination. To harden the seedlings, there was no irrigation for the first 55–60 days after sowing. Then throughout the growing season, the irrigation interval was 9–10-d, for a total of nine applications. The single irrigation amount for Qitai and Banjiaogou was 56.67 mm, and that for the Gongqingtuan is 76.67 mm. The optimal amount of irrigation water (540 mm at Banjiegou and Qitai; 720 mm at Gongqingtuan) for one season in these regions had been determined previously (Zhang et al., 2017; Wang et al., 2021b). In all years, 60 kg ha^{-1} of N, 120 kg ha^{-1} of P, and 45 kg ha^{-1} of K were applied at sowing, and an additional 240 kg ha^{-1} of N was applied over the entire irrigated, growth period. The crops never suffered water or fertilizer stresses. All weeds, diseases, and pests in the experimental plots were controlled equally.

2.4. Sampling and measurements

2.4.1. Accumulated temperature measurements

The active accumulated temperature (Ta, °C) (Yan et al., 2011; Hou et al., 2014) and accumulated temperature utilization rate (URAT) (Bai et al., 2011) were calculated as follows:

$$Ta = \Sigma_{i=1}^{n} Ti, \tag{1}$$

where Ti is the daily average temperature (°C) and when a day's temperature < 10 °C, Ti = 0; n is the number of days in the calculation period.

$$\text{URAT}\ (\%) = \frac{\text{Active } Ta \text{ of maize}}{\text{Annual total active } Ta} \times 100, \tag{2}$$

where URAT is the ratio of active Ta is at ≥10 °C in a maize growing period to the annual total active Ta is at ≥10 °C.

2.4.2. Grain yield

When the maize crops reached physiological maturity, we counted the total number of plants and ears and determined grain moisture content using a portable moisture meter (PM8188, Kett Electric Lab., Tokyo, Japan) and then the grain yield (at 14 % moisture) for each plot.

2.4.3. Economic analysis

Economic return was assessed using the following equations:

$$\text{Economic return}(\text{US\$ ha}^{-1}) = \text{grain yield return}(\text{US\$ ha}^{-1}) - \text{total cost}(\text{US\$ ha}^{-1}). \tag{3}$$

$$\text{Grain yield return}\ (\text{US\$ ha}^{-1}) = \text{grain yield}\ (\text{kg ha}^{-1}) \times \text{maize price}\ (\text{US\$ kg}^{-1}), \tag{4}$$

where mean maize price was 0.228 US\$ kg^{-1} (mean, 2017–2019), and maize price was 0.285 US\$ kg^{-1} in 2020.

The costs of maize production management practices in NM and PFM systems in the 3 study areas are shown in Supplementary Table 1. We calculated the actual economic returns and the costs from data collected from a survey of local farms during 4 study years.

2.4.4. Estimation of agricultural carbon emissions

We used the life cycle assessment method to estimate GHG emissions (expressed as CO_2-eq) in our PFM system (He et al., 2018).

To begin, we calculated the amount of plastic film used, 60 kg ha^{-1}, given 0.01 mm film

$$\text{thickness} \times 7000\ \text{m}^2\ \text{ha}^{-1}\ \text{coverage area} \times 0.857\ \text{g cm}^{-3}\ \text{film density} \tag{5}$$

and calculated GHG emissions as follows (He et al., 2018):

$$\text{GHG emissions} = \Sigma_{i=1}^{n} AI_i \times EF_i, \tag{6}$$

where, AI_i is the agricultural input during crop production, including seed, fertilizer, pesticides, fuel, plastic film, and manpower (Supplementary Table 2); EF_i is a specific GHG emissions coefficient of an individual agricultural input in the life cycle (Supplementary Table 3); and n is the number of agriculture inputs. The specific GHG emissions of the agricultural inputs are shown in Supplementary Table 4.

Table 1
Geographic and meteorological parameters of the 3 experimental sites in northern Xinjiang, China.

