Research on high photosynthetic efficient cultivation with drip irrigation under different mulch of maize
Yu Bai and Jinhua Gao

ABSTRACT
Maize refers to one of the major food crops worldwide. Its yield has a direct effect on global food security. Moreover, cultivated lands in the world have been undergoing serious degradation. In the present study, field experiments were performed in the middle of Jilin, China. A novel maize cultivating method, combining drip irrigation under film mulch cultivation and high photosynthetic efficient cultivation, is presented. NUE, WUE, accumulated temperature, plant growth and yield were determined in high photosynthetic efficient cultivation with drip irrigation under mulch and with there being under the mulch transparent and black film, respectively. As revealed from the results, the high photosynthetic efficient cultivation based on drip irrigation cultivation could increase the yield of rain-fed treatment by 53%; high photosynthetic efficient cultivation with drip irrigation under film mulch cultivation could also improve NUE and WUE compared with conventional drip irrigation under film mulch cultivation; transparent mulch could more significantly raise the soil temperature than black mulching, as well as improving the maize yield. The present study presents a novel planting mode in accordance with reliable theory to sustainably develop maize.

Key words | accumulated temperature, drip irrigation under mulch, high photosynthetic efficient cultivation, maize, nitrogen use efficiency, water use efficiency

HIGHLIGHTS
- Combined high photosynthetic efficient cultivation with drip irrigation and mulch cultivation.
- Transparent film can increase yield of maize more than black film.
- WUE and NUE are discussed under this cultivation method.
- Economic analysis of this cultivation method has been given.
- Further work for this cultivation method has been given.

INTRODUCTION
Food has been more increasingly demanded year by year, and it has been estimated that the demand for food will grow by 70% by 2050. Under the rising food demand, the yield of maize should be improved by at least 40% in the next four decades (Sui et al. 2018). Besides in China (Jiang et al. 2016; Wang et al. 2017; Fang & Su et al. 2019), maize is also of vital importance to the world’s food production (Hammad et al. 2017; Zamora-Re et al. 2020). How to design effective maize cultivating methods and methods to reduce soil degradation can more effectively support global food security and help reduce global arable land degradation (Fagúndez et al. 2016; Gao et al. 2017).

Over the past few years, with the emergence of drip irrigation in maize seed components, it has been shown that maize yield can be significantly improved (Wang et al. 2018; Wu et al. 2019). In several cold areas, drip fertigation has been used in combination with plastic mulching (Ma et al. 2007; Wei & Chen 2011). In addition, since the late 1990s, Xinjiang has...
implemented drip irrigation based on mulch film technology (Hu & Li 2005). Drip irrigation under film mulch cultivation is capable of raising soil temperatures and reducing water evaporation in comparison with conventional drip irrigation (Jayakumar et al. 2017; Li et al. 2017). It also controls pesticides and has been extensively studied in recent years (Qin et al. 2016). Moreover, many scholars’ results have proved the effects of drip irrigation with film mulch on crop production (Yang et al. 2017). Most conventional drip irrigation methods under film use transparent film, while there have also been some studies on the application of black mulch (Decoteau et al. 2013). Locascio et al. (2005) demonstrated that black mulch can improve the yield of strawberries and more effectively control the weed population (96%) compared with other colors of mulch (Sinha et al. 2019).

Currently, there is another maize cultivating method in Jilin Province, termed ‘high photosynthetic efficient cultivation’. It was implemented by the Northeast Institute of Geography and Agroecology as administrated by the Chinese Academy of Sciences in Jilin Province. Compared with conventional maize cultivation methods, four differences are identified in high photosynthetic efficient cultivation. First, uniform planting of rows is changed into wide–narrow (40–160 cm) rows. Second, the land rests once for four years (Figure 1), and the ridge moves sideways every other year and protects the fertility of the soil. Third, the conventional ridge direction was changed to be perpendicular to the orbit of the sun, which can more effectively increase the sunlight on the plants. Fourth, the plant distance can be much less than in conventional cultivation. Such a type of cultivating method was used in Dehui, Jilin, from 2010 to 2012, and the results suggested that it can improve the maize yield to 13.5%. Altering the ridge direction and the ridge distance can prolong the illumination time and fully exploit solar energy (Chenu et al. 2008; He et al. 2010).

