Evaluating the effects of biodegradable and plastic film mulching on soil temperature in a drip-irrigated field

Ning Chen, Xianyue Li, Jiří Šimůnek, Haibin Shi, Qi Hu, Yuehong Zhang

Article Info

A B S T R A C T

The use of plastic film mulching (PM) has steadily increased in the past few decades due to many advantages compared to no film mulching (NM). However, PM also has many drawbacks, such as producing plastic film residues and causing high temperatures at later crop growth stages. Thus, biodegradable film mulching (BM) has recently been used as an excellent alternative solution. In this study, the effects of three mulching types, including PM, BM, and NM, on soil temperatures ($T_s$) are evaluated using field experiments. Three mulching types with an irrigation depth of 22.5 mm (i.e., PM$_{22.5}$, BM$_{22.5}$, and NM$_{22.5}$) and three irrigation depths of 15, 22.5, and 30 mm with BM (i.e., BM$_{15}$, BM$_{22.5}$, and BM$_{30}$, respectively) were compared. Additionally, the $T_s$ fluctuations and distributions during different crop growth stages were simulated using HYDRUS (2D/3D). The results showed that HYDRUS (2D/3D) successfully simulated $T_s$ with RMSE of 2.11–4.00 °C, EF of 0.63–0.85, and MRE of 8.1%–11.6% during the validation period. There were large differences in $T_s$ among PM$_{22.5}$, BM$_{22.5}$, and NM$_{22.5}$ in different crop growth stages. In the elongation and tasseling stages, $T_s$ under PM$_{22.5}$ and BM$_{22.5}$ was not significantly different but markedly improved compared with NM$_{22.5}$. In the filling and maturation stages, higher variability of $T_s$ was observed under BM$_{22.5}$ compared with PM$_{22.5}$. The standard deviation (SD), the deviation variance ($D^2$), and the kurtosis coefficient ($K$) under BM$_{22.5}$ were by 6.7, 32.6, and 19.3% higher than under PM$_{22.5}$ while accumulated soil temperature (AT) and the ratio of effective accumulated soil temperature ($AET$, $\geq 10$ °C) to AT ($R_T$) decreased by 3.8% and 4.0%, respectively. Additionally, apparent differences in $T_s$ between BM$_{22.5}$ and PM$_{22.5}$ appeared mainly in the soil surface layer (0–10 cm). The area with “optimal $T_s$” (i.e., corn growth is optimal in the $T_s$ range of 20–24 °C) in the 0–30 cm soil layer increased by 33.5% under BM$_{22.5}$ compared with PM$_{22.5}$. Moreover, $T_s$ decreased with an increase in the irrigation depth from BM$_{15}$ to BM$_{22.5}$ and BM$_{30}$, with the maximum size of the “optimal $T_s$” area under BM$_{22.5}$. Generally, BM has more advantages in terms of heat preservation and preventing high temperatures compared with NM and PM, respectively. Therefore, the biodegradable film can be recommended as an alternative material to replace the traditional polyethylene film.

1. Introduction

The use of plastic film mulching (PM) in agriculture has been steadily increasing around the world, including in Germany (Nader et al., 2019), Spain (Mari et al., 2019), and China (Ma et al., 2020). Its objective is to preserve soil water (Lamptey et al., 2019; Ibrahim et al., 2020), improve soil temperature ($T_s$) (Lee and Park, 2020; Gu et al., 2019), and decrease unproductive water consumption (Borrowman et al., 2020). The technology can also significantly improve the seed emergence rate (Liang et al., 2018) and enhance the root physiological activity (Sekhon et al., 2019; Yin et al., 2020), crop yield, and field productivity (Majumder et al., 2018; MacAlister et al., 2020; Yin et al., 2020). However, since the plastic film is mainly made of non-degradable polyethylene materials, its use results in large amounts of plastic film residues in the field, which incur a series of negative impacts on the soil environment and agricultural production (Briassoulis et al., 2015; Li et al., 2020; Hu et al., 2020). Additionally, during later crop growth stages, PM often results in high temperatures, restricting crop growth and yield due to heat stress (Hou et al., 2019; Yin et al., 2020).
et al., 2010; Gu et al., 2017). Compared with the polyethylene film, the biodegradable film made of cellulose and starch can self-degrade by assimilating soil microbes under a suitable C/N ratio (Chiellini et al., 2006) and does not cause any environmental pollution. Moreover, biodegradable film mulching (BM) can also resolve adverse effects of PM, such as poor soil aeration and excessive temperatures during later crop growth stages as a result of its larger disintegration area (Gu et al., 2017; Chen et al., 2019, 2020). For example, Hou et al. (2010) showed a small positive mulching effect when the PM duration was more than 60 days, mainly due to excessive temperatures. Therefore, BM is a promising agricultural technology to replace PM (Souza et al., 2020; Sintim et al., 2020; Borrowman et al., 2020).

Soil heat dynamics under different mulching treatments have been studied in some previous studies. For example, Lee et al. (2018) reported that PM increased mean soil water contents and \( T_s \) by 15–22 % and 1.2–2.7 °C compared with NM, respectively. Gu et al. (2017) analyzed and compared PM and BM’s effects on \( T_s \) and found out that \( T_s \) was significantly lower under BM than PM 150 days after sowing. Additionally, several previous studies have explored the \( T_s \) characteristics under different BM treatments. For instance, Yin et al. (2019) attempted to identify a biodegradable film’s optimal degradation rate, demonstrating that \( T_s \) for the fast and moderate degradation rates was approximately 1.3–2.0 °C lower than for the slow degradation rate. Braunack et al. (2020) studied differences in \( T_s \) under a sprayable biodegradable polymer membrane and oxo-degradable plastic film mulching, showing similar heat phenomena for both materials, closely related to the mulching area.

However, most of these studies focused on field experiments, which are very time-consuming and costly. Therefore, the generalization of these results using a numerical model, as an alternative and low-cost approach, would be highly welcomed. Moreover, numerical models can provide additional details about soil temperature characteristics. Currently, only soil water and soil nitrogen dynamics under BM have been studied using numerical models (e.g., Chen et al., 2019, 2020, respectively). The soil heat transport under BM, as related to surface latent and sensible heat fluxes, especially as a function of the disintegrated area of the biodegradable film, has not yet been studied using numerical models.

