Modeling the effects of plastic film mulching on irrigated maize yield and water use efficiency in sub-humid Northeast China

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Abstract: In sub-humid Northeast China, plastic film mulching (PFM) is increasingly used with drip irrigation system in maize (*Zea mays* L.) to cope with seasonal droughts and low temperatures during seedling stage. Although there were several studies showing the benefits of PFM on maize production in the region, quantification of the effects of PFM in sub-humid Northeast China are still lacking. Hybrid-Maize model has a special version that can not only simulate the effects of PFM on reduction of soil evaporation and rise of topsoil temperature, but also simulate the effects of PFM on crop development and other physiological processes. This paper reports how to verify the Hybrid-Maize model against observations and then applying the model to quantify effects of PFM on grain yield and water use efficiency (WUE) under irrigated scenarios. The Hybrid-Maize model was added the heating effects of PFM on rising surface-soil temperature and promoting subsequent crop development by establishing equations between surface-soil temperature and air temperature before V6 stage. A 3-year field experiment including maize growth and yield data measured at a drip-irrigated field in Heilongjiang Province was used to serve the model calibration. The simulated results indicated that the Hybrid-Maize model performed well in simulation of seasonal soil water storage and in-season aboveground dry matter in three years, but overestimated the leaf area index (LAI) for both treatments and underestimated the final aboveground dry matter at maturity for mulched treatments. Although the Hybrid-Maize model overestimated the grain yield and WUE, it did still reflect the effects of PFM on increasing grain yield and WUE during the three growing seasons. The average simulated grain yield and WUE for mulched treatments were 8% and 13% greater compared to non-mulched treatments using 30 years weather data, which were in agreement with observations that average grain yield and WUE was 11% and 14% increased by PFM, respectively. For evapotranspiration (ET), the average simulated ET for mulched treatments was 22 mm less than non-mulched treatments mainly due to less soil evaporation. For simulated irrigation requirements, at most 69 mm of irrigation water could be saved by PFM. In conclusion, PFM with drip irrigation could improve irrigated maize production in sub-humid Northeast China.

Keywords: film mulch, maize yield, water use efficiency, Hybrid-Maize model, drip irrigation, Northeast China
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1 Introduction

Maize production in three provinces of Northeast China (Heilongjiang, Jilin and Liaoning) accounts for 33.6% of China's national total production[1] and spring maize is one of the most popular grain crops in this

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region[2]. In Northeast China, drought and low temperature during the seedling stage of maize often affects crop establishment[3-5]. Normally, poor rainfall distribution often leads to water stress at critical stages, resulting in lower maize yield. Plastic film mulching (PFM) has been found to be an effective way to boost and stabilize maize production[15,16]. Firstly, it can increase the topsoil temperature to promote the early stage of plant growth[6,7]. Secondly, soil evaporation reduction[8,9] and increasing water use efficiency (WUE) are benefit for crop production[4,7]. Thirdly, PFM can prevent nutrient losses through decreasing nitrate leaching[10,11] and weed growth[12]. Although there are extensive studies on maize yield and WUE of PFM, several researches are concern with the quantification of PFM on maize growth and yield in irrigated systems in cool sub-humid environments like Northeast China.

In sub-humid Northeast China, increasing surface-soil temperature and reducing soil evaporation can be the two most important benefits of plastic film mulching. While the effectiveness of PFM varies greatly, depending on the region, climate conditions, cropping system, management practices, and soil type[17]. It has been difficult to explain the complex interactions between PFM and other conditions based on a limited number of field experiments. Crop simulation modeling is a good method to evaluate the effects of field managements on crop growth and yield under different conditions[18]. Several crop growth models, such as AquaCrop model[19,20] and DNDC model[21,22], are potentially capable of simulating PFM. In AquaCrop model, the effects of PFM are accounted for reducing soil evaporation via varying the surface cover ratio and covered time period, but not topsoil temperature[23]. The DNDC model simulates the effects of changing topsoil temperature and moisture on soil biochemical processes except crop development under PFM condition[17]. An integrated dynamic model of crop growth can help in understanding maize development under PFM. In the present study, the Hybrid-Maize model of Yang et al.[24,25] was considered because it synthesized two major types of crop model: a model built on crop-specific attributes and phenology, the CERES maize model[43]; and generic crop physiology–based models such as SUCROS, WOFOST, and INTERCOM that contained explicit photosynthesis and respiration functions. The Hybrid-Maize model is a process-based model that simulates maize development and growth on a daily time-step under growth conditions without limitations from nutrient deficiencies, toxicities, insect pests, diseases, or weeds[24,25]. The model has been widely tested under rainfed and irrigated conditions and applied to the US corn-belt[33-35], South Asia[36], and North China[37,38] to predict maize production. A special version (PFM module) of the Hybrid-Maize model[24, 25] not only simulate the effects of PFM on reduction of soil evaporation and rising of topsoil temperature, but also crop development and other physiological processes[26,27]. It uses surface-soil temperature within 5 cm depth under plastic film for simulating maize development prior to 6-leaf stage (V6), whereas air temperature is used for physiological processes including photosynthesis and respirations. As soil temperature is not routinely measured, the effects of PFM on rising surface-soil temperature and subsequent crop development should be transferred to the effects on accumulated growing degree days (GDD) of the air temperature during the maize growing season. As a consequence, a new method based on compensating heating effects of PFM was put forward in this study.

The objectives of this study were to (1) test the modified module in Hybrid-Maize model for effects of PFM, and (2) apply the revised model to assess the effects of PFM on maize yield and WUE on irrigated conditions for improving the field management of maize planting in sub-humid Northeast China.

2 Materials and methods

2.1 Experimental site and design

A field experiment was conducted for three years (in 2011, 2012 and 2013) at a research experimental station (45°22'N, 125°45'E, 220 m above sea level), located in Harbin, Heilongjiang Province in Northeast China (Figure 1). The region had a sub-humid climate with an long-term (from 1980 to 2014) average seasonal (May to September) air temperature of 20.5 °C and rainfall of 421 mm. Table 1 described some of the characteristics for the experiment site. Dominant soil texture was silt[28] (Table 2). At three locations of the field, undisturbed soil samples were taken at three depth intervals (0-20 cm, 20-40 cm, and 40-80 cm) for measurements of bulk density using 100 cm^3 rings, field capacity following the method by Veihmeyer and Hendrickson[29], and wilting point at 1.5 MPa pressure using a centrifugal method (CR 21GII, Hitachi, Japan) (Table 2). Daily weather data, including maximum and minimum temperature (recorded at 1.5 m height above the ground), relative humidity, wind speed, and solar radiation were obtained from an automatic weather station located approximately 500 m from the experimental field, while rainfall data were collected manually from four rain gauges installed at each corner of the field.