Conventional research tends to discuss how to improve maize yield, whereas this will significantly damage soil fertility. How to use fallow rotation to achieve a high yield of maize and ensure soil fertility is worth analyzing. Combining high photosynthetic efficient cultivation with drip irrigation under film mulch may solve the mentioned problem, and this cultivation requires in-depth studies. Moreover, the effect of different plastic film mulch on high photosynthetic efficient cultivation with drip irrigation under film mulch is worth studying.

In this study, a novel type of maize cultivation, high photosynthetic efficient cultivation with drip irrigation under transparent and black mulch, is proposed, and the field experiment was performed in Hexin County, Changchun City, China. The aims of this study are elucidated as follows. (1) A new maize cultivating method for fallow rotation is provided, and the effects of this method on water use efficiency (WUE) and nitrogen use efficiency (NUE) are discussed. (2) The effects of transparent and black film mulch on crop accumulated temperature and yield are analyzed. This study will be conducive to maize planting development, and it can be theoretically referenced for ensure soil fertility.

Figure 1 | The layout of high photosynthetic efficient cultivation.
STUDY AREA AND METHODS

Experimental site

The experiments were performed in Hexin County, Changchun, China, in 2016. The test station is in the hinterland of the Northeast Songliao Plain, located at 43°57′E, 125°59′N. Pertaining in the area is a continental monsoon climate that has four distinct seasons. It has an average temperature of 4.8°C, a maximum temperature of 39.54°C, a minimum temperature of −39.8°C, sunshine time of 2,688 h, average annual rainfall of 522–615 mm, and concentrated precipitation from June to August. Table 1 lists the physical and chemical properties of the tested soil, and Table 2 presents the weather conditions in the planting period.

Experimental design

The treatments of the three-year experiment are presented in Table 3, and each treatment was repeated three times. The experiment was primarily performed using two planting methods (i.e., drip irrigation under mulch, high photosynthetic efficient cultivation with drip irrigation under mulch) under three different types of film mulch (i.e., no film mulch, transparent film mulch and black film mulch); the conventional rain-fed group was classified as the control group. The ridge distance of drip irrigation under mulch was 40–90 cm with a plant distance of 25 cm. The ridge distance of high photosynthetic efficient cultivation with drip irrigation under mulch varied from 40–160 cm to 50–110 cm with a plant distance of 20 cm to elevate the utilization rate of land, and the ridge direction was altered into 19°54′ south by west to be perpendicular to the Sun’s orbit (Figure 2). The area of drip irrigation under mulch and the rain-fed plot was 3.9 × 15 m, and the high photosynthetic efficient cultivation with drip irrigation under mulch plot was 6.4 × 15 m.

Table 1 | Soil properties

<table>
<thead>
<tr>
<th>Bulk density (g/cm³)</th>
<th>Allowable water (%)</th>
<th>Available nitrogen (mg/kg)</th>
<th>Available phosphorus (mg/kg)</th>
<th>Available potassium (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.46</td>
<td>25.86</td>
<td>134</td>
<td>37</td>
<td>192</td>
</tr>
</tbody>
</table>

The maize was sown on May 1, given the conditions of temperature and moisture. The plant period could be divided into five stages, i.e., VE (emergence), VJ (jointing), VT (tasselling), R2 (filling) and R6 (physiological maturity). The amount of fertilizer was 150 kg/ha according to the experience of experts in Lvyuan district agricultural extension station. In addition, the irrigation scheduling was determined by the upper and lower limits of soil water content, and the irrigation amount was calculated by Equation (1):

$$Q_i = A \times H \times (\theta_{up} - \theta_{low}) \times P/\mu$$

where $\theta_{up}$ and $\theta_{low}$ denote the upper and lower limits of soil water content, respectively; $\theta_{up}$ was taken as 100%, and different values of $\theta_{low}$ were achieved in different treatments. $A$
denotes the plot area (m²), \( H \) represents the designed moisture layer of soil (cm), \( P \) is the percentage of wetting area, and \( \mu \) is the application efficiency.

\[
P = \frac{0.785D_w}{S_eS_i} \times 100\
\]

where \( D_w \) denotes the width of the wet zone; \( S_e \) represents dripper spacing; \( S_i \) is the interval of the drip irrigation tape.