In the past decades, several types of numerical models, such as RZ-SHAW (Flerchinger et al., 2000), DNDC (Gilhespy et al., 2014), and HYDRUS (Simunek et al., 2016), have been used to assess the pattern of \( T_s \) in the tillage layer (0–30 cm). However, these models vary widely in terms of statistical accuracy, model efficiency, and modeling parameters. For example, although RZ-SHAW can simulate \( T_s \) in the soil boundary layer, \( T_s \) was overpredicted during an early growing season (Gillette et al., 2017). Poor simulations of \( T_s \) were found for the mulched field using DNDC, since the simulated downward heat flux was reduced by neglecting downward longwave radiation reflected from the plastic film (Zhou et al., 2020). Compared with these models, HYDRUS (2D/3D) considers more processes and factors when modeling \( T_s \). It can capture variations in the soil surface heat flux, \( T_s \) gradients, and soil thermal properties to improve simulation accuracy (Saito et al., 2006). HYDRUS (2D/3D) has been widely used to simulate soil heat dynamics under PM in a drip-irrigated field. For example, Zhao et al. (2018) studied soil heat flow in the ridge cultivation using HYDRUS (2D/3D), illustrating that \( T_s \) under PM was similar to under straw mulching, although daily temperature fluctuations significantly increased. Zhang et al. (2018) evaluated soil water and heat transport for different wetted soil surface areas, finding that \( T_s \) were similar for soil surfaces wetted between 35 % and 75 %. However, similar research on soil heat dynamics under a biodegradable film using HYDRUS (2D/3D) is still lacking, especially concerning the \( T_s \) distribution in the soil profile and \( T_s \) fluctuations during different crop growth stages.

The main objectives of this study thus are 1) to calibrate and validate the HYDRUS (2D/3D) under PM, BM, and NM using measured soil water contents and \( T_s \), 2) to evaluate \( T_s \) under PM, BM, and NM during different crop growth stages, 3) to compare fluctuations of \( T_s \) during different crop growth stages under PM, BM, and NM, and 4) to analyze differences in \( T_s \) distributions in the tillage layer under PM, BM, and NM.

2. Materials and methods

2.1. Field experiment

The experiment was conducted at the Jiuzhuang Water Saving Comprehensive Station, Inner Mongolia, China (40°41′N, 107°18′E). The soil texture at the site was sandy loam. The mean annual precipitation, mean air temperature, and the annual sunshine duration were 138.8 mm, 6.8 °C, and 3230 h, respectively. These factors were classified as a typical warm temperature climate. The soil had in the tillage layer (0–30 cm) a pH of 7.6, the organic matter content of 1.2 %, total nitrogen of 0.093 %, total phosphorus of 0.07 %, total potassium of 1.60 %. Average soil bulk density and field capacity were 1.42 g cm\(^{-3}\) and 0.41 cm\(^{-3}\) within the 0–100 cm soil layer, respectively.

Corn seed was sown on May 1 and 4 and harvested on September 14 and 20 in 2018 and 2019, respectively. The crop rows, crop spacing, and seed rate were 50 cm, 30 cm, and 66,700 viable seeds ha\(^{-1}\), respectively. A conventional flat planning system was adopted in all experimental plots. The experiment was a completely random design, comprising three replicates of five treatments, i.e., 15 field plots. Each plot was 20 m wide and 4 m long, separated by a 1 m wide bar. There were three types of mulching treatments, including plastic film mulching (PM\(_{22.5}\), made of polyethylene), biodegradable film mulching (BM\(_{22.5}\), made of corn starch, polycaprolactone, and masterbatch in a 30:65:5 ratio), and no film mulching (NM\(_{22.5}\)), with a local recommended irrigation depth of 22.5 mm (80 % of field capacity). The width and thickness of the plastic film (manufactured by Linhe Tianbao Environmental Protection Technology Co., Ltd.) and biodegradable film (manufactured by Shandong Tianzhuang Environmental Protection Technology Co., Ltd.) were 80 cm and 0.008 mm, respectively. Additionally, the local recommended irrigation depth was either increased or decreased by 7.5 mm (85 % or 75 % of field capacity) for BM, leading to the BM\(_{30}\) (30 mm) and BM\(_{15}\) (15 mm) scenarios, respectively. Irrigation was applied to each plot when the soil water content was less than 65 % of field capacity (0.27 cm\(^{-3}\)), and 10 and 9 irrigation events were used in 2018 and 2019, respectively. Surface water with an average temperature of 21.6 °C was used for irrigation during the crop growing season. One drip line with a 30 cm emitter spacing and an irrigation rate of 2.4 L h\(^{-1}\) was placed in the middle of two cornrows using an automatic sowing-mulching-fertilization machine. Before sowing, each plot was fertilized with 50 kg ha\(^{-1}\) of urea, 100 kg ha\(^{-1}\) of (NH\(_4\))\(_2\)HPO\(_4\), and 100 kg ha\(^{-1}\) of K\(_2\)O as basal fertilizer. Moreover, 210 kg ha\(^{-1}\) of the Carbamide solution (CO(NH\(_2\))\(_2\), N ≥ 32 %) as topdressing was mixed with irrigation water and applied to each plot in the elongation stage (63 kg ha\(^{-1}\)), the tasseling stage (84 kg ha\(^{-1}\)), and the filling stage (63 kg ha\(^{-1}\)). Sowing, mulching, and basal-fertilizer application were carried using an automatic sowing-mulching-fertilization machine.

2.2. Measurements and methods

2.2.1. Meteorological data

Daily precipitation, solar radiation, air temperatures, and wind speed were measured in the experimental field using the automatic meteorological station (Onset Computer Inc.; U30, Hobo, USA) at a one-hour interval, and the 24-h statistics (averages) were computed (Fig. 1).
2.2.2. Soil water content and soil temperature

Two TDR probes were installed in each plot in the middle of two cornrows and under the bare area for measuring soil water contents (SWC). Horizontal distances between TDR probes in the mulched area and the crop row, drip line, and mulching boundary were about 24 cm, 1 cm, and 39 cm, respectively, while corresponding distances in the bare area were 25 cm, 50 cm, and 10 cm, respectively. SWCs were taken once every 5–7 days at soil depths of 0–20, 20–40, 40–60, 60–80, and 80–100 cm, and these data were verified by gravimetric measurements using a soil auger (Beijing New Landmark Soil Equipment Co., Ltd., 0301, XDB, CHN). Soil temperatures ($T_s$) were measured in the tillage layer (0–30 cm) using thermocouples (Beijing Huize Agriculture Technologies Inc., HZR-8 T, CHN) every 2 h at soil depths of 5, 15, and 25 cm. The horizontal position of thermocouple probes was consistent with TDR probes. Additionally, soil temperatures were averaged every 24 h.