Year	Site	Location	Altitude (m)	Daily mean temperature (°C)	Daily maximum temperature (°C)	Daily minimum temperature (°C)	≥10 °C Accumulated Temperature (°C)	Frost free duration (d)	Precipitation (mm)
2017	Qitai	43°50′ N 89°42′ E	1020	18.6	25.6	12.7	3240.2	173	178.1
2018	Gongqingtuan	44°31′ N 87°42′ E	393	21.8	29.5	13.7	3809.6	195	71.9
	Qitai	43°50′ N 89°42′ E	1020	17.6	24.6	10.9	3160.3	177	212.9
	Banjiegou	43°58′ N 89°81′ E	1335	16.8	23.2	10.7	2585.7	158	148.1
2019	Gongqingtuan	44°31′ N 87°42′ E	393	22.4	30.6	14.8	3798.5	199	148.7
	Qitai	43°50′ N 89°42′ E	1020	18.1	25.3	11.0	3185.5	178	138.5
	Banjiegou	43°58′ N 89°81′ E	1335	16.7	23.3	11.0	2521.6	177	245.1
2020	Qitai	43°50′ N 89°42′ E	1020	18.9	25.5	12.3	3196.1	181	190.2

Note: The meteorological data are means obtained during the 2017–2020 maize growing seasons.

2.5. Statistical analyses

We performed statistical analyses using SPSS ver. 21.0 (SPSS Inc., Chicago, IL, USA) and graphs were plotted using either Sigmaplot 12.5 (Systat Software, Inc., San Jose, CA, USA) or Excel 2019 (Microsoft, Inc., Redmond, WA, USA). The relationships of maize URATs and grain yield rates was fitted by nonlinear regression. Analysis of variance was used to test for differences in yield and economic returns among PFM treatments. Means were compared using Fisher's least significant difference tests with $P < 0.05$ ($LSD_{0.05}$).

3. Results

3.1. Grain yield and economic responses to PFM and planting density

Both the maize grain yield and economic returns in the different *Ta* areas were affected by PFM (Figs. 1 and 2). For all the maize varieties grown in the HAT area (Gongqingtuan), yields of the PFM and NM treatments within each planting density were not significantly different (Fig. 1A), but the NM treatments' economic returns were significantly higher than those of the PFM treatments (Fig. 2A). Compared with plastic film mulching treatments, the PFM-TD and NM-HD treatments had of 10.2 % and 33.3 % higher yields and economic returns, respectively. Both the yields and economic returns of LM maize were higher than those of MM maize, which was higher than those of EM maize (Figs. 1A and 2A). Overall, yields were not affected by the higher temperatures in the HAT area, regardless of whether or not plastic film was used, but film use reduced economic returns, and increased planting density increased both maize grain yield and economic returns.

In the MAT area (Qitai), compared to NM, PFM did not significantly affect EM and MM maize yields (Fig. 1B) and the economic returns of both those maize types were either reduced (EM) or no different (MM) (Fig. 2B). However, the yields of LM maize increased significantly with PFM compared to those of the NM treatments, but the economic returns did not increase (Figs. 1B and 2B). In addition, the average grain yields and economic returns of PFM-HD were significantly higher than those of NM-TD: 6.2 % and 26.0 % (yields) and 14.7 % and 32.9 % (returns), respectively. The MAT area results also showed that the growth needs of LM maize were not sufficiently met by the local *Ta* alone, and PFM was needed to increase those temperatures to improve yield. However, the yields of PF mulched EM and MM varieties were not different from those of EM and MM varieties grown without plastic mulch, but there were no plastic film costs with NM. For EM and MM varieties, the increased planting density along with filmless planting can significantly increase maize yield. For LM varieties, the yield loss under filmless planting can be compensated for by increasing the planting density to increase the grain yield. Therefore, it is feasible to productively and economically use filmless planting in the MAT area.

In the LAT area (Banjiegou), compared with NM, PFM significantly increased the yields of all 3 maize maturity types (Fig. 1C), but it did not significantly affect economic returns (Fig. 2C). Furthermore, the average grain yield of PFM-HD was significantly higher than those of PFM-TD and NM-TD (18.1 % and 30.3 %, respectively), and the economic returns of PFM-HD was also higher than those of PFM-TD and NM-TD (46.3 % and 65.0 %, respectively). So, in this area of lowest *Ta*, the economic value of plastic film's warming effect is most likely limited. Also, both yield and economic returns of MM maize were higher than those of LM maize, suggesting that even if covered with plastic film, LM maize, with its long growth period, did not have its *Ta* demands met and could not reach normal maturity. Therefore, yield increases with PFM in the LAT areas.