**Soil moisture and fertility**

The soil was collected by an auger and then taken to the laboratory for measurement. The available nitrogen was measured with a K1160 Kjeldahl nitrogen analyzer (Shandong Manon Scientific Instrument Co., Ltd). The available potassium, organic matter and available phosphorus were measured with a ZYD-TF soil nutrient quick tester (Beijing Zhiyunda Technology Co., Ltd). The soil moisture content was identified with TZS-1 K soil moisture probes (Nanjing Tuopu Technology Co., Ltd) every day.

**Measurement of plants**

The measured factors of plants included plant height, stem diameter, leaf area index (LAI), nitrogen quality and dry matter quality at each growth phase. A meter exhibiting a precision of 1 mm was adopted to measure the plant height, and a Vernier caliper exhibiting a precision of 1 mm was employed to measure the stem diameter. The dry matter was measured by the drying method; to be specific, it was dried at 105 °C for 1 h and then at 75 °C for 72 h, weighed and subsequently ground to 0.5 mm. Next, the nitrogen quality of the plant powder was measured with a Kjeldahl nitrogen analyzer. The leaf area was determined by YMJA (Zhejiang Tuopuyun Agricultural Technology Co., Ltd), and the LAI was calculated by:

\[
LAI = \frac{1}{10000} \times \frac{\sum s_i}{s}
\]

where \( \sum s_i \) denotes the sum of the leaf area of a single plant; \( s \) is the area covered per plant.

**Measurements of meteorological factors**

The meteorological data collected in this study included solar radiation, air temperature, wind speed, evaporation and rainfall. In the vicinity of the test area, a watchdog meteorological automatic recorder was installed to automatically collect and record the mentioned meteorological information every 5 min.
Accumulated temperature

The temperature was measured by RS485 soil moisture sensor temperature and humidity probes, which were buried in each plot. The data were collected per 5 min. After the temperature of the soil was determined, the soil accumulated temperature ($T_c$, °C) was calculated by:

$$T_c = \sum (T_{\text{mean}} - T_{\text{base}})$$  \hspace{1cm} (4)

where $T_{\text{base}}$ denotes the base temperature for maize growth (°C). In this study, $T_{\text{base}} = 10$ °C, $T_{\text{mean}}$ represents the daily average soil temperature (°C). When $T_{\text{mean}}$ is less than $T_{\text{base}}$, the negative values should be ignored.

Plant growth and yield measurements

Yield measurement area was selected by $1.3 \times 15$ m for drip irrigation under film mulch cultivation and the rain-fed plot and $3.2 \times 15$ m for HPE drip irrigation under film mulch cultivation. The grain yields were determined according to 12% water content. Other factors were measured as follows.

Ear number: all the production ears in a yield measurement area were counted; ear length: ten representative ears in each plot were taken to measure the ear length by a meter exhibiting a precision of 1 mm; ear diameter: ten representative ears in each plot were taken to measure the ear diameter by a Vernier caliper exhibiting a precision of 1 mm; 100-grain weight: the weight of 100 maize grains was measured five times in each plot, and the average value was taken.

WUE and NUE

Actual evapotranspiration is defined as (El-Hendawy & Schmidhalter 2010; Zhang et al. 2017):

$$ET_c = P + I + C_r - R - D \pm \Delta S$$  \hspace{1cm} (5)

where $ET_c$ denotes the actual evapotranspiration (mm) in the growing season; $I$ represents the amount of irrigation water applied (mm); $P$ is the precipitation (mm); $C_r$ is the capillary rise (mm); $D$ is the percolation (mm); $R$ is the runoff (mm); $\Delta S$ is the change in soil moisture content (mm).

The WUE (kg/m³) is expressed as (Lovelli et al. 2007):

$$WUE = \frac{Y}{ET_c}$$  \hspace{1cm} (6)

where $Y$ denotes the maize yield (kg/ha).