2.2.3. Soil evaporation

Since plastic film mulching can entirely cut off water vapor flow between the soil surface and atmosphere, soil evaporation from the soil under plastic film mulching was neglected in this study, similarly as in many other studies (e.g., Li et al., 2013; Saglam et al., 2017). Soil evaporation from the soil under biodegradable film mulching and bare soil was determined using cylindrical micro-lysimeters with and without a biodegradable film, respectively. Micro-lysimeters with the biodegradable film had a similar disintegrated area as in the field (Wu et al., 2017). The installed micro-lysimeters had a diameter of 11 cm and a height of 20 cm. Micro-lysimeters were weighed twice daily at 8:00 and 17:00 using an electronic scale with a precision of 0.01 g. Micro-lysimeters were reinstalled after irrigation or precipitation to ensure measurement precision.

2.2.4. Corn leaf area and height

Five plants from each plot were chosen to determine the corn leaf area and plant height (using a tape with a precision of 0.1 cm) once every 7–15 days. The leaf area index (LAI) was calculated using the FAO method (Allen et al., 1998).

2.2.5. Disintegrated area of the biodegradable film

A digital camera (Canon EOS Rebel T3, Japan) was used to take photos of the biodegradable film’s disintegrated area under daylight from a distance of about 25 cm between the camera and the film’s surface once every 20 days (Chen et al., 2019). Images were processed using a geometric correction and a background subtraction, and the average disintegrated area was calculated using the Auto CAD 2020 software (Autodesk Inc., USA).

2.2.6. Radiative properties of the plastic film, biodegradable film, and bare soil

The reflectivity and transmissivity of mulch materials were determined using a spectrophotometer (PerkinElmer model 402, USA) at normal incidence (Liakatas et al., 1986). The mulch emissivities for thermal radiation were measured according to Fuchs and Tanner (1966). Radiative properties of the plastic film, biodegradable film, and bare soil are summarized in Table 1.

2.2.7. Groundwater table and its temperature at the experimental site

A pressure transducer (Onset Computer Inc.; U20, Hobo, USA), installed in the observation well 3 m deep with a 5 cm internal diameter, was used to measure the groundwater table depth and its temperature at the experimental site. Data were averaged and recorded at one-day intervals and stored in a datalogger, from which they were automatically downloaded.

2.3. Calculations of soil temperature

Two indices were used to evaluate differences in $T_s$ fluctuations and “heat preservation” among different mulched fields, i.e., an average increase ($T_u$) and decrease ($T_d$) in daily temperatures (Han et al., 2018). $T_u$ and $T_d$ were used to assess increasing and decreasing trends in soil temperature in the tillage layer, respectively:

$$T_u = \frac{1}{m_1} \sum_{i=1}^{n-1} \max(T_{s,i} - T_s, 0)$$

$$T_d = \frac{1}{m_2} \sum_{i=1}^{n-1} \min(T_{s,i+1} - T_s, 0)$$

$$n - 1 = m_1 + m_2$$

where $T_s$ is the average daily temperature ($^\circ$C), $T_u$ is an average increase in temperature on days with increasing temperature ($^\circ$C), $T_d$ is an average decrease in temperature on days with decreasing temperature.

---

Table 1: Measured radiation properties of the plastic film, biodegradable film, and bare soil for wavelengths between 0.3 and 50 μm.

<table>
<thead>
<tr>
<th>Property</th>
<th>Radiation</th>
<th>Plastic film</th>
<th>Biodegradable film</th>
<th>Bare soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflectivity</td>
<td>Short wave (0.3–2.5 μm)</td>
<td>0.28</td>
<td>0.25</td>
<td>0.15 (wet)</td>
</tr>
<tr>
<td></td>
<td>Long wave (2.5–50 μm)</td>
<td>0.02</td>
<td>0.01</td>
<td>0.26 (dry)</td>
</tr>
<tr>
<td>Transmissivity</td>
<td>Long wave (2.5–50 μm)</td>
<td>0.81</td>
<td>0.76</td>
<td>1</td>
</tr>
<tr>
<td>Emissivity</td>
<td></td>
<td>0.97</td>
<td>0.96</td>
<td>1</td>
</tr>
</tbody>
</table>

---

Fig. 1. Precipitations, groundwater table depths, and relative humidities at the experimental site during the crop growth seasons of 2018 (left) and 2019 (right).
(°C), n is the total number of data points, \( m_1 \) is the total number of days with increasing temperatures (i.e., positive values of \( T_{1-1-T_1} \)), and \( m_2 \) is the total number of days with decreasing temperatures (i.e., negative values of \( T_{1-1-T_1} \)).

2.4. Numerical simulation

2.4.1. Soil water flow and heat transport

Soil water contents and soil temperatures under BM, PM, and NM during both years were simulated using HYDRUS (2D/3D) (Simunek et al., 2016). The model is a multi-purpose finite-element model developed to simulate the movement of water, solutes, and heat in variably-saturated porous media under various irregular and complex boundary conditions. A modified form of the Richards equation was used in HYDRUS (2D/3D) as follows:

\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i} \left[ K_s(\theta) \frac{\partial h}{\partial x_i} \right] + K_c - S(h)
\]  

(4)

where \( \theta \) is the volumetric water content (cm\(^3\) cm\(^{-3}\)), \( h \) is the pressure head (cm), \( K \) is the unsaturated hydraulic conductivity (cm day\(^{-1}\)), \( t \) is time (day), \( S \) is the root water uptake term (cm\(^3\) cm\(^{-3}\) day\(^{-1}\)), \( x \) is the x-axis, and \( z \) is the vertical coordinate. The root water uptake term, \( S \), is affected by the potential uptake rate, \( T_p \), and the water stress factor, \( a \) (Feddes et al., 1978):

\[
S(h) = a(h) - b(s,z) - L - T_p
\]  

(5)

where \( a(h) \) is a dimensionless function of the soil water pressure head, \( T_p \) is the potential transpiration rate (cm day\(^{-1}\)), \( L \) is the surface length associated with transpiration (cm), and \( b(s,z) \) is the normalized root water uptake distribution (cm\(^2\)).