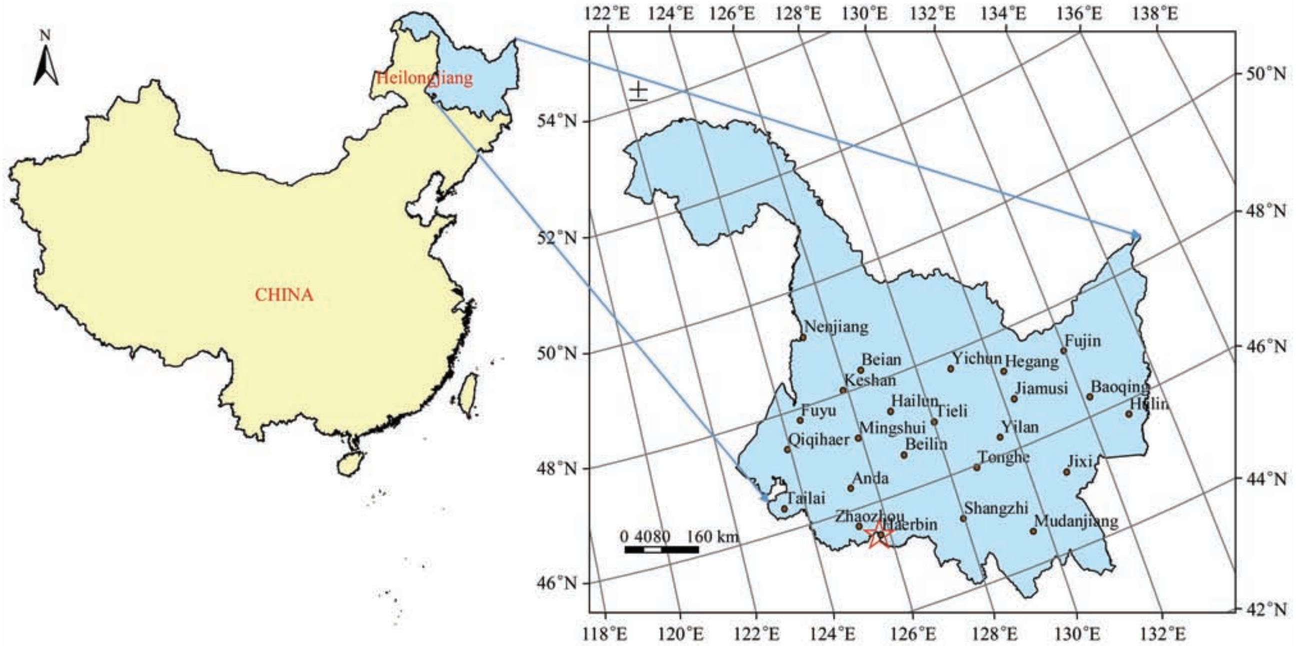


Figure 1 Field experiment site (45°22'N, 125°45'E, 220 m above sea level, red star) is located in Harbin, Heilongjiang Province in Northeast China with a sub-humid climate

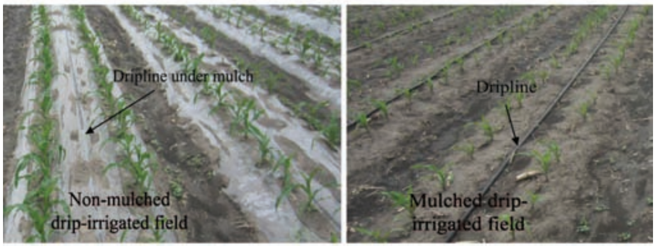
Table 1 Site characteristics (statistics from 1980 to 2014)

Characteristics	Value
Elevation above mean sea level	220 m
Annual ≥10°C accumulated temperature	3124°C
Annual average temperature	5.0°C
Lowest daily temperature ever recorded	–37.7°C
Highest daily temperature ever recorded	39.2°C
Average annual precipitation	540 mm
Average total annual sunlight	2399 h
Average total radiation	3840 MJ $m^{-2}\cdot year^{-1}$

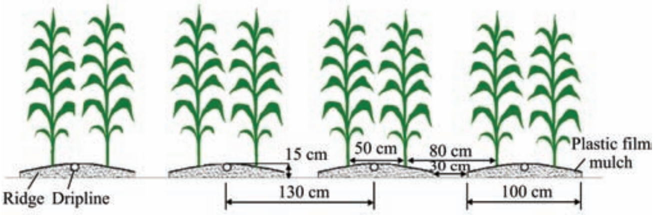
Table 2 Major soil properties of experimental field

Depth /cm	Texture	Soil bulk density /$g\cdot cm^{-3}$	Organic matter content /$g\cdot kg^{-1}$	Soil water content at 33 kPa /$cm^3\cdot cm^{-3}$	Soil water content at 1500 kPa /$cm^3\cdot cm^{-3}$
0-20	Silt	1.28	31.6	0.35	0.20
20-40	Silt	1.29	25.5	0.36	0.20
40-80	Silt	1.35	18.1	0.38	0.20

The experiment included two treatments with three replicates: mulched drip irrigation (MDI, Figure 2), and non-mulched drip irrigation (NDI). Each plot was 5.2 m wide and 40 m long. Prior to planting, the field was prepared to have 1.0 m wide ridges with 0.3 m wide furrows in between (Figure 2). For each ridge two rows of maize were seeded with a spacing of 0.5 m. Each plot had eight rows of maize crop. Maize was planted on May 5 in 2011, May 4 in 2012, and May 9 in 2013. A similar plant spacing of 0.33 m along a row was used for the three growing seasons, and the resultant plant density was about 46,620 plants per hectare. After planting and before emergence, a dripline was laid in the middle of the two rows in each ridge and a 1.2 m wide strip of plastic film of 0.008 mm thick was laid to cover the driplines and the soil surface (Figure 2). Immediately after emergence, an opening of about 5 cm in diameter was manually punched in the plastic film at the position where a plant emerged to let come through the mulch. For local growers, these practice of planting, dripline installation, PFM, and plant emerge opening were completed simultaneously by a mulch seeder machine[30]. Pest and weed control followed conventional practices in the region. Local farmers usually harvest maize crop during China's National Day holidays from end of September to the beginning of the October even if the crop is not fully matured. This is due largely to high labor availability during this short period of time. In this experiment, the maize was harvested on September 15 in 2011, September 27 in 2012, and September 25 in 2013. After harvest, plastic films and maize stalks were removed from the field.