Nitrogen use efficiency (NUE, %) is written as:

$$NUE = \frac{GY_N}{N_{\text{rate}}}$$  \hspace{1cm} (7)

where $GY_N$ represents the grain yield under the application of nitrogen fertilizer.

Economic analysis

Economic return was assessed as follows:

$$Economic (\text{CNY ha}^{-1}) = Grain \text{ yield benefit (CNY ha}^{-1}) - \text{Total cost (CNY ha}^{-1})$$  \hspace{1cm} (8)

$$Grain \text{ yield benefit (CNY ha}^{-1}) = GY \times \text{maize price (CNY kg}^{-1})$$  \hspace{1cm} (9)

$$Total \text{ cost (CNY ha}^{-1}) = \text{land use fee (CNY ha}^{-1}) + \text{machinery operating cost (CNY ha}^{-1}) + \text{irrigation equipment cost (CNY ha}^{-1}) + \text{fertilizer cost (CNY ha}^{-1}) + \text{pesticide cost (CNY ha}^{-1}) + \text{seed cost (CNY ha}^{-1}) + \text{labor cost (CNY ha}^{-1}) + \text{electricity cost (CNY ha}^{-1}) + \text{water cost (CNY ha}^{-1})$$  \hspace{1cm} (10)

Statistical analyses

By variance tests in SPSS 14.0, the data (i.e., yield, yield components, nutrient accumulation, LAI, dry matter accumulation, WUE and NUE) were analyzed. In all cases, the differences were considered statistically significant if $p \leq 0.05$. 
RESULTS

The 100-grain weight was from 30.22 to 35.97 g among all the treatments (Table 4), and a significant difference was identified between black and transparent film mulch in the two drip irrigation methods. The ear diameter ranged from 3.4 to 5 cm among all the treatments (Table 4). The black, transparent and non-film mulch slightly impacted ear diameter. The ear length was from 18.2 to 23.6 cm among all the treatments (Table 4), and a significant difference was identified among black and transparent film mulch in the two drip irrigation methods. The ear number was from 62,443 to 69,934 among all the treatments (Table 4), and the black, transparent and non-film mulch slightly impacted ear number.

Among all the treatments, the yield ranged from 10,624 to 16,302 kg/ha (Table 5), and a significant difference was identified among none, black and transparent film mulch under the two drip irrigation methods. The irrigation water was from 67 to 95.5 mm since the rainfall of 2016 was 317 mm from May to September. The WUE ranged from 26.85 to 36.45 kg/ha/mm, and the color of the film mulch significantly impacted WUE. The NRE was from 70.83 to 108.68 kg/kg, and the color of the film mulch significantly impacted NRE. The maximum yield was 53% higher than RFN.

The LAI ranged from 0.12 to 4.54 (DN), 0.13 to 4.91 (DMT), 0.13 to 4.74 (DMB), 0.12 to 4.48 (HDN), 0.13 to 5.01 (HDMT), 0.14 to 5.01 (HDMB), and 0.11 to 3.56 (RFN) over both growing seasons (Table 6). As indicated from the comparison of DMT, DMB, HDMT and HDMB, the LAI of transparent film was significantly higher than that of black film. Comparing DN, DMT, DMB, HDN, HDMT and HDMB, the film could significantly increase the LAI. In the VE, VJ and VT periods, the growth rate of plant height was the fastest, and then it tended to decrease. The height of plants decreased because of the fragile fracture of stamens after dehydration in the R6 period.

The plant height ranged from 0.2 to 3.11 m (DN), 0.21 to 3.23 m (DMT), 0.13 to 3.18 m (DMB), 0.18 to 3.05 m (HDN), 0.18 to 3.28 m (HDMT), 0.13 to 3.24 m (HDMB), and 0.17 to 2.78 m (RFN) over both growing seasons (Table 7). As indicated from the comparison of DMT, DMB, HDMT and HDMB, the plant height for transparent film was significantly higher than for black film. As suggested from the comparison of DN, DMT, DMB, HDN, HDMT and HDMB, the film could significantly increase the plant height. In the VE and