The two-dimensional heat transport equation, ignoring the effect of water vapor, is as follows:

\[
\frac{\partial C(\theta) T}{\partial t} + \frac{\partial}{\partial x} \left[ C_s(\theta) \frac{\partial T}{\partial x} \right] + C_t(\theta) = \frac{10}{l} Q
\]  

(6)

where \( C(\theta) \) and \( C_s(\theta) \) are the volumetric heat capacities of soil and water (J cm\(^{-3}\) °C\(^{-1}\)), respectively, \( \lambda(\theta) \) is the soil apparent thermal conductivity (W cm\(^{-1}\) °C\(^{-1}\)), \( T \) is the temperature (°C), and \( q \) is the water flux (cm day\(^{-1}\)). \( C(\theta) \) was calculated using the following equation (Hillel, 1998):

\[
C(\theta) = (2 \times 10^6 BD/2.65) + 4.2 \times 10^3 \theta + 2.5 \times 10^6 f_0
\]  

(7)

where \( BD \) is the bulk density (mg cm\(^{-3}\)), and \( f_0 \) is the volumetric soil organic matter fraction (cm\(^3\) cm\(^{-3}\)). The soil apparent thermal conductivity, \( \lambda(\theta) \), was calculated as follows:

\[
\lambda(\theta) = \lambda_L C_s |q| \delta_x + (\lambda_L - \lambda_T) C_s \frac{q |q|}{|q|} + \lambda_0(\theta) \delta_x
\]  

(8)

where \( \lambda_L \) and \( \lambda_T \) are the longitudinal and transverse thermal dispersivities (cm), respectively, \( \delta_x \) is the Kronecker delta, and \( \lambda_0(\theta) \) is the thermal conductivity (W cm\(^{-1}\) °C\(^{-1}\)) that can be obtained by Chung and Horton (1987):

\[
\lambda_0(\theta) = b_1 + b_2 + b_3 \theta^{0.5}
\]  

(9)

where \( b_1, b_2, \) and \( b_3 \) are empirical parameters (W cm\(^{-1}\) °C\(^{-1}\)).

2.4.2. Soil hydraulic functions, thermal parameters, and time-variable boundary parameters

The soil profile was divided into three layers (0–20, 20–40, and 40–100 cm soil depths). Soil hydraulic parameters for different soil layers were first estimated using the Rosetta software package (Schaap et al., 2001) from the soil textural information and the bulk density (Table 2). Selected soil hydraulic parameters (the empirical shape parameters \( a \) and \( n \), and the saturated hydraulic conductivity \( K_s \)) were then adjusted using a Marquart-Levenberg-type parameter optimization algorithm in HYDRUS (2D/3D) (Table 2). The thermal parameters (\( b_1, b_2, \) and \( b_3 \)) were simultaneously optimized using observed SWCs and \( T_r \) for different mulching treatments at different soil depths (5, 10, 15, and 30 cm) during the entire crop growth season.

The model requires daily rainfall, potential soil evaporation (\( E_p \)), potential crop transpiration (\( T_p \)), and emitter fluxes as inputs to define the upper boundary condition. Daily precipitation data measured at the automatic meteorological station was used. Potential evapotranspiration (\( ET_p \)) was calculated using the Penman-Monteith equation (Allen et al., 1998). \( E_p \) and \( T_p \) can be obtained as a fraction of \( ET_p \) (Campbell and Norman, 1989):

\[
E_p = \exp(-kLAI) / ET_p
\]  

(10)

\[
T_p = |1 - \exp(-kLAI)| / ET_p
\]  

(11)

where \( k \) is the extinction coefficient of the crop canopy, and \( LAI \) is the leaf area index.

Assuming that evaporation (\( E_p \)) does not occur from the area with non-disintegrated biodegradable film, the surface flux (\( q_s \)) was applied as a time-variable flux (\( q \)) boundary condition on a 10 cm long boundary (in daily intervals) (Chen et al., 2020):

\[
q = Q / L'
\]  

(13)

\[
Q = 1000 \times q_s / l
\]  

(14)

where \( q \) is the boundary water flux (cm d\(^{-1}\)), \( Q \) is the amount of water applied by the emitter during one day (cm\(^2\) d\(^{-1}\)), \( L' \) is the boundary width with the time-variable flux boundary condition (cm), \( q_s \) is the emitter flux rate (L h\(^{-1}\)), \( l \) is the irrigation duration (h) (less than 24 h), 1000 is a unit conversion constant, and 1 represents the scale transformation factor from three-dimensions to two-dimensions (cm). The length of the time-variable flux boundary condition was assumed to be the same for different irrigation depths. The difference between different irrigation depths was mainly reflected in different boundary water fluxes (\( q \)).

Table 2

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Soil particle size distributions</th>
<th>Bulk density</th>
<th>( \theta_0 )</th>
<th>( \theta_r )</th>
<th>( a )</th>
<th>( n )</th>
<th>( K_s )</th>
<th>( l )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–20</td>
<td>Clay: 4.5%, Silt: 88.4%, Sand: 7.1%</td>
<td>1.28</td>
<td>0.057</td>
<td>0.459</td>
<td>1.69</td>
<td>69.4</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>20–40</td>
<td>Clay: 4.4%, Silt: 88.2%, Sand: 7.4%</td>
<td>1.60</td>
<td>0.053</td>
<td>0.429</td>
<td>1.65</td>
<td>46.5</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>40–100</td>
<td>Clay: 3.1%, Silt: 89.3%, Sand: 7.6%</td>
<td>1.39</td>
<td>0.044</td>
<td>0.385</td>
<td>0.09</td>
<td>1.58</td>
<td>24.4</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Additionally, heat fluxes in the mulched region and the bare area for heat transport simulations were obtained from the energy balance equations:

\[ R_n - H_n - LE_n - G_n = 0 \]  
\[ R_b - H_b - LE_b - G_b = 0 \]

(15)  
(16)

where \( R_n \) is the net radiation received by the soil (W m\(^{-2}\)), \( H_n \) and \( H_b \) are the sensible heat flux densities in the mulched region and bare area (W m\(^{-2}\)), respectively, \( L \) is the latent heat of vaporization (equal to 2.45 MJ kg\(^{-1}\)), \( E_m \) and \( E_b \) are the evaporation rates in the mulched region and bare area (kg m\(^{-2}\) s\(^{-1}\)), respectively, which were measured using a microlysimeter, and \( G_m \) and \( G_b \) are the surface heat flux densities in the mulched region and bare area (W m\(^{-2}\)), respectively.