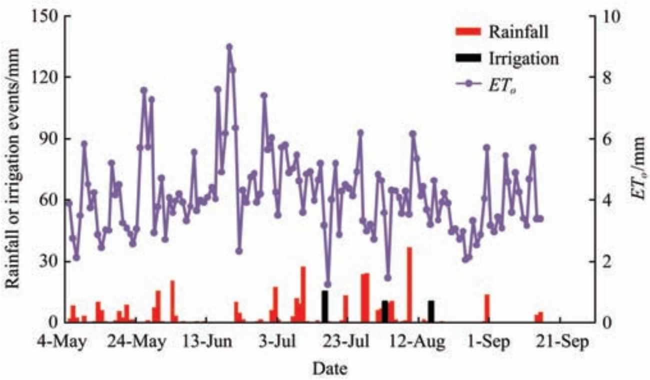
a. Mulched drip-irrigated field (MDI) b. Non-mulched drip irrigated field (NDI)



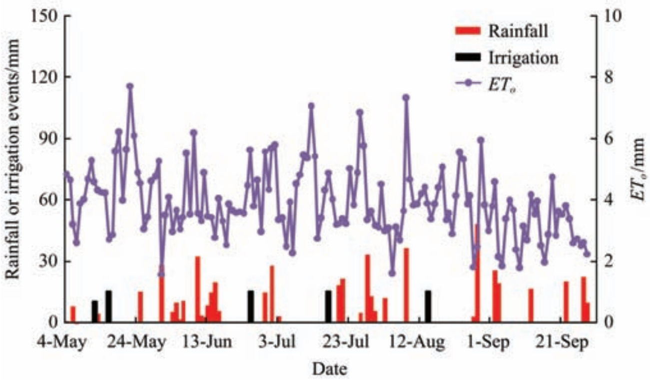
c. The schematic diagram of the cropping pattern and lateral layout of the driplines under the plastic mulch used for maize

Figure 2 The photographs for the two treatments

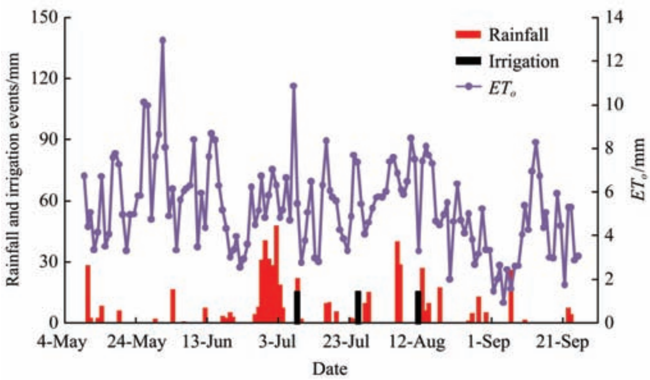
The field was irrigated using drip irrigation with one dripline in the middle of each ridge with two rows of maize crop (Figure 2) and emitters spaced at 0.3 m (IrriGreen Ltd., Beijing, China). The nominal flow rate for each emitter was 2.0 L/h at 0.1 MPa. Due to relatively sufficient rainfall amounts during the three growing season, the main purpose of the irrigation events in this study were fertigation and seasonal supplemental irrigation. In 2011 season, the field received 349 mm of rainfall and 35 mm of irrigation in three irrigation events (Figure 3a). In 2012 season, the field received 515 mm of rainfall and 70 mm of irrigation in five irrigation events including one irrigation during seedling stage due to an extended dry spell (Figure 3b). In 2013 season, the field received 569 mm of rainfall and 45 mm of irrigation in three irrigation events (Figure 3c). Compared with the historical seasonal rainfall, the precipitation during the maize growing season was normal for 2011, wet for 2012 and 2013.



a. 2011



b. 2012



c. 2013

Figure 3 Daily rainfall, irrigation, and ET_o of the 2011, 2012, and 2013 maize growing season

All treatments received 54 kg N/hm^2 and 138 kg P_2O_5/hm^2 in the form of diammonium phosphate and 81 kg K_2O/hm^2 of potassium sulfate prior to planting in the 2011 and 2012 season. For 2013 season, no pre-planting fertilizers were applied. A total of 150 kg N/hm^2 of urea was applied through drip irrigation equally during the jointing, silking, and start of effective grain filling stages in the 2011, 2012, and 2013 seasons.

2.2 Sampling and measurement

2.2.1 Soil moisture-temperature measurements and crop evapotranspiration estimation

For each season, soil samples were taken at five depths of 0-10 cm, 10-20 cm, 20-40 cm, 40-60 cm, and 60-80 cm in each plot 12 d after planting as well as at harvest to obtain the initial and final soil water contents, respectively. Specifically, the soil samples were taken from the middle of two central rows of each plot. For 2011, the soil water data was missing. Soil samples at depths of 0-10 cm, 10-20 cm, 20-40 cm, 40-60 cm, and 60-80 cm were also collected 3 d to 7 d before and after each irrigation event to obtain the seasonal change of water content in the soil. Soil samples were dried at 105°C to a constant weight to determine gravimetrical water content. In this study, soil water content of the total profile (0-120 cm) was calculated by accumulating soil water content of each layer. The average soil water content at depth of 80-120 cm was assumed to be the same as the average at depth of 60-80 cm due to minor difference beyond 60 cm depth based on experimental observations.

Actual evapotranspiration (ET) during the growing season was estimated using soil water balance approach. Runoff and capillary rise were negligible because of the flat terrain and deep groundwater level (>2 m). Deep drainage beyond crop rooting depth was estimated by dividing the whole rooting zone into layers of 10 cm, and water balance was computed layer by layer from the top to bottom. For the top layer, water input was the daily precipitation and/or irrigation minus water lost through surface runoff and canopy interception. For other layers, water input equaled water drain from the layer immediately above it. The soil holded water only up to field capacity and excess water drains to the subsequent soil layer underneath. Water that drained from the bottom to the final rooting depth was lost as deep drainage[31]. The simplified equation for the soil water balance was:

$$ET = P + I - D - \Delta S \quad (1)$$

where, ET is cumulative actual evapotranspiration (mm); P is cumulative precipitation (mm); I is total irrigation amount (mm); D is the drainage (mm); ΔS is the change in the amount of soil water in the whole soil profile (mm).

Thermometers were installed at five soil depths of 5 cm, 10 cm, 15 cm, 20 cm, and 25 cm between two plants along one the central rows in each plot. Soil temperature was recorded three times daily at around 8 am, 2 pm, and 6 pm during the three growing seasons but the data of 2011 were not used because of non-completed data.

2.2.2 Crop measurements

Plant height and leaf area index (LAI) were measured in three 13 m sections of the four center rows in each plot. In each section, three average plants were selected for the measurement of plant height and LAI at jointing, silking and around blister stages. For LAI measurements, the length and the maximum width of each leaf were recorded. In addition, the actual area for 15 typical leaves selected other than the marked plants were measured using coordinate grids. A linear regression between the actual area and the product of the length and width of the leaf was obtained for each measurement. The product of the leaf length and width for the three marked plants was then converted to the actual leaf area using the linear regression model. Finally LAI was calculated by dividing the total actual leaf area of the three marked plants by the ground area (3 × 0.65 m × 0.33 m = 0.64 m^2).

For aboveground biomass, three average plants were collected in each plot by clipping the plant at the soil surface. The stalks and ears of three plants were harvested separately in each plot at maturity. All plant samples were oven-dried at 70°C to a constant weight.

For grain yield (GY) determination, maize ears were hand-harvested from four approximately equally distributed locations of six consecutive plants per location (totally 24 plants) in each plot and grain yield was expressed at a moisture content of 14%[32]. And WUE was then calculated as:

$$WUE = GY/ET \quad (2)$$

where, ET is the seasonal accumulated evapotranspiration.