### Table 4 | The production factors of maize

<table>
<thead>
<tr>
<th>Treatment</th>
<th>100-grain weight (g)</th>
<th>Ear diameter (cm)</th>
<th>Ear length (cm)</th>
<th>Grain number per ear</th>
<th>Ear number (ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DN</td>
<td>33.54c</td>
<td>4.7a</td>
<td>22.7a</td>
<td>612b</td>
<td>69,032a</td>
</tr>
<tr>
<td>DMT</td>
<td>35.97a</td>
<td>4.8a</td>
<td>23.4a</td>
<td>635a</td>
<td>68,973a</td>
</tr>
<tr>
<td>DMB</td>
<td>34.78ab</td>
<td>4.8a</td>
<td>23.6a</td>
<td>643a</td>
<td>70014a</td>
</tr>
<tr>
<td>HDN</td>
<td>33.66c</td>
<td>5a</td>
<td>23.7a</td>
<td>613b</td>
<td>68,974a</td>
</tr>
<tr>
<td>HDMT</td>
<td>35.73a</td>
<td>4.8a</td>
<td>22.2a</td>
<td>658a</td>
<td>69,405a</td>
</tr>
<tr>
<td>HDMB</td>
<td>34.42ab</td>
<td>5a</td>
<td>23.1a</td>
<td>637a</td>
<td>69,934a</td>
</tr>
<tr>
<td>RFN</td>
<td>30.22</td>
<td>3.4</td>
<td>18.2</td>
<td>538</td>
<td>62,443</td>
</tr>
</tbody>
</table>

Note: Statistical analysis according to Duncan’s multiple range test (p < 0.05); the same letters mean no differences between treatments.

### Table 5 | The yield, WUE and NRE

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Yield (kg/ha)</th>
<th>Irrigation (mm)</th>
<th>Effective rainfall (mm)</th>
<th>WUE (kg/ha/mm)</th>
<th>NUE (kg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DN</td>
<td>14,362c</td>
<td>103.7</td>
<td>317</td>
<td>29.93c</td>
<td>95.75c</td>
</tr>
<tr>
<td>DMT</td>
<td>15,982a</td>
<td>74.1</td>
<td>317</td>
<td>35.56a</td>
<td>106.55a</td>
</tr>
<tr>
<td>DMB</td>
<td>15,278b</td>
<td>76.5</td>
<td>317</td>
<td>33.50b</td>
<td>101.85b</td>
</tr>
<tr>
<td>HDN</td>
<td>14,553c</td>
<td>106.9</td>
<td>317</td>
<td>29.89c</td>
<td>97.02c</td>
</tr>
<tr>
<td>HDMT</td>
<td>16,302a</td>
<td>69.8</td>
<td>317</td>
<td>36.45a</td>
<td>108.68a</td>
</tr>
<tr>
<td>HDMB</td>
<td>15,443b</td>
<td>72.3</td>
<td>317</td>
<td>34.17b</td>
<td>102.95b</td>
</tr>
<tr>
<td>RFN</td>
<td>10,624</td>
<td>0</td>
<td>317</td>
<td>26.85</td>
<td>70.83</td>
</tr>
</tbody>
</table>

Note: Statistical analysis according to Duncan’s multiple range test (p < 0.05); the same letters mean no differences between treatments.

### Table 6 | LAI in all growth periods

<table>
<thead>
<tr>
<th>Run</th>
<th>VE</th>
<th>VJ</th>
<th>VT</th>
<th>R2</th>
<th>R6</th>
</tr>
</thead>
<tbody>
<tr>
<td>DN</td>
<td>0.12</td>
<td>2.16</td>
<td>3.77</td>
<td>4.54</td>
<td>3.36</td>
</tr>
<tr>
<td>DMT</td>
<td>0.13</td>
<td>3.17</td>
<td>3.92</td>
<td>4.91</td>
<td>3.46</td>
</tr>
<tr>
<td>DMB</td>
<td>0.13</td>
<td>2.94</td>
<td>3.66</td>
<td>4.74</td>
<td>3.38</td>
</tr>
<tr>
<td>HDN</td>
<td>0.12</td>
<td>2.14</td>
<td>3.85</td>
<td>4.48</td>
<td>3.20</td>
</tr>
<tr>
<td>HDMT</td>
<td>0.14</td>
<td>3.52</td>
<td>4.16</td>
<td>5.01</td>
<td>3.51</td>
</tr>
<tr>
<td>HDMB</td>
<td>0.13</td>
<td>2.93</td>
<td>3.65</td>
<td>4.86</td>
<td>3.49</td>
</tr>
<tr>
<td>RFN</td>
<td>0.11</td>
<td>2.02</td>
<td>2.97</td>
<td>3.56</td>
<td>2.84</td>
</tr>
</tbody>
</table>