\( R_n \) can be calculated using the following equation (Liaketas et al., 1986):

\[ R_n = (1 - \rho) S + L_n \]

(16)

where \( \rho \) is the reflection coefficient of the soil, \( S \) is the flux density of net solar radiation on a horizontal surface under the canopy, which was measured using a tube net radiometer mounted 40 cm above the mulch (Biscoe et al., 1974), and \( L_n \) is net thermal radiation received by the soil beneath a mulch, which can be obtained using the following equation (Liaketas et al., 1986):

\[ L_n = \tau L_d + \epsilon_n \sigma T_n^4 - \sigma T_s^4 \]

(17)

where \( \tau \) is the transmission coefficient of the mulch for thermal radiation, \( L_d \) is the incident flux of solar radiation (W m\(^{-2}\)) measured using a LICOR radiometer installed in 40 cm above the mulch (Tripathi and Katiyar, 1984), \( \epsilon_m \) is the emissivity of the mulch, \( \sigma \) is the Stefan-Boltzmann constant (56.7 \times 10\(^{-9}\) Wm\(^{-2}\) K\(^{-4}\)), and \( T_m \) and \( T_s \) are the mean temperatures of the mulch and the soil, respectively.

The surface heat flux densities were computed using the following equation (Rai et al., 2019):

\[ G_m = \frac{dT_m}{dZ} \]

\[ G_b = \lambda \frac{dT_s}{dZ} \]

(18)  
(19)

where \( \frac{dT_m}{dZ} \) and \( \frac{dT_s}{dZ} \) are the temperature gradients in the mulched region and bare area, respectively, and \( \lambda \) is the thermal conductivity (W cm\(^{-1}\) C\(^{-1}\)).

2.4.3. Initial and boundary conditions

The SWCs (in the 0–100 cm soil layer) and \( T_s \) (in the 0–30 cm soil layer) measured at the beginning of the simulation period were taken as the initial conditions. The time-variable pressure head boundary condition was specified at the bottom of the flow domain (Fig. 2). The no-flow boundary condition was prescribed on the left and right sides of the domain. Additionally, there are three types of upper boundary conditions for the BM, PM, and NM treatments. First, the Time-Variable Flux boundary condition was applied in the mulched area of the BM treatments to represent biodegradable film’s disintegration. Second, the No-flow boundary condition was applied in the mulched area of the PM treatment. Third, the Atmospheric boundary condition was applied in the bare area of the BM and PM treatments and the entire upper boundary of the NM treatment.

The third-type boundary condition (for heat transport) was used on the upper boundary for the BM and NM treatments. Additionally, the third-type boundary condition was also applied in the emitter part and on the bare area for the PM treatment to represent the actual heat flux in the mulched and bare areas. However, the first-type boundary condition was applied in the mulched area of the PM scenario since this boundary had a no-flow boundary condition for water flow.

2.5. Statistical analysis

The model efficiency was evaluated using the root mean square error (RMSE), the modeling efficiency (EF), and the mean relative error (MRE):

\[ RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (S_i - O_i)^2} \]

\[ EF = 1 - \frac{\sum_{i=1}^{n} (S_i - O_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2} \]

\[ MRE = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{S_i - O_i}{O_i} \right| \times 100\% \]

(20)  
(21)  
(22)

where \( S \) is the simulated value, \( M \) is the observed value, \( i \) is the observation data point, and \( n \) is the number of measurements.

3. Results

3.1. Efficiency of HYDRUS (2D/3D) to simulate soil temperature

In this study, the measured SWC and \( T_s \) (average daily values) data from different treatments and different soil depths in 2018 were used to calibrate the soil hydraulic and heat transport parameters. The
Table 3
Statistical results for soil water contents (SWC) in 0-20, 20-40, 40-100 cm and soil temperatures ($T_s$) at 5, 15, and 25 cm soil depths under plastic film mulching (PM$_{22.5}$), biodegradable film mulching (BM$_{22.5}$), and no film mulching (NM$_{22.5}$), with an irrigation depth of 22.5 mm, and biodegradable film mulching with an irrigation depth of 30 (BM$_{30}$) and 15 (BM$_{15}$) mm during 2018 (calibration) and 2019 (validation). RMSE - root mean square error, EF - modeling efficiency, MRE - mean relative error.

<table>
<thead>
<tr>
<th>Year</th>
<th>Depth (cm)</th>
<th>SWC 0-20</th>
<th>PM$_{22.5}$ 0-20</th>
<th>NM$_{22.5}$ 0-20</th>
<th>BM$_{30}$ 0-20</th>
<th>BM$_{15}$ 0-20</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RMSE (cm$^3$cm$^{-3}$)</td>
<td>EF (%)</td>
<td>MRE (%)</td>
<td>RMSE (cm$^3$cm$^{-3}$)</td>
<td>EF (%)</td>
</tr>
<tr>
<td>2018</td>
<td>0-20</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>40-100</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3.07</td>
<td>0.82</td>
<td>9.3</td>
<td>2.73</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>1.97</td>
<td>0.88</td>
<td>7.7</td>
<td>2.04</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>2.44</td>
<td>0.80</td>
<td>8.8</td>
<td>1.86</td>
<td>0.89</td>
</tr>
<tr>
<td>2019</td>
<td>0-20</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>40-100</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3.44</td>
<td>0.73</td>
<td>10.4</td>
<td>3.34</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>2.57</td>
<td>0.81</td>
<td>8.7</td>
<td>2.64</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Fig. 3. Simulated (line) and observed (dots) daily soil temperatures in the 5 (top), 15 (middle), and 25 (bottom) cm soil depths under plastic film mulching (PM$_{22.5}$), biodegradable film mulching (BM$_{22.5}$), and no film mulching (NM$_{22.5}$) with an irrigation depth of 22.5 mm, and biodegradable film mulching with irrigation depths of 30 (BM$_{30}$) and 15 (BM$_{15}$) mm in a) 2018 (calibration) and b) 2019 (validation).
corresponding 2019 data were used to validate the model (Table 2). The results showed that the range of RMSE, EF, and MRE values in the calibration period for BM22.5, PM22.5, NM22.5, BM30, and BM15 were 0.01–0.03 cm³ cm⁻³, 0.76–0.93, and 4.6 %–10.7 %, respectively, for SWCs, while they were 1.86–4.13 °C, 0.69–0.89, and 7.4 %–12.6 %, respectively, for \( T_s \) (Table 3). In the validation period, the corresponding statistical parameters were 0.02–0.04 cm³ cm⁻³, 0.70–0.85, and 8.2 %–13.2 %, respectively, for SWCs, while they were 2.11–4.00 °C, 0.63–0.85, and 8.1 %–11.6 %, respectively, for \( T_s \). Among different mulching treatments, the PM22.5 scenario had the highest simulation accuracy with RMSE of 0.02–0.03 cm³ cm⁻³ (the range of values refers to multiple depths), EF of 0.70–0.89, and MRE of 7.9 %–9.1 % for SWCs, and RMSE of 1.86–3.34 °C, EF of 0.63–0.89, and MRE of 7.4 %–11.3 % for \( T_s \). Additionally, the visual inspection was used to assess the correspondence between simulated and measured daily \( T_s \) values for different mulching and irrigation treatments (Figs. 3 and 4). The correspondence between simulated and measured values significantly improved with increasing soil depth. Generally, HYDRUS (2D/3D) could well capture the soil heat flux dynamics.