2.3 Hybrid-Maize model description

The Hybrid-Maize model requires daily weather variables including solar radiation, maximum and minimum air temperature to simulate corn stages and dry matter accumulation for irrigated systems; for rainfed systems, the model also requires precipitation, wind speed and humidity in order to simulate crop water uptake and soil water balance. In the special version of the Hybrid-Maize model for this study, the heating effect by PFM was taken into account for GDD_{10} (growing degree days above 10°C) accumulation before V6 stage as the maize growing point remains below soil surface until then[39]. Surface-soil temperatures at 2:00 pm and 8:00 am were used as daily highest (T-high) and lowest (T-low) values to establish new mathematical functions with air temperature according to observation from Zhang et al.[40] (Figure 4). The differences of the surface-soil temperatures between mulched and non-mulched treatments were described as equations (3) and (4) for T-high and T-low, respectively.

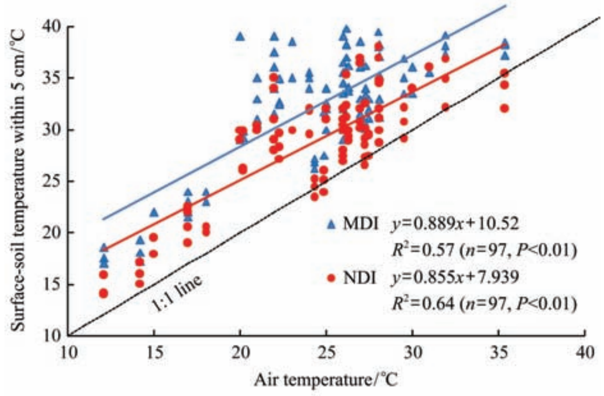
For T-high:

$$T_{soil-MDI} - T_{soil-NDI} = 0.034 \times T_{air} + 2.581 \quad (3)$$

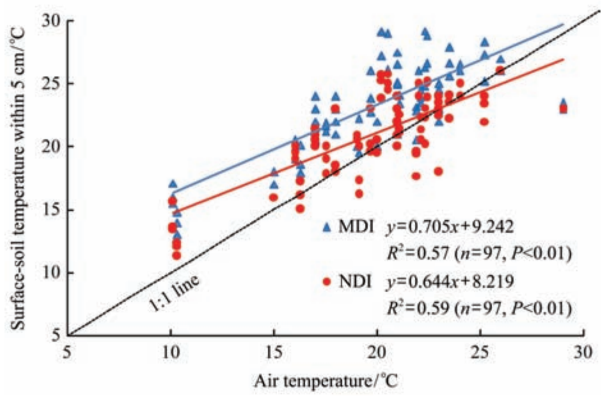
For T-low:

$$T_{soil-MDI} - T_{soil-NDI} = 0.061 \times T_{air} + 1.023 \quad (4)$$

where, $T_{soil-MDI}$ and $T_{soil-NDI}$ means the surface-soil temperature within 5 cm for mulched and non-mulched treatments, respectively. T_{air} means the air temperature. After V6 stage, no heating effect of PFM was considered as the maize growing point had risen above soil surface and was supposed to be outside the plastic film.



a. T-high



b. T-low

Figure 4 Relationship between (a) daily highest surface-soil temperature (T-high) and (b) lowest surface-soil temperature (T-low) within 5 cm and air temperature during the growing period from emergence to V6 for mulched (blue) and non-mulched (red) fields

For simulation of soil water dynamics, water input included precipitation and/or irrigation while water output included the losses through surface runoff, canopy interception, soil evaporation, crop transpiration, and drainage below crop rooting depth. The model also simulated increase of crop rooting depth based on GDD accumulation and the maximum rooting depth was reached shortly after silking. The crop was assumed to take up water only from the active rooting zone when soil water content is above the permanent wilting point. The whole rooting zone is divided into layers of 10 cm, and water balance is computed layer by layer from the top to bottom[24].

Actual soil evaporation (cm/d) is estimated using the 2 step evaporation scheme as in FAO 56[41]. According this scheme, soil evaporation occurs in the top 10 cm soil depth, and evaporation rate will be at maximum when soil is wet (i.e., first step). Evaporation rate will start to decrease, and continuously so, when soil water content is below a threshold (step 2). Considering the plastic film breakage during the growing season, average soil surface coverage rate of the PFM treatment was set as 50% of that without plastic film before plastic film broke although initial plastic film coverage rate was about 77% (Figure 2). Actual transpiration ($Transp_{actual}$, cm/d) was estimated from the maximum water uptake by roots from all layers where roots had reached in comparison with maximum transpiration ($Transp_{max}$, cm/d) estimated from accounting for referenced ET and canopy size[24]. Water stress index was expressed as Equation (5):

$$Water\ stress = 1 - \frac{Transp_{actual}}{Transp_{max}} \quad (5)$$

The crop suffered no stress and full stress when water stress was equal to 0 and 1, respectively.

Following Keating et al.[42], the water stress index is used as a reduction factor for CO_2 assimilation and leaf area expansion, as well as an acceleration factor for leaf area senescence after silking. A value of Stress=0 indicates absence of water stress that limits crop growth so that CO_2 assimilation is not reduced, whereas CO_2 assimilation stops completely at Stress=1. For leaf area expansion before silking, daily leaf area expansion occurs at the maximum rate when Stress=0; leaf area expansion decrease linearly until Stress=0.5 when leaf area expansion stops completely. After silking, in addition to the leaf senescence due to leaf age and heat stress, leaf area senescence accelerates due to water stress: no leaf area senesces due to water stress at Stress=0, whereas 5% of current green leaf area senesces at Stress=1.

For simulating irrigation requirements with drip irrigation system in sub-humid Northeast China, irrigation was called whenever crop water stress started to appear to achieve stress-free growth. The maximum amount of water that could be applied in each irrigation event was set as 30 mm and irrigation target soil water content in top 30 cm was set at 85% of the field capacity. The actual amount of irrigation required would also depend on the efficiency of the irrigation system because the Hybrid-Maize assumed that all water that reaches the soil surface enters the soil water pool. It did not account for evaporation or non-uniformity of irrigation.

All simulation inputs were grouped into three panels: general input (weather data, simulation mode, planting date, hybrid choice/maturity, plant population), water (yield potential or water-limited), and soil & field (soil and field properties relevant for simulating soil moisture). Default values were provided for most of these settings. To calibrate the Hybrid-maize model, the phenological development parameters related to silking and maturity dates were used (see Table 3 for a detailed description of these parameters) obtained from the 2011 to 2013 field experiments. Simulations were based on the actual soil type, and actual crop sowing, silking, and physiological maturity dates.