Note: Statistical analysis according to Duncan’s multiple range test (p < 0.05); the same letters mean no differences between treatments.
VT periods, the growth rate of LAI was the fastest and then gradually decreased. It peaked at R2 and then decreased again due to dehydration and shrinkage of the leaves.

The TC was calculated by Equation (3), and the TC in the full growth period is illustrated in Figure 3. The TC for transparent film mulch was higher than for the other treatments, and TC are 3,279, 3,554, 3,438, 3,253, 3,602, 3,425, 3,254 at the date of 150 days after sowing, respectively. TC increased slowly in the early stage, at the fastest speed in the middle stage and then gradually in the later stage. On the other hand, the TC will impact the date of the growth stage, and the dates of each stage are listed in Table 8. The period of transparent film mulch will be 6–10 days ahead of non-film mulch treatments.

### Economic analysis

A comparison was drawn in terms of the cost of drip irrigation under mulch and drip irrigation with high photosynthetic efficient cultivation with the conventional rain-fed one (Tables 9 and 10). Fertilizer, land use and pesticide cost were basically the same. The planting densities were 62,500 plant/ha for RNF and DMT, and 61,538 plant/ha for HDMT. As impacted by the larger ridge distance of drip irrigation with high photosynthetic efficient film mulch, less drip irrigation belt and film mulch are required, and the labor cost of installation is also less. For the machine use fee, drip irrigation under film and drip irrigation with high photosynthetic efficient cultivation need conventional ridging, as well as a machine laying drip irrigation belt and field film, so the machine cost is higher than that of the RNF group. Electricity and water charges were calculated from actual consumption. Lastly, the yields of the three planting methods were 27,097 CNY/ha, 33,778 CNY/ha, 35,062 CNY/ha, respectively.

### DISCUSSION

#### WUE and NUE

By comparing the WUE of DN, HDN and RFN (Figure 4), it is revealed that drip irrigation can effectively improve WUE, with an average increase of 13.2%, which agrees with previous studies (Wang et al. 2018; Wu et al. 2019). It is also demonstrated that the mulching group is generally higher than the non-mulching irrigation group, because mulching can effectively reduce additional soil water, thereby improving water use efficiency. This may be caused by film mulch that

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**Table 7 | Plant height in all growth periods (m)**

<table>
<thead>
<tr>
<th>Run</th>
<th>VE</th>
<th>VJ</th>
<th>VT</th>
<th>R2</th>
<th>R6</th>
</tr>
</thead>
<tbody>
<tr>
<td>DN</td>
<td>0.20</td>
<td>1.35</td>
<td>2.77</td>
<td>3.11</td>
<td>3.08</td>
</tr>
<tr>
<td>DMT</td>
<td>0.21</td>
<td>1.47</td>
<td>2.96</td>
<td>3.23</td>
<td>3.20</td>
</tr>
<tr>
<td>DMB</td>
<td>0.13</td>
<td>1.46</td>
<td>2.84</td>
<td>3.18</td>
<td>3.14</td>
</tr>
<tr>
<td>HDN</td>
<td>0.18</td>
<td>1.57</td>
<td>2.82</td>
<td>3.05</td>
<td>2.98</td>
</tr>
<tr>
<td>HDMT</td>
<td>0.18</td>
<td>1.34</td>
<td>3.00</td>
<td>3.28</td>
<td>3.26</td>
</tr>
<tr>
<td>HDMB</td>
<td>0.13</td>
<td>1.62</td>
<td>2.89</td>
<td>3.24</td>
<td>3.12</td>
</tr>
<tr>
<td>RFN</td>
<td>0.17</td>
<td>1.35</td>
<td>2.48</td>
<td>2.78</td>
<td>2.62</td>
</tr>
</tbody>
</table>