3.2. Relationships of URAT with grain yield and economic return using PFM

Depending on the *Ta* environment, the yields of maize varieties with different maturity times respond differently with PFM, and there exists a particular relationship between the increasing yield rate using PFM and the URAT of certain maize varieties (Fig. 3A). When the maize URAT is lower than 86.6 %, maize matures normally and PFM does not increase yield. When the maize URAT is higher than 86.6 %, URAT and grain yield increases are positively related, indicating that, depending on the ecological area, when a maize variety's URAT is 86.6 % or more, PFM effectively increases production. Similarly, PFM affects maize yields as well as economic returns. When a maize variety's URAT reached 88.8 % or more, the economic returns with PFM also increased and surpassed those of NM (Fig. 3B). So, PFM of varieties with URATs below 88.8 % will likely not deliver better economic returns than those of NM.

3.3. NM effect on GHG emissions

As the URAT increased, greenhouse gas (GHG) emissions first decreased and then increased (Fig. 4). Under PFM, the lowest GHGs emitted while

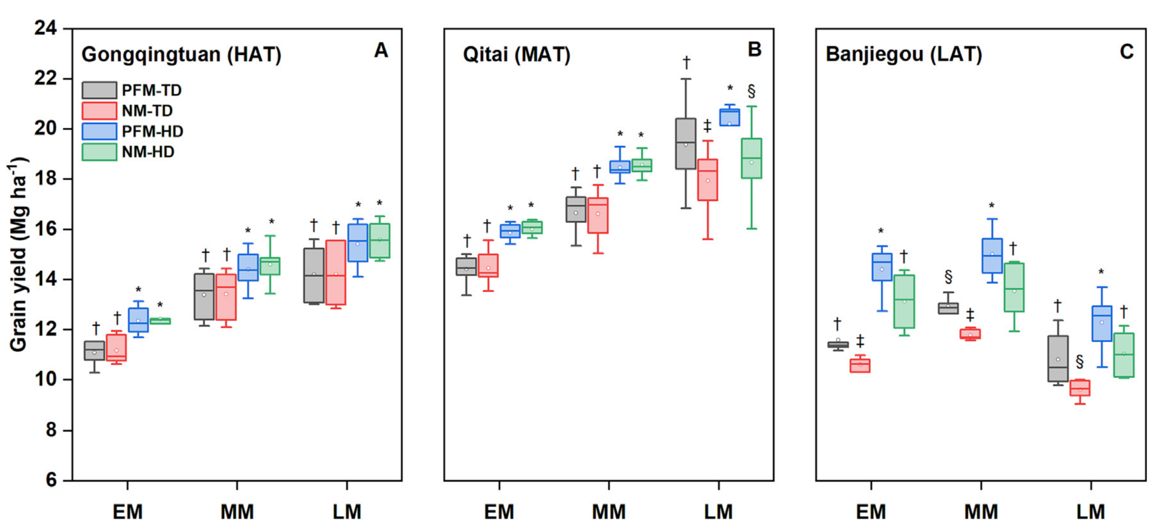

Fig. 1. Comparisons of grain yields of maize varieties with different maturities grown with either plastic film mulching (PFM) or no mulching (NM) in different accumulated temperature areas: HAT, high accumulated temperature area (A); MAT, middle accumulated temperature area (B); and LAT, low accumulated temperature area (C). Along with PFM and NM, 2 planting densities were examined: traditional density (TD, 9.0 plants m^{-2}) and high-density (HD, 12.0 plants m^{-2}). The maize varieties were either EM, early maturing; MM, medium maturing; or LM, late maturing. In the graphs, means topped by the same footnote symbols for different yield levels were not significantly different at the level of $P < 0.05$. The solid line and circles within the boxes indicate medians and means, respectively; upper and lower box edges represent the 25th and 75th percentiles, respectively; and the bottom and top bars represent the 5th and 95th percentiles, respectively.