### 3.2. Daily and diurnal fluctuations of soil temperatures under PM, BM, and NM

A significant difference was found in surface \( T_s \) (5 cm) between the PM, BM, and NM treatments with different mulching areas. In general, the lowest seasonal average surface \( T_s \) of 30.5 and 26.6 °C occurred in NM22.5 in 2018 and 2019, respectively, which was 2.2 and 4.7 °C lower than in PM22.5, and 2.5 and 4.2 °C lower than in BM22.5, respectively. The lowest average \( T_s \) of 25.6 °C appeared in BM30 during the entire crop growth season (Fig. 3), decreasing by 0.4 and 1.6 °C compared with the BM22.5 and BM15 treatments, respectively. Additionally, there were significant spatio-temporal differences in \( T_s \) for different treatments in different hydrological years. In 2018 (a wet year), the \( T_s \) variation had a downward parabola shape during the crop growing season with the maximum values during DAS 60–100. However, in 2019 (a dry year), the \( T_s \) variations showed a logarithmic, linear tendency, i.e., \( T_s \) was high during early crop growth stages while it was low during late crop growth stages.

To further capture diurnal fluctuations of \( T_s \), three consecutive days after irrigation in the early (DAS 28–30 in 2018 and DAS 31–33 in 2019) and late (DAS 120–122 in 2018 and DAS 108–110 in 2019) crop growth stages were chosen (Fig. 4). In the early crop growth stages, diurnal \( T_s \) fluctuations at different soil depths under BM and PM were very similar. In the late crop growth stages, significant differences in diurnal \( T_s \) fluctuations occurred under BM and PM, especially at the 5 cm soil depth. \( T_s \) at nighttime under BM was 2.8 % and 2.1 % lower than under PM in 2018 and 2019, respectively, but it was similar in the daytime. The largest variations of diurnal \( T_s \) among different mulching treatments occurred in the NM treatment. During the daytime, average soil temperatures \( T_s \) at the 5 cm soil depth under NM were 4.8 % and 5.3 % higher than under BM and PM, respectively, while they were 37.0 % and 38.7 % lower during nighttime. Additionally, differences in diurnal \( T_s \) fluctuations among NM, BM, and PM decreased as the soil depth increased. Diurnal \( T_s \) fluctuations were almost the same for different irrigation depth treatments (Fig. 4), i.e., the highest \( T_s \) value occurred at 2:00–3:00 pm while the lowest \( T_s \) value occurred at 5:00–6:00 am.

### 3.3. Soil temperatures under PM, BM, and NM

Interactions between the soil surface and atmosphere are different for different types of mulches, resulting in different vapor transport and SWCs. Furthermore, the soil thermal properties, such as \( C(0) \) and \( \lambda(\theta) \), will also be different due to variations in SWCs during the crop growing season. During the elongation and tasseling stages, temperatures \( T_c \) under two film mulching treatments (PM) (i.e., PM22.5 and BM22.5) were not significantly different, but markedly improved and stabilized.
compared to the NM22.5 treatment (Table 4). The average $T_1$ ($T_{\text{avg}}$) under BM22.5 and PM22.5 were 27.9 and 28.2 °C, respectively, increasing by 1.09 and 1.43 °C compared with NM22.5. Moreover, the standard deviation (SD) and deviation variance (DV) under BM22.5 were 2.23 and 4.51, respectively, decreasing by 30.0 % and 52.9 % compared with NM22.5, the corresponding parameters (i.e., SD and DV) under PM22.5 were 2.33 and 4.86, respectively, which was 27.0 % and 49.2 % lower than under NM22.5. The maximum temperature range $T_{\text{range}}$ (i.e., the difference between the maximum and minimum values) of 12.3 °C occurred in NM22.5, with the kurtosis coefficient (K) of -0.73. During the filling and maturation stages, BM22.5 resulted in higher variability of $T_1$ values than in PM22.5. The SD, DV, and K values for BM22.5 were 6.7 %, 32.6 %, and 19.3 % higher than for PM22.5, respectively, while accumulated soil temperature (AT) and the ratio of effective accumulated soil temperature (AT, $T_{\text{avg}}$) under BM22.5 increased by 7.6 %, 28.1 %, and 3.6 %, respectively, and $T_{\text{range}}$ increased by 0.1–1.4 °C. However, there are apparent differences in $T_{\text{avg}}$ during the filling and maturation stages in both years due to different air relative humidities. $T_{\text{avg}}$ under NM22.5 in 2018 increased by 0.8 °C compared with FM, while $T_{\text{avg}}$ under BM22.5 in 2019 was 2.1 °C lower than under FM. The high relative humidity increased heat losses for NM22.5 in 2019 (Fig. 1).

There is an inverse relationship between $T_1$ and the irrigation depth under the same mulching treatment. When the irrigation depth was 30 mm (BM30), higher by 7.5 mm than 22.5 mm (BM22.5), the AT, AET, and $T_{\text{avg}}$ values decreased by 17.3 °C, 9.0 °C, and 0.81 °C, respectively. Meanwhile, SD and DV increased by 1.4 % and 2.2 % compared with BM22.5, respectively, but $R_1$ and K were not significantly different. When the irrigation depth was 15 mm (BM15), lower by 7.5 mm than 22.5 mm (BM22.5), the AT, AET, and $T_{\text{avg}}$ Values increased by 43.0 °C, 20.2 °C, and 0.78 °C, respectively. SD, DV, and K decreased by 1.4 %, 7.4 %, and 2.2 %, respectively, and $R_1$ was about the same.