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**Figure 3 | The TC over the growth period.**
can more significantly maintain the soil moisture (Wu et al. 2017). It was therefore proved that combined with drip irrigation, the film mulch improved WUE by 23% to 91% (Fan et al. 2015; Bu et al. 2016). The WUE of transparent film was higher than that of black film (Figure 4), and as expressed in Equation (2), the $P$ of high photosynthetic efficient cultivation is smaller by the larger interval of the drip irrigation tape, which is more water-saving than conventional drip irrigation under mulch film. Under a small yield difference, high photosynthetic efficient cultivation with drip irrigation under film mulch is more water-saving, and the WUE is higher.

The NUE of drip irrigation and drip irrigation with film mulch increased significantly more than rain-fed treatment at the identical nitrogen rate (Figure 5). It is consistent with drip irrigation increasing the NUE more than rain-fed (Zhang et al. 2017). The NUE of the film mulching group is higher than that of the non-mulching group, since film mulching can enhance crop growth efficiency and nitrogen utilization efficiency, agreeing with existing studies (Sui et al. 2017). The NUE of the transparent film was higher than that of the black film as the transparent film can raise the temperature and the growth of crops better than black film mulch, thus improving the absorption of nitrogen.

### Different types of film mulch on maize growth

The TC of treatment without film mulch was 3,279, 3,253 and 3,254 °C, respectively, fitting the data given by Hou et al. (2014). The TC in Jilin ranged from 3,149 to 3,513 °C from 2007 to 2012. The TC and yield under transparent mulch

### Table 8 | Dates of the maize development stages in 2016

<table>
<thead>
<tr>
<th>Treatment</th>
<th>VE</th>
<th>VJ</th>
<th>VT</th>
<th>R2</th>
<th>R6</th>
</tr>
</thead>
<tbody>
<tr>
<td>DN</td>
<td>5–17</td>
<td>6–7</td>
<td>7–15</td>
<td>8–2</td>
<td>8–29</td>
</tr>
<tr>
<td>DMT</td>
<td>5–9</td>
<td>5–29</td>
<td>7–5</td>
<td>7–22</td>
<td>8–22</td>
</tr>
<tr>
<td>DMB</td>
<td>5–12</td>
<td>6–1</td>
<td>7–10</td>
<td>7–26</td>
<td>8–24</td>
</tr>
<tr>
<td>HDN</td>
<td>5–16</td>
<td>6–6</td>
<td>7–14</td>
<td>8–2</td>
<td>8–29</td>
</tr>
<tr>
<td>HDMT</td>
<td>5–9</td>
<td>5–28</td>
<td>7–6</td>
<td>7–22</td>
<td>8–22</td>
</tr>
<tr>
<td>HDMB</td>
<td>5–13</td>
<td>6–2</td>
<td>7–11</td>
<td>7–27</td>
<td>8–25</td>
</tr>
<tr>
<td>RFN</td>
<td>5–18</td>
<td>6–7</td>
<td>7–16</td>
<td>8–3</td>
<td>8–30</td>
</tr>
</tbody>
</table>

### Table 9 | Economic analysis of each run (CNY/ha)

<table>
<thead>
<tr>
<th>Run</th>
<th>Economic</th>
<th>Grain yield benefit</th>
<th>Total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>RNF</td>
<td>27,097</td>
<td>31,872</td>
<td>4,775</td>
</tr>
<tr>
<td>DMT</td>
<td>33,778</td>
<td>48,906</td>
<td>15,128</td>
</tr>
<tr>
<td>HDMT</td>
<td>35,062</td>
<td>47,946</td>
<td>12,884</td>
</tr>
</tbody>
</table>