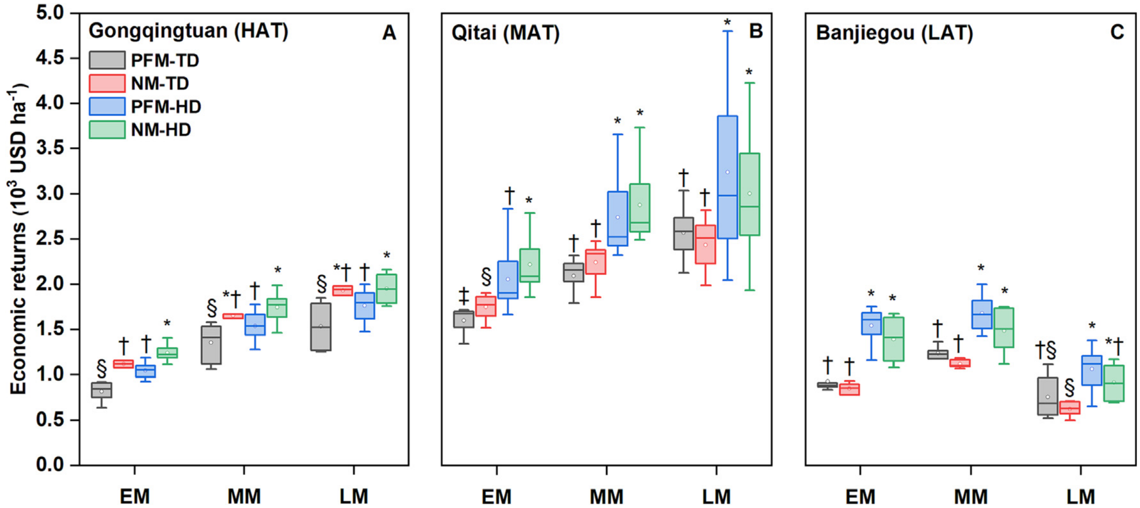

Fig. 2. Comparisons of the economic returns of maize varieties with different maturities grown with either plastic film mulching (PFM) or no mulching (NM) in different accumulated temperature areas: HAT, high accumulated temperature area (A); MAT, middle accumulated temperature area (B); LAT, low accumulated temperature area (C). Along with PFM and NM, 2 planting densities were examined: TD, traditional density and HD, high-density. The maize varieties were either EM, early maturing; MM, medium maturing; or LM, late maturing. In the graphs, means topped by the same footnote symbols for different economic return levels were not significantly different at the level of $P < 0.05$. The solid lines and circles within the boxes indicate medians and means, respectively; upper and lower box edges represent the 25th and 75th percentiles of all the data, respectively; and the bottom and top bars represent the 5th and 95th percentiles, respectively.

producing 100 kg of grain (26.9 kg of CO_2-eq) occurred when the URAT was 88.2 %, but under NM conditions, the lowest emissions (18.7 kg of CO_2-eq) occurred when the URAT was 89.2 %. So, maize varieties with URATs between 88.2 % to 89.2 % produced the lowest GHG emissions. Therefore, reasonable use of Ta resources can reduce GHG emissions. Additionally, NM significantly reduced GHG emissions, by 26.0 %, compared to the emissions produced by conventional PFM. Furthermore, NM-HD can reduce GHG emissions by 33.1 %, compared to PFM with TD. For each 100 kg of grain produced, GHG emissions from NM decreased an average of 7.9 kg of CO_2-eq (reduction range: 16.2–35.7 kg of CO_2-eq) compared to that from PFM.

4. Discussion

PFM in maize production is mainly used to increase temperature and save water and thus increase production. In this study, at Gongqingtuan (HAT), where *Ta* resources are relatively abundant, PFM did not significantly increase maize yields, and it actually reduced economic returns, compared to those of NM (Figs. 1A, 2A). So, when the environment's *Ta* alone accommodates crop growth requirements, PFM provides no positive effects, results that mirror those of previous studies (Zhang et al., 2008; Ma et al., 2007; Yu, 2019). In the MAT region (Qitai), compared to the NM results, PFM significantly increased both the yield and economic returns of late maturing maize, results that agree with those of previous studies that showed that PFM increases both temperature and production (Li et al., 1999; Wang et al., 2005). However, PFM did not significantly improve the yields of early- and middle-maturing maize varieties grown at that site, and it also reduced the economic returns of those varieties, compared to NM results (Figs. 1B, 2B). However, the low Ta in our high-altitude area (Banjiegou) was insufficient for good maize growth, and because PFM provides an obvious warming effect, maize grain yields and economic returns