Table 3 Phenological development parameters used as inputs for the Hybrid-maize model

Experiment	Planting date /MM-DD	Silking date /MM-DD	Maturity Date /MM-DD	Total GDD_{10} /°C	Total GDD_{10} to silking /°C
2011	5-5	7-17	9-28	1580	799
2012	5-4	7-15	9-24	1580	807
2013	5-9	7-15	9-20	1580	805

2.4 Hybrid-Maize model calibration

Hybrid-Maize model was calibrated using the observed data of 2012 for soil water content over the rooting depth, LAI, aboveground dry matter and grain yield. Two parameters selected to be calibrated were the potential kernel number per ear (*G*2) and light extinction coefficient (*k*). Potential kernel number varies from about 560 kernels to 834 kernels per plant[43]. In the field, *G*2 can be estimated from final kernel number on plants grown at low population densities with no water or nutrient stresses when mean daily temperatures are 20°C-30°C[43]. The default value of 675 for potential number of kernels per ear in Hybrid-Maize model is for hybrids suited to high plant densities[24], while potential number of kernels per ear of 800 gave better simulation results for hybrids used in this study. Such an adjustment was also suggested by Jones and Kiniry[43]. The canopy light extinction coefficient (*k*) is a parameter that describes the efficiency of light interception for the canopy of a terrestrial ecosystem. A low *k* indicates that much radiation can reach the bottom of the canopy. Conversely, a high *k* indicates that only a little radiation can penetrate into the understory of the canopy. Theoretically, *k* is determined by leaf inclined angle (α) and solar zenith angle (θ). The light extinction coefficient, *k*, had been shown to be around 0.65 for maize and the extinction coefficient was affected by row spacing[49]. Inbreds with more erect leaves had a *k* value of 0.59 when the canopy was fully developed as opposed to inbreds with more horizontal leaves having a *k* of 0.72[49]. In this study, the default *k* of 0.55 was calibrated to 0.75, which was still within the range of possible value for maize *k*[44-46]. The calibrated model was then tested and validated using data of 2011 and 2013.

2.5 Application of the Hybrid-Maize model

The calibrated Hybrid-Maize model was applied on irrigated conditions to study the impacts of PFM on grain yield and WUE using 30 years of the historical weather data from 1981 to 2010. The historical weather data was acquired from local meteorological bureau and the air temperature was measured at 1.5 m above the ground. The simulated results included grain yield, crop water consumption, and estimated irrigation amount requirement. The hybrid-specific input parameters of the applied model were the same as the field experiment in this study. The planting time was set as May 1 uniformly because the local farmers usually planted during the seeding window from the end of April to the start of May. Although the crop was usually harvested at the matured date, the simulation of the growth was set to stop running on September 30 even if the crop was not fully matured. The grain yield on September 30 would be used for harvest yield. This was because local farmers usually harvest maize crop during the period from end of September to the beginning of the October. Initial soil water content was set as 40% of soil available water (the soil water content between field capacity and permanent wilting point) in the root zone due to occasionally spring drought during the seedling stage of maize.

2.6 Statistical analyses

The Nash-Sutcliffe index of model efficiency (ME), root mean square error (RMSE) and index of agreement (*d*-index)[47] were employed for quantitative comparisons. A positive ME value means better model prediction than the mean of observations with the perfect fit of ME of 1[48]. The RMSE has a minimum value of 0 being perfect fit between of simulations with measurements. The value of *d* ranges from 0 to 1, with 1 representing a perfect fit of the data. ME, RMSE and *d* are calculated as Equations (6) to (8). The least significant difference (LSD) was also calculated on field results in three years for grain yield and WUE between PFM and non-PFM treatments using the SPSS 16.0 software[49].

$$ME = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - O)^2} \quad (6)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(O_i - P_i\right)^2}{n}} \quad (7)$$

$$d = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(|O_i - O| + |P_i - O|)^2} \quad (8)$$

where, O_i and P_i are the observed and modeled values; *O* and *P* are their respective averages and *n* is the number of values.

3 Results

3.1 Relationship between surface-soil temperature and air temperature

Between the two treatments, MDI had a higher surface-soil temperature than NDI (Figure 4), which meant maize GDD accumulation for MDI was faster than that for NDI before V6 stage[39]. Meanwhile, the daily surface-soil temperature within 5 cm could increase 2.0°C to 3.5°C daily under PFM before V6 stage when daily air temperature varied from 15°C to 35°C (Figure 4). Furthermore, the accumulated GDD_{10} from planting to the end of June (i.e., around V6 stage of maize) for MDI was about 52°C to 75°C days greater than that for NDI during the early growing seasons of maize (Table 4), which was in agreement with the report that the PFM increased 50°C-70°C days of the GDD_{10} during the seedling stage confirmed by Bu et al.[7]

Table 4 Accumulated GDD_{10} (°C days) in mulched (MDI) and no-mulched (NDI) during the same early growing stage from planting time to the end of June

Year	MDI	NDI	Difference
2011	569	499	70
2012	599	524	75
2013	605	553	52
Average	591	529	62

3.2 Verification of Hybrid-Maize model

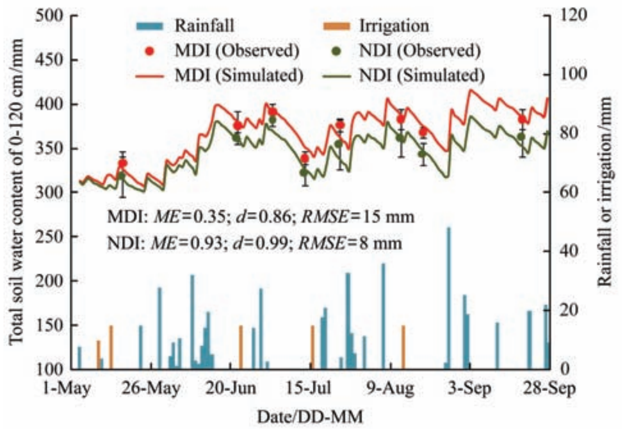
3.2.1 Total soil water storage

The Hybrid-Maize model performed well in the simulation of total soil water storage in 0-120 cm for 2013 (Figure 5). For 2012, the simulated soil water content was slightly greater than the observed values but still showed the same tendency. Year 2011 had no data available.

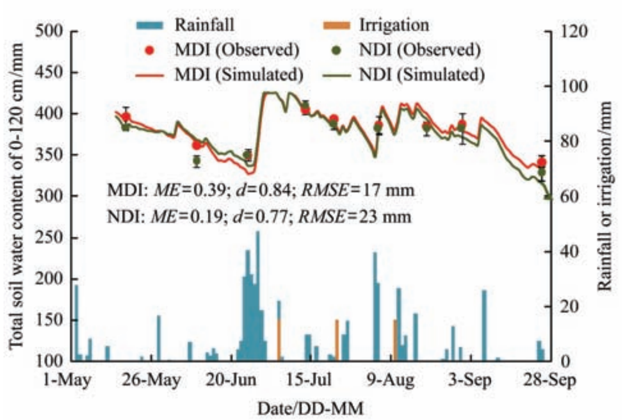
Figure 5 showed that total soil water storage of MDI treatment was greater than that of NDI treatment throughout the growing season of 2012, but saw similar soil water content in the two treatments in 2013. For 2013, the average daily soil water content in MDI ranged 5% (simulated) to 8% (measured) greater than that for NDI, respectively. The reason was that PFM decreased soil evaporation during the whole 2012 and 2013 growing seasons which increased soil water content for mulched conditions. However, the initial soil water content and the precipitation in 2013 (569 mm) was greater than that in 2012 (515 mm).