### 3.4. Seasonal fluctuations of soil temperatures under PM, BM, and NM

To capture differences in soil temperatures $T_1$ among the PM, BM, and NM treatments in the tillage layer, the two indices (see Section 2.3)
were adopted in this study, i.e., an average temperature increase on days with increasing temperature ($T_u$) and an average temperature decrease on days with decreasing temperature ($T_d$). The largest difference in $T_u$ between BM$_{22.5}$ and PM$_{22.5}$ occurred in the soil surface layer (5 cm), especially in the later crop growth stages (Fig. 5). $T_u$ in BM$_{22.5}$ was 0.53 °C lower than in PM$_{22.5}$, while $T_d$ increased by 0.12 °C compared with PM$_{22.5}$. Seasonal fluctuations of $T_u$ decreased with an increase in the soil depth for FM. In the 15 cm soil depth, $T_u$ was higher by 0.13 °C under BM$_{22.5}$ compared with PM$_{22.5}$, but $T_d$ was lower by 0.14 °C. In the 25 cm soil depth, $T_u$ increased by 0.10 °C under BM$_{22.5}$ compared with PM$_{22.5}$, while $T_d$ decreased 0.04 °C, respectively. Seasonal fluctuations of $T_u$ under NM$_{22.5}$ were more intensive since they were easily affected by air temperature and humidity. On the other hand, significant differences in $T_d$ fluctuations between BM$_{22.5}$ and PM$_{22.5}$ appeared only in the soil surface layer and during later crop growth stages.

The soil temperature $T_s$ in the surface soil was also markedly affected by SWC. When the irrigation depth was increased to 30 mm (BM$_{30}$), and $T_u$ and $T_d$ increased by 0.03 °C and 0.10 °C compared with BM$_{22.5}$, respectively. Moreover, $T_u$ and $T_d$ decreased by 0.13 °C and 0.05 °C, respectively, for BM$_{15}$ (an irrigation depth of 15 mm) compared with BM$_{22.5}$. However, there were no obvious differences in $T_s$ fluctuations among treatments with different irrigation depths in the 15 and 25 cm soil depths.

3.5. Two-dimensional $T_s$ distributions under PM, BM, and NM

Two-dimensional daily average $T_s$ values in the tillage layer under different mulching and irrigation scenarios were compared on DAS 38 (one day before irrigation), DAS 40 (one day after irrigation), DAS 118 (one day before irrigation), and DAS 120 (one day after irrigation) in 2018 (Fig. 6). The two-dimensional $T_s$ distributions were similar for BM$_{22.5}$ and PM$_{22.5}$ on DAS 38 and DAS 40, but the “optimal $T_s$” (i.e., 20–24 °C) (Yan and Tu, 2003) area under FM was markedly larger compared with NM$_{22.5}$. Differences in $T_s$ distributions for different mulching scenarios occurred mainly in the 0–10 cm soil layer and increased with time. On DAS 118, the “optimal $T_s$” areas under NM$_{22.5}$ and BM$_{22.5}$ were 256.08 and 66.48 cm$^2$, respectively, which represented an increase of 82.7 % and 33.5 % compared with PM$_{22.5}$, respectively. However, the areas with “relatively high $T_s$” (i.e., $T_s$ ≥ 25 °C) were 46.5 % and 4.9 % lower for NM$_{22.5}$ and BM$_{22.5}$, respectively, than for PM$_{22.5}$. On the other hand, the areas with “relatively low $T_s$” (i.e., $T_s$ < 19 °C) were the same (all were zero). After irrigation (DAS 120), the $T_s$ distribution in the 0–10 cm soil layer was visibly uneven regardless of the treatment. The areas with “optimal $T_s$” under BM$_{22.5}$, PM$_{22.5}$, and NM$_{22.5}$ accounted for 14.0 %, 10.9 %, and 28.8 % of the tillage layer, respectively. Generally, BM effectively regulated soil temperature in an optimal range for crop growth, and the biodegradable film can thus be recommended as an alternative material to replace the traditional polyethylene film.

Fig. 5. $T_u$ and $T_d$ in the 5 (top), 15 (middle), and 25 (bottom) cm soil depths during the elongation, tasseling, filling, and maturation stages in 2018 (left) and 2019 (right) under plastic film mulching (PM$_{22.5}$), biodegradable film mulching (BM$_{22.5}$), and no film mulch (NM$_{22.5}$) with an irrigation depth of 22.5 mm, and biodegradable film mulching with an irrigation depth of 30 (BM$_{30}$) and 15 (BM$_{15}$) mm. $T_u$ - an average temperature increase on days with increasing temperature, $T_d$ - an average temperature decrease on days with decreasing temperature.
When the irrigation depth was increased to 30 mm, the “relatively low” area increased by 53.5 %, while the “optimal” area decreased by 47.2 %. The “relatively high” areas remained the same for all scenarios. Additionally, when the irrigation depth decreased to 15 mm, the areas with “relatively low” and “optimal” decreased by 70.1 % and 16.3 %, respectively, while the area with “relatively high” increased by 37.9 %.

4. Discussions

4.1. Model evaluation

The HYDRUS model has been widely used in agricultural sciences due to its flexible boundary conditions, high simulation accuracy, and user-friendly interface (Sahaar and Niemann, 2020; Fishkis et al., 2020; Fernandez-Bou et al., 2020) to simulate soil water contents (Elliott and price, 2019), soil salinities (Phogat et al., 2020), and soil nitrogen (Chen et al., 2020). Much less research has been published, in which HYDRUS was used to simulate soil temperatures $T_s$. HYDRUS can solve the partial differential equation proposed by Philip and de Vries (1957) to simulate soil heat fluxes while considering soil surface latent heat fluxes, sensible heat fluxes, water fluxes, and thermal properties and their dependence on soil water contents (Siminek et al., 2016). HYDRUS-1D also considers the subsurface movement of liquid water and water vapor driven by pressure head and temperature gradients (Saito et al., 2006). This updated model was applied in a special scenario with high gas permeability materials, e.g., straw mulching (Dahiya et al., 2007). Not all of these processes (e.g., vapor flow or thermal liquid flow) are currently considered by HYDRUS (2D/3D). However, HYDRUS (2D/3D) can provide good simulation accuracy for soil temperatures under mulching with low gas permeability, especially for impermeable plastic film mulching. For example, Zhao et al. (2018) estimated $T_s$ variations under PM using HYDRUS (2D/3D), obtaining a very low RMSE for $T_s$ of only $0.032 - 0.055 ^\circ C$. Zhang et al. (2018) also obtained good modeling accuracy ($RMSE = 1.0 - 4.2 ^\circ C$) by evaluating differences in $T_s$ at different soil depths and locations in a drip-irrigated field. In this study, similar results were obtained for the PM22.5 treatment with RMSE of $1.86 - 3.34 ^\circ C$. Differences between the model and experimental data can be explained by the simplification of surface heat fluxes in the mulched region.