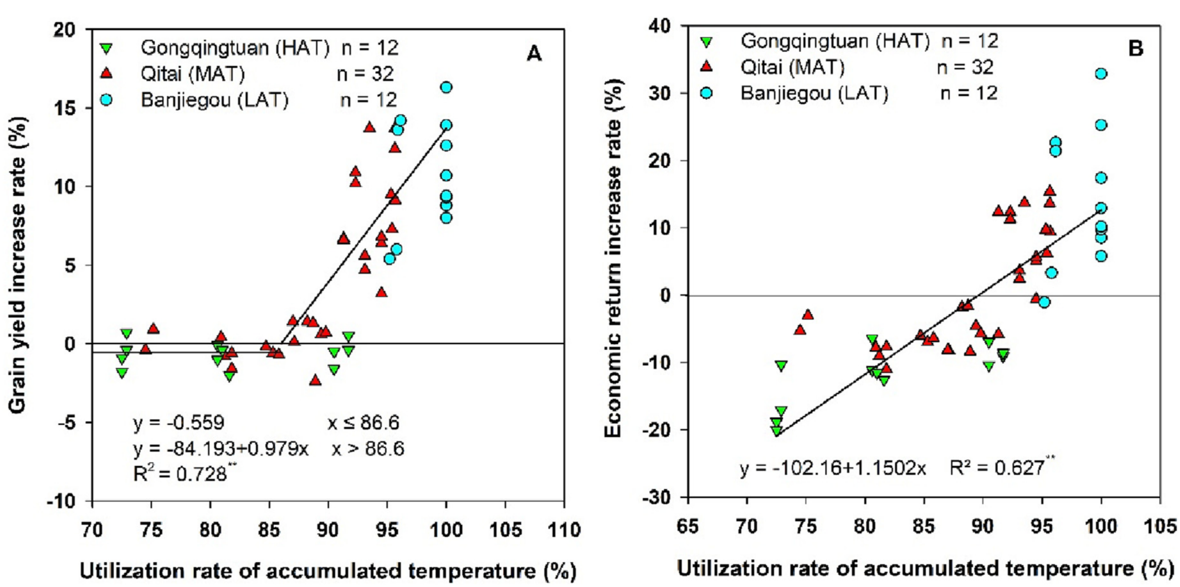

Fig. 3. Relationships of maize accumulated temperature utilization rates with grain yield rates (A) and with economic returns (B) using plastic film mulch. The 3 experimental areas had either a high accumulated temperature (HAT), middle accumulated temperature (MAT), or low accumulated temperature (LAT).$**P < 0.01$.

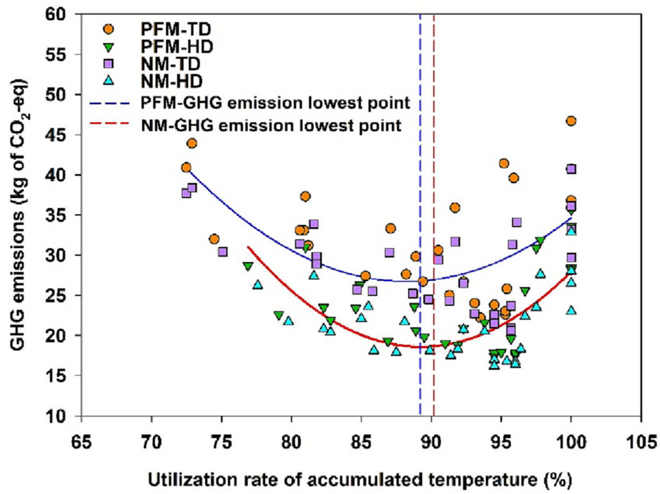

Fig. 4. Greenhouse gas (GHG) emissions from the production of 100 kg of grain while using either plastic film mulching (PFM) or no mulching (NM) and either traditional (TD, 9.0 plants m^{-2}) or high planting density (HD, 12.0 plants m^{-2}).