3.2.2 Leaf area index

The simulated LAI showed the similar seasonal pattern with the observed LAI for both MDI and NDI treatments in the three years. Although the simulated



a. 2012



b. 2013

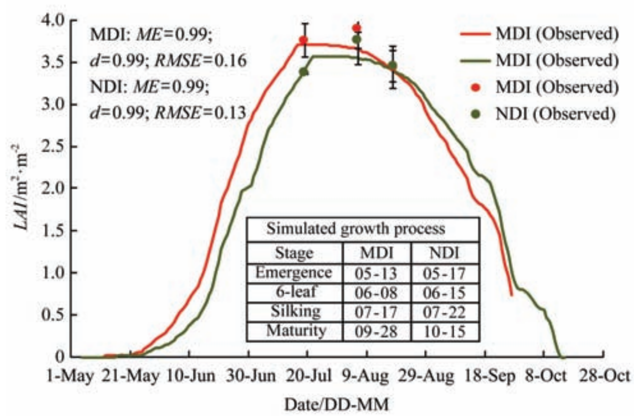
Figure 5 Comparison of observed and simulated total soil water content within the root zone (0-120 cm) in (a) 2012 and (b) 2013. Vertical bars in measured values are standard deviations (SD)

LAI was slightly greater than the observed values in 2012 and 2013, the simulated difference between mulched and non-mulched treatments was near to the observed difference (Figure 6). Furthermore, it was also found that the difference of the LAI between MDI and NDI was greater in observations than that of simulated, probably because the PFM might have reduced nitrate leaching in the MDI treatment while which was not the case in the NDI treatment due to relatively frequent rainfall during the growing seasons of 2012 and 2013 as indicated in Figure 3.

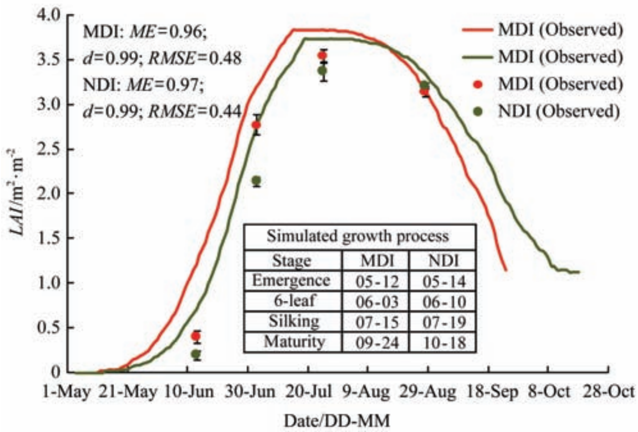
3.2.3 Aboveground dry mater accumulation

The simulated results showed a relatively good agreement with observations in aboveground dry matter accumulation for both MDI and NDI treatments although the model underestimated the final aboveground dry matter in 2011 and 2013 for mulched treatment (Figure 7). Figure 7 also indicated that Hybrid-Maize model overestimated the aboveground dry matter during the maize vegetative growth stage in 2013. This was because the maize in 2013 might suffer from nitrogen stress but the Hybrid-Maize model simulated the crop growth without nutrition limitations.

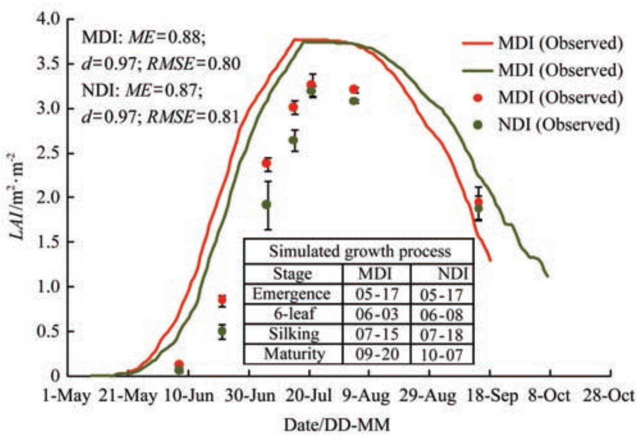
In simulation, the MDI treatment arrived at silking stage about 3-5 d earlier and reached to physiological maturity stage two weeks earlier than NDI treatment (Figure 7) because of the accumulated heating effect of PFM, resulting in lower total biomass in MDI treatment (Figure 7).



a. 2011

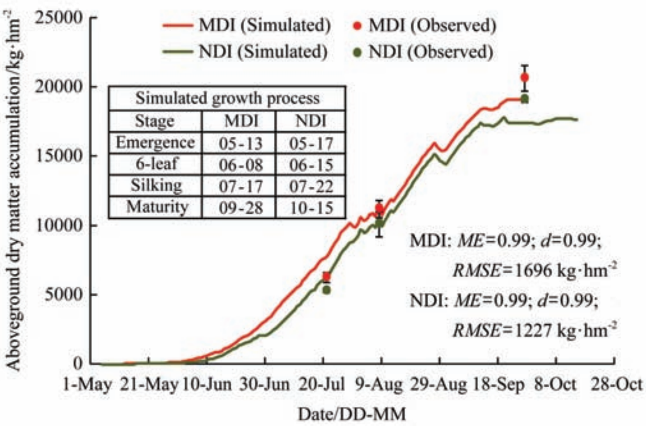


b. 2012

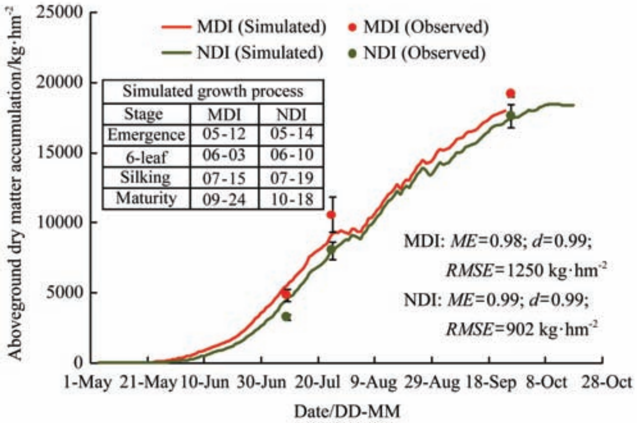


c. 2013

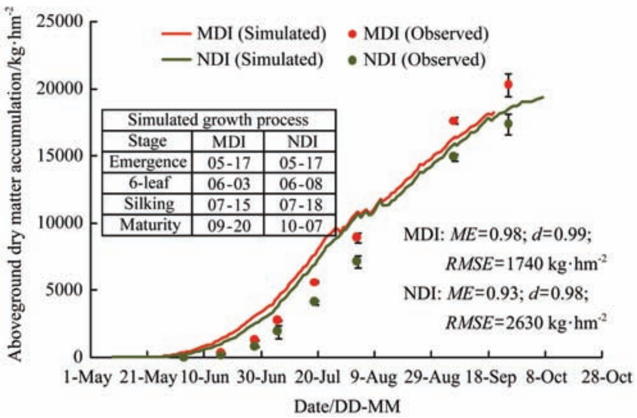
Figure 6 Comparison of observed and simulated leaf area index (*LAI*) in 2011, 2012, and 2013. Vertical bars in measured values were standard deviations (SD). The MDI treatment came to maturity earlier than the NDI treatment due to the heating effect



a. 2011



b. 2012



c. 2013

Figure 7 Comparison of observed and simulated aboveground dry matter accumulation in (a) 2011, (b) 2012, and (c) 2013. Vertical bars in measured values are standard deviations (SD). The MDI treatment came to maturity earlier than the NDI treatment due to the heating effect

The aboveground dry matter at maturity for NDI was greater than that for MDI in 2013. It was because the mulched maize developed faster due to the heating effect and reached maturity earlier compared to non-mulched treatments. However, the aboveground dry matter for MDI at the harvest date was greater than that for NDI. The PFM could make farmers harvest more when the harvest time was earlier than maturity date.