### Table 10 | Total cost of each run (CNY/ha)

<table>
<thead>
<tr>
<th>Run</th>
<th>Land use, fertilizer, pesticide cost</th>
<th>Machinery operating cost</th>
<th>Irrigation equipment cost</th>
<th>Seed cost</th>
<th>Labor cost</th>
<th>Electricity cost</th>
<th>Water cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>RNF</td>
<td>1,250</td>
<td>500</td>
<td>0</td>
<td>2,000</td>
<td>200</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DMT</td>
<td>1,250</td>
<td>1,500</td>
<td>7,000</td>
<td>2,000</td>
<td>1,000</td>
<td>516</td>
<td>1,037</td>
</tr>
<tr>
<td>HDMT</td>
<td>1,250</td>
<td>1,500</td>
<td>5,200</td>
<td>1,970</td>
<td>700</td>
<td>493</td>
<td>916</td>
</tr>
</tbody>
</table>

**Figure 4** | The effect of irrigation amount on yield and WUE.
will increase by 9.6% and 11.7% over those with no mulch, and the TC and yield under black mulch will increase by 5.2% and 6.2% over those with no mulch. The consistent result was presented that the film mulch will significantly increase the TC (Sinha et al. 2019) and every 1 °C increase in the minimum temperatures in May and September leads to an increase in the yield of maize by 303 kg/ha and 284 kg/ha (Chen et al. 2011). Moreover, the rise of accumulated temperature caused the maize growth period to be shortened (Table 8), agreeing with the existing conclusion that the increasing temperature will shorten the growing season of spring maize in NEC (Liu et al. 2015). The regularity of TC under film mulch in NEC could guide the sowing time of maize in which the optimal sowing dates and cultivars are determined by the temperature change (Zhao et al. 2018). From the results, regardless of whether of the accumulated temperature or the output, the transparent film was higher than the black film. Black film exhibited another advantage, that the light transmittance of black film was relatively low, and black film could effectively inhibit the growth of weeds when planting cash crops (Locascio et al. 2005). However, the poor light transmittance also hinders the soil’s exposure to the Sun, causing the relatively slow growth of the accumulated temperature. For maize, however, the weeds hardly grow after spraying pesticide on black film and transparent film. Accordingly, the application of transparent film is recommended.

**The advantage of this method and subsequent work in this field**

Water saving and yield increase have constantly been the major problems facing agriculture, and often they should seek a balance point. Through economic analysis, this study determines that after changing the planting mode, crop yield can be significantly increased, and water consumption is also within the controllable range. Table 9 clearly indicates that high photosynthetic efficient cultivation with drip irrigation under film mulch can significantly improve the economic benefits of maize. On the other hand, the drip pipe system can be reused for many years under the condition of providing maintenance, and the income of the following years will be higher. Moreover, high photosynthetic efficient cultivation with drip irrigation under film mulch can better save water resources (as larger $P$ in Equation (2)). With the increase in ridge spacing, the amount of film mulch and drip pipe used is less than for conventional drip irrigation under mulch, so the pollution and cost are less. Such a planting mode should be more extensively promoted for economic and environmental reasons worldwide.

Subsequently, the crop model has been increasingly used in research to simulate the growth of maize (Dokoohaki et al. 2016; Babel et al. 2019; Jiang et al. 2019). Under the rise of the crop model, modern optimization algorithms can be adopted to solve the optimal management system of maize (Azmathullah et al. 2008; Li et al. 2020). One of the subsequent works is to determine the coupling law of water and fertilizer for crop optimization under this planting mode according to the optimization algorithm combined with the crop model.

**CONCLUSIONS**

By the field experiment, the effect of high light efficiency with drip irrigation under film on yield WUE and NUE was obtained as follows.
(1) The yield of maize was significantly higher compared with conventional drip irrigation under mulch. As demonstrated by the economic analysis, the economic benefit of this mode was higher, and the pollution of field film mulch was less. Moreover, NUE and WUE of this cultivation were higher, so the cultivation mode of high photosynthetic efficient cultivation with drip irrigation under film mulch should be considered in the future as well.

(2) Transparent mulch is more conducive to raising soil temperature than black mulching, and the period of transparent film mulch will be 6–10 days ahead of non-film mulch treatments. The raising of soil temperature will also improve the maize yield, so the use of transparent mulch is preferred in the project of drip irrigation under mulch.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES


Jiang, R., He, W., Zhou, W., Hou, Y., Yang, J. Y. & He, P. 2019 Exploring management strategies to improve maize yield and...