for that area were significantly better with PFM than with NM (Figs. 1C, 2C). Therefore, our results showed that the main reason for maize yield differences between PFM and NM was how *Ta* resources were utilized in different *Ta* regions (Fig. 3A). For maize varieties in all maturity classes (early, middle, and late maturing), when the *Ta* demand was 86.6 % or higher than the local *Ta*, PFM increased temperature and thus increased production (Fig. 3A). However, when a maize variety's URAT was <86.6 % that of the local *Ta*, that *Ta* alone can meet that variety's normal *Ta* demand, and PFM will not increase production. Additionally, using PFM with maize varieties that have URATs lower than 88.8 % reduces economic returns because of plastic film and residual film recovery costs (Fig. 3B). During times of a serious food shortages, maize yields can be increased by using PFM in areas with insufficient *Ta*. Therefore, the maturity times of crop varieties may be matched with local *Tas* (*Ta* >10 °C per growing season) to effectively use environmental *Ta* resources to improve crop yield without PFM. However, PFM also preserves soil moisture and thus improves water use efficiency (Yaghi et al., 2013; Qin et al., 2016; Li et al., 2018). For maize, PFM's water conservation effect occurs mainly in the early stage of crop ridge closure. Due to maize seedlings' relatively small water needs, soil water evaporation is the main source of water consumption (Zhang et al., 2019). Once the growing crop canopy closes the ridges, soil water evaporation decreases to a minimum (Men et al., 2002). In our technical agricultural system, the extensive use of drip irrigation technology effectively reduces soil water evaporation and saves irrigation water (Ibragimov et al., 2007). Most likely, the effects of PFM on the water use efficiencies of maize varieties with different maturities will vary, and we plan to investigate those effects and variations in future studies.

Maize farmers in irrigated areas are accustomed to using PFM to obtain high yields and ample incomes, regardless of the *Ta* area. However, with plastic film pollution becoming increasingly serious, what might be a practical and economical way to reduce PFM and thus reduce plastic film pollution and its costs? We already demonstrated that when a maize variety's URAT is <86.6 %, its yield is not significantly reduced when it is planted without PFM, and that effectively reduces plastic film pollution. However, if farmers do not properly apply the correct no-film planting methods and technologies, yield losses are inevitable. Since increased planting density is an effective way to increase maize yield (Zhang et al., 2017; Grassini et al., 2011), yield losses may be mitigated by using that strategy. Our experiments in 3 different *Ta* areas of northwest China included increasing the planting density from the standard 9 plants m^{-2} to 12 plants m^{-2} without PFM (Fig. 1). As a result, grain yields and economic returns increased significantly with increased planting density in the region with sufficient *Ta* (HAT, Gongqingtuan). However, in the cold and insufficient *Ta* region (LAT, Banjiegou), there was no significant difference in yields between NM with 12 plants m^{-2} (NM-HD) and PFM-TD (9.0 plants m^{-2}), regardless of maturity class (Figs. 1C, 2C). When food supplies are adequate, environmental safety and sustainable development may be considered and NM-HD can be used to reduce plastic film use. Therefore, increased planting density with NM is a viable strategy for many maize varieties in warmer regions, and that strategy can reduce production costs, energy consumption, and plastic film residue and pollution.

While it has aided crop yields, PFM has also created serious environmental pollution problems. Globally, China uses a greater amount and coverage area of plastic film than any other country, and "white pollution" and plastic film residue problems caused by long-term plastic film use is becoming more and more serious (Daryanto et al., 2017; Xu et al., 2018). Traditional agricultural plastic film, mainly polyethylene, degrades extremely slowly in the natural environment and effective management measures do not exist. Agricultural waste plastic film increases annually in farmland soil, and this residual film pollution hinders capillary water and natural water penetration into the soil, reduces soil permeability, and destroys soil structure, resulting not only in crop yield reductions and food safety concerns, but also adversely affecting green and sustainable agriculture development (Shi et al., 2019; Jiang et al., 2017; Li et al., 2020). Previous studies have disclosed the serious consequences of residual plastic film pollution in farmland (Yan et al., 2014; Yan et al., 2016), and since the plastic film recovery rate is <2/3 in China (Wang et al., 2016), >1/3 of the plastic film remains as residue in the soil. Therefore, assuming that the amount of plastic film used in 1 ha is 60.0 kg, the plastic film residue in a growing season may be at least 20 kg ha^{-1}. In 2017, we investigated irrigated, north China agricultural areas (Xinjiang, Gansu, Ningxia, and Inner Mongolia Provinces) that use PFM in maize production and found the areas of plastic-mulched maize to be 9.13×10^5 ha, 4.24×10^5 ha, 2.05×10^5 ha, and 12.39×10^5 ha, respectively. So, assuming that PFM is reduced based on both our research findings and recommendations and on the 20 kg ha^{-1} plastic film residue estimate, Xinjiang, Gansu, Ningxia, and Inner Mongolia could reduce 18.26×10^6 kg, 8.48×10^6 kg, 4.1×10^6 kg, and 24.78×10^6 kg plastic film residue, respectively, in a growing season.