3.2.4 Grain yield and *WUE*

The simulated grain yield and WUE were greater than observed values for MDI and NDI because the simulated grain yield by Hybrid-Maize model represented the potential yield (Table 5). The difference of observed and simulated grain yield for MDI and NDI varied from 4.8% to 17.9% and 9.4% to 27.8%, respectively (Table 5). And the average of simulated grain yield for MDI and NDI was 9.8% and 15.6% greater than observed grain yield, respectively. The maximum difference between observed and simulated grain yield and WUE occurred in 2013. The possible reason was that heavy rainfall in late June and early July of 2013 (Figure 3) increased the risk of nitrate leaching and decreased nitrogen uptake of maize, which eventually led to decrease observed grain yield[50,51]. For WUE, the difference of observed and simulated MDI and NDI varied from 4.2% to 13.9% and 11.7% to 12.6%, respectively.

Table 5 Comparisons of simulated and observed grain yield (at 14% moisture content) and water use efficiency (WUE) in mulched (MDI) and no-mulched (NDI) treatments

Items	Year	Observed		Simulated	
		MDI	NDI	MDI	NDI
Grain yield /Mg·ha^{-1}	2011	10.97±0.25 a[a]	9.99±0.46 b	11.78	10.92
	2012	12.39±0.77 a	11.06±0.06 b	12.99	12.18
	2013	11.19±0.09 a	10.12±0.24 b	13.05	12.93
	Average	11.52	10.39	12.65	12.01
WUE /kg·m^{-3}	2011	—	—	2.50	2.30
	2012	2.56±0.64 a	2.10±0.13 b	2.67	2.38
	2013	2.02±0.20 a	1.88±0.40 b	2.30	2.12
	Average	2.22	1.95	2.46	2.27

Note: [a] Treatments with the same letter in the row are not significantly different at a probability level of $p<0.05$.

Although the simulated results overestimated grain yield and the WUE in three years, especially in 2013, the Hybrid-Maize model did reflect the effects of PFM on grain yield and WUE. The simulated yield and WUE increase by PFM was near to the observed yield and WUE increase during 2011 and 2012 growing seasons (Table 5). However, the observed yield increase by PFM (11%) was much greater than the simulated yield increase (1%) in 2013 because the maize might suffer from nitrogen stress in experiment in 2013 but not suffer any nitrogen stress in simulated conditions.

3.3 Simulation of grain yield and WUE from 1981 to 2010

3.3.1 Effects of PFM on seasonal ET and irrigation requirements

The average estimated seasonal ET and estimated irrigation requirement for MDI was less than NDI (Table 6). The average estimated irrigation requirement for MDI was 18% (21 mm) lower than NDI and the average ET for MDI was 4% (22 mm) lower than NDI (Table 6). On dry years, at most 69 mm of irrigation amounts (about twice of drip irrigation events) may be saved compared to non-mulch treatments (Table 6). Furthermore, the difference of average ET between MDI and NDI was almost in a good agreement with the difference of average irrigation requirements.

Table 6 Simulated seasonal accumulated evapotranspiration (ET) and irrigation requirements (IR) in mulched (MDI) and non-mulched (NDI) treatments on irrigated conditions from 1981 to 2010

Items	Rank	MDI	NDI	|*MDI−NDI*|
ET/mm	Max	709	711	74
	Min	456	490	0
	Average	591	613	22
	CV[a]	0.12	0.10	0.81
IR/mm	Max	254	274	69
	Min	0	0	0
	Average	115	136	21
	CV	0.60	0.53	1.06

Note: [a] CV is the coefficient of variation. |*MDI−NDI*| is the absolute value of differences between MDI and NDI. Same as below.

3.3.2 Effects of PFM on grain yield and WUE

The grain yield and WUE for mulched treatments were obviously greater than those of non-mulched treatments for irrigated fields (Table 7).

Table 7 Simulated grain yield (at 14% moisture content) and water use efficiency (WUE) for mulched (MDI) and non-mulched (NDI) treatments from 1981 to 2010

Items	Rank	MDI	NDI	|*MDI−NDI*|
Grain yield /Mg·hm^{-2}	Max	15.2	14.8	2.5
	Min	9.8	7.5	0
	Average	12.9	11.9	1.0
	CV	0.13	0.17	
WUE /kg·m^{-3}	Max	2.87	2.67	0.52
	Min	1.60	1.15	0.03
	Average	2.21	1.96	0.25
	CV	0.18	0.22	

The grain yield for mulched treatments varying from 9.8 Mg/hm^2 to 15.2 Mg/hm^2 was averagely 8% (ranged from 0 to 30%) greater than that for non-mulched treatments varying from 7.5 Mg/hm^2 to 14.8 Mg/hm^2. The WUE for mulched treatments varying from 16.0 kg/m^3 to 28.7 kg/m^3 was averagely 13% (ranged from 1% to 39%) greater than that for non-mulched treatments varying from 11.5 kg/m^3 to 26.7 kg/m^3.

4 Discussion

Based on literature review, there were currently three crop models (DNDC, AquaCrop and Hybrid-Maize) that took the effects of PFM into consideration. Among these three models, DNDC model and Hybrid-Maize model considered the effects of PFM on surface soil temperature. In this study, the heating effect by PFM was taken into account for crop development before V6 stage (GDD_{10} was equal to 280°C·d). With plastic mulching the accumulated GDD_{10} difference before V6 stage was about 50°C to 75°C days greater than non-mulched treatment, which meant that the crop under PFM developed faster, resulting in lower risk of early frost damage.

The method of heating effect in Hybrid-Maize model was different from other crop models in considering the effects of PFM on soil temperature. In DNDC model, the new surface soil temperature was simulated by the energy exchange between the air and soil by the film thickness and thermal conductivity[17]. Then the biochemical response and denitrification-decomposition in soil could be influenced by the surface-soil temperature, which meant the effects of PFM on surface soil temperature in DNDC model relied more on soil biochemical process, water and nutrition uptake of the root system. For Hybrid-Maize model, the surface soil temperature was simulated by establishing regression relationship between surface soil temperature and air temperature instead of energy balance. The increased GDD accumulation by PFM directly promoted crop development and growth according to crop phenology. For capturing the effect of PFM on soil evaporation, these three models all considered two factors including covered percent of the soil surface and covered time period.