4.2. Effects of mulching treatments on soil temperature fluctuations

Different $T_s$ fluctuations under different mulching treatments occurred mainly in the mulching area. The field with a larger mulching area can effectively decrease the near-ground wind speed, reduce water vapor losses (Shahzad et al., 2019), and regulate $T_s$ (Ma et al., 2020; Hwang et al., 2019). On the other hand, the field with a small mulching area can produce increased soil surface temperature fluctuations due to high radiation reflection and intense near-ground wind speed (Kader et al., 2020). For example, in this study, average $T_s$ for PM was $1.12 ^\circ C$ higher than for NM in 2018 and 2019, while related SD and DV increased by $27.0 \%$ and $49.2 \%$, respectively, for NM compared with PM. Lee and Park (2020) found similar results when comparing $T_s$ in the root zone under different mulching treatments, with $T_s$ under PM 0.5–1.8 $^\circ C$ higher than under NM. Díaz-Pérez and Batal (2002) further illustrated that NM had higher $T_s$ fluctuations than PM, mainly due to NM’s low heat preservation, especially the significantly decreased soil heat flux at night.

Fig. 6. Simulated two-dimensional soil temperature distributions in the tillage layer (0-30 cm) on (from top down) DAS 38 (1 day before irrigation), DAS 40 (1 day after irrigation), DAS 118 (1 day before irrigation), and DAS 120 (1 day after irrigation, bottom row) in 2018 under (from left to right) plastic film mulching (PM22.5), biodegradable film mulching (BM22.5), and no film mulching (NM22.5) with an irrigation depth of 22.5 mm, and biodegradable film mulching with irrigation depths of 30 (BM30) and 15 (BM15) mm.
Compared with PM and NM, BM has more advantages in heat preservation and heat stress prevention. For example, $T_h$ increased by about 1.1 °C in the BM treatment compared with NM during early crop growth stages, which was similar to that of PM (Shen et al., 2019; Yin et al., 2019). However, during later crop growth stages, BM could effectively overcome the shortcomings of PM, such as root lignifications and activity decline (Lincoln and Eduardo, 2010), by regulating $T_h$ within an optimal range (20–24 °C suggested by Yan and Tu (2003)) due to its oxidation and microbial degradation (Borrowman et al., 2020; Sintim et al., 2020; Braunnack et al., 2020). The result of this study showed that $T_h$ under BM mostly remained in the 20–24 °C interval during the late crop growth stage (Fig. 3). However, $T_v$ under PM increased on average by 0.4 °C compared with BM, causing heat stress on some days. Gu et al. (2017) evaluated differences in $T_v$ under PM and BM, finding that $T_v$ under BM was lower than under PM after DAS 150. Moreover, Sun et al. (2018) also similarly reported that $T_v$ under BM decreased by 0.4–1.4 °C compared with PM after DAS 60.

4.3. Effect of irrigation levels on soil temperature in the tillage layer

In general, $T_v$ fluctuations and distributions in the tillage layer are closely related to SWCs (Philip and de Vries, 1957; Saito et al., 2006). For example, low $T_v$ usually occurred in high SWC regions. In this study, $T_v$ in the treatment with a high irrigation depth (i.e., the BM$_{22.5}$ treatment) was generally lower than in other irrigation treatments, but the $T_v$ fluctuations significantly increased (Fig. 5 and Table 4). The reason is that the specific heat capacity of soil water is higher than that of soil particles. Romić et al. (2020) evaluated the effects of the extreme meteorological conditions on grape yield and anthocyanin content, finding that the adverse impact of long-lasting high-temperature events could be partially avoided by applying irrigation. Additionally, two-dimensional $T_v$ distributions under different irrigation levels varied widely due to the different sizes of the wetted area (Fig. 6). For example, the maximum depth of the area with “relatively low $T_v$” under BM$_{50}$ reached 9.8 cm, increasing by 42.9 % and 79.6 % compared with BM$_{22.5}$ and BM$_{15}$, respectively. The corresponding maximum width under BM$_{50}$ reached 13.2 cm, which was 59.3 % and 75.0 % higher than under BM$_{22.5}$ and BM$_{15}$, respectively. Generally, a high irrigation depth treatment results in a significant increase of the area with “relatively low $T_v$” and a decrease of the area with “optimal $T_v$.” Compared with the high irrigation depth treatment, the low irrigation depth treatment can reduce the area with “relatively low $T_v$” and increase the area with “relatively high $T_v$.” The results showed that only the medium irrigation depth treatment, among different treatments considered in this study, provided the maximum size of the area with “optimal $T_v$.” Therefore, we recommend the medium irrigation depth treatment (22.5 mm) as the optimal irrigation strategy. However, by observing the $T_v$ distribution under different irrigation depths, Ren et al. (2019) found the maximum area with “optimal $T_v$” for a 46.9 mm irrigation depth treatment. Their results were very different from the recommended value in our study. The main reason may be the differences in precipitation and ground-water table depths at different experimental sites.

5. Conclusions

This study evaluated the effects of different mulching and different irrigation depth treatments on $T_v$ using experimental and simulated results. A good agreement between experimental data and the HYDRUS (2D/3D) model was obtained, with RMSE of 2.11–4.00 °C, $E_F$ of 0.63–0.85, and $MRE$ of 8.1 %–11.6 % during the validation period. In the elongation and tasselling stages, $T_v$ under film mulching treatments (PM) (i.e., PM$_{22.5}$ and PM$_{22.0}$) was not significantly different but markedly increased and stabilized compared with