Agricultural plastic film use increases GHG emissions (Cuello et al., 2015; Nan et al., 2016; He et al., 2018) and every kilogram of used agricultural film contributes CO_2-C equivalent GHG emissions of up to 22.7 kg CO_2-eq kg^{-1} to the environment (He et al., 2018; Wang et al., 2017). We estimated the GHG emissions per-100 kg grain production in different *Ta* regions (Fig. 4), and found that maize production with NM can reduce GHG emissions by 26.0 % that of maize production with PFM. The *Ta* resources in northern China's irrigated maize area are alone relatively sufficient for maize production, and there are functioning water-saving irrigation facilities and technologies in place. So, by both choosing maize varieties that are suitable for the local *Ta* and using filmless planting, both yield and economic returns can improve, and GHG emissions would also reduce. Based on our investigation of plastic-mulched and irrigated maize farmland in Xinjiang, Gansu, Ningxia, and the Inner Mongolia Provinces, we estimated that GHG emissions due to conventional agricultural film use (60 kg ha^{-1}) could be reduced by 38.1×10^8 kg of CO_2-eq ha^{-1} in a growing season if NM is used instead of PFM. Therefore, by first using maize varieties matched to an area's environmental *Ta*, then reasonably increasing the planting density and using appropriate drip irrigation technology, NM planting can effectively reduce GHG emissions. Considering the global warming situation, reduction of PFM can effectively contribute to a reduction in both plastic film residual pollution and GHG emissions.

Ensuring food security is the primary task of agricultural production. When food is scarce, we can effectively increase maize yield to improve food security, although at the expense of environmental health, by using PFM in LAT areas. Currently, however, food production is stable and global warming is a serious threat, so we can stabilize crop yield by optimizing agronomic management technology, reducing the application of environmentally unfriendly technologies, and leading the green and sustainable development of agriculture.

5. Conclusion

Our study shows that when the maize URAT in northwest China's irrigated farmland is lower than 86.6 %, PFM has no effect on maize yield. Additionally, no-film planting with a planting density increased by 3 plants m^{-2} can improve maize yields and economic returns, as well as reduce GHG emissions by 33.1 %, compared to PFM with TD. Since maize varieties with URATs between 88.2 % to 89.2 % had the lowest GHG emissions, the reasonable use of *Ta* resources can also reduce GHG emissions. Therefore, to reduce plastic mulch film use and its environmental pollution, farmers should consider the *Ta* resources of their ecological regions and choose maize varieties suited to those available heat resources. Then, using the appropriate crop varieties with filmless planting, reasonably increased planting density, and water and fertilizer integration technologies they may realize effectively increased crop yields and boosted economic returns. These advances in agronomic management are important steps toward reducing pollution and GHG emissions. Our results provide a strategy for promoting green and sustainable agricultural development and for helping achieve carbon peak and carbon neutrality goals.

CRediT authorship contribution statement

Guoqiang Zhang, Investigation, Data curation, Writing-original draft. **Bo Ming**, Supervision, Formal analysis, Conceptualization. **Ruizhi Xie**, Project administration, Funding acquisition. **Jianglu Chen**, Investigation, Supervision. **Peng Hou**, Conceptualization, Supervision. **Jun Xue**, Conceptualization, Supervision. **Dongping Shen**, Investigation, Data curation, Supervision. **Rongfa Li**, Investigation, Supervision. **Juan Zhai**, Investigation, Data curation. **Yuanmeng Zhang**, Investigation, Data curation. **Keru Wang**, Designed research, Supervision, Funding acquisition. **Shaokun Li**, Designed research, Conceptualization, Supervision.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.163507.

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