Hybrid-Maize model simulates maize growth under optimal management conditions and as a result of often overestimates crop growth, including leaf area index and biomass. However in field experiment, there might be nutrition limitations such as nitrogen stress introduced by nitrate leaching or lack of supplement. In this research, the basal fertilizer was not applied before planting in 2013 and the initial soil water content was pretty high due to melting snow of the last winter, which might lead to nitrate leaching[51]. Furthermore, the factor that plant N accumulation was markedly promoted by PFM during the post-silking stage[52] was also not considered in the model. In addition, we also found that the crop nitrogen uptake in 2013 was significantly lower than that in 2011 and 2012 (not shown in this paper) which implied that the maize in 2013 might suffer nitrogen deficiency. All those could lead to differences between the simulated and observed grain yield in 2013. Although the new PFM module of the Hybrid-Maize model overestimated the maize yield and WUE under mulched and non-mulched conditions, the simulated results did reflect the growth and yield difference between the mulched and non-mulched treatments. The reason for the model overestimating the LAI in 2012 and 2013 might be that the Hybrid-Maize model simulates maize development and growth for optimal conditions and the function of leaf area expansion in the Hybrid-Maize model might not fully reflect the cultivars used in China. The reason for underestimating final dry matter accumulation at maturity in 2011 and 2013 for mulched treatments might be that the Hybrid-Maize model was developed and calibrated largely for high plant density systems in North America, leading to underestimation for lower density systems in Northeast China.

In this study, we got two sensitive and meaningful parameters including potential number of kernels per ear and light extinction coefficient. Values of both parameters were related to plant population a hybrid has adapted to, which was also related to dominant type of farming operations. Farm operations for planting and harvest are completely mechanized in the US and other developed countries while manual or semi-mechanized operations are common in China[53]. Mechanized operations implement more easily higher maize plant densities (60 000 to 85 000 plants/hm^2), which is one of the effective ways to achieve higher yield, while manual or semi-mechanized field operations prefer lower plant densities (35 000 to 50 000 plants/hm^2). Maize hybrids suited to higher densities tend to have smaller and more vertical leaves, and smaller ears and fewer kernels, while hybrids suited to lower densities tend to be the opposite[43,54,55]. Compared to smaller and more vertical leaves, larger and more flatten leaves have larger values of light extinction coefficient[56]. Some other parameters might also need to be adjusted for the low density system in Northeast China according to other experimental observations or reasonable explanations.

The effects of PFM on increasing maize yield and WUE were stronger in rainfed fields in semi-arid Northwest China than irrigated fields in sub-humid Northeast China. After simulating the maize yield using the 30 year historical weather, about 0-30% of grain yield increases and 1%-39% of WUE increase were found for mulched treatments. The increase ranges were much lower than results from rainfed maize in arid environments of Northwest China (Table 8). As shown in Table 8, the rate of increase for grain yield in rainfed fields by PFM ranged from 13%[57] to 600%[13] in Northwest China and the rate of increase for WUE ranged from 10%[9] to 1100%[13]. The greatest rate of increase for grain yield and WUE was observed by Zhou et al.[13] comparing the treatment of two ridges and furrow under plastic film mulch with the treatment of flat plot without plastic mulch in a semi-arid region of Loess Plateau. There were also some other studies based on multi sites and long years. For example, Wang et al.[16] reported 76% yield increase in rain-fed maize (8.9 Mg/hm^2 compared to 5.1 Mg/hm^2) under PFM in semi-arid areas of Northwest China based on five sites and up to 6 years at each site. This might be due to the fact that the effects of PFM on increasing grain yield and WUE in sub-humid Northeast China mainly relied on increasing topsoil temperature and promoting maize growth during early stages but not too much relied on decreasing soil evaporation. Since there were usually averagely 400-500 mm of total rainfall amounts during maize growing seasons, which could roughly met crop water demand. However in semi-arid regions like Northwest China, reduction of soil evaporation played a more important role in maintaining soil moisture on rainfed conditions and increasing grain yield and WUE under PFM. Moreover, PFM could still increase topsoil temperature and accelerate maize growth in semi-arid Northwest China. That was why the effects of PFM on increasing grain yield and WUE were much greater in semi-arid regions than that in sub-humid Northeast China. Therefore, the effects of PFM on increasing maize yield and WUE were stronger in rainfed fields in semi-arid Northwest China than irrigated fields in sub-humid Northeast China.

Table 8 Comparison of effects of plastic film mulching on increasing maize yield and *WUE*, and decreasing *ET* in different rainfed/irrigated fields of China

Irrigated/rainfed	Location	Climate	Yield increase/%	*ET* decrease/%	*WUE* increase/%	References
Rainfed	Northwest	Semi-arid	576-1043	7-8	675-1177	[13]
	Northwest	Semi-arid	8-24	1-4	0-20	[57]
	Northwest	Semi-arid	23-42	4-6	22-33	[58]
	Northwest	Semi-arid	17-23	1-7	17-31	[59]
	Northwest	Semi-arid	16			[17]
	Northwest	Semi-arid	12-14	1-5	8-12	[9]
	Northwest	Semi-arid	28-88		23-90	[7]
	Northeast	Semi-arid	10-17	6-15	21-35	[23]
	Northwest	Semi-arid	30-107			[16]
Irrigated	North Plain	Sub-humid	9-56	4-18	33-75	[60]
	Northeast	Sub-humid	0-30	0-16	1-39	This study

Seasonal supplemental irrigation was the most practical method of crop water replenishment for local farmers in Northeast China when droughts happened among the rain-fed and irrigated conditions, which are the worst and optimal conditions. Compared to the drip-irrigated fields where the crop did not suffer water stress during the whole season, the rainfed crop were more likely to suffer great water stress at critical growing stage, resulting in losing plenty of grain yields. Therefore, integrating the practice of PFM with drip irrigation system could be a good choice for the maize production in sub-humid Northeast China.

5 Conclusions and suggestions

(1) The calibration results indicated that the new PFM (plastic film mulching) module of the Hybrid-Maize model did reflect the effects of PFM on accelerating maize growth, increasing grain yield and WUE, although the model underestimated final aboveground dry matter at maturity and overestimated grain yield and WUE for both mulched and non-mulched treatments in 2013.

(2) Compared with the non-mulched treatments, the PFM accelerated growing degree days, lowered estimated irrigation requirements, increased grain yield and WUE by increasing the surface-soil temperature before V6 stage and reduced soil evaporation during the maize growing season.

(3) The effects of PFM on increasing grain yield and WUE in a water-abundant irrigated field in sub-humid Northeast China was weaker than the effects in a water-stress rainfed fields such as arid Northwest China. In all, the practice of PFM with drip irrigation could play an important role in guaranteeing the irrigated maize production in Northeast China.

(4) In this study, only the effects of PFM on increasing surface soil temperature and decreasing soil evaporation were considered. In reality, PFM might have the advantage of promoting organic nitrogen mineralization and reducing nitrate leaching in sub-humid region. This study gave no consideration to the nitrogen transport and transformation, which, to a certain extent, affects the simulation results. Therefore, it is necessary to improve the Hybrid-Maize model established in the future to formulate nitrogen module.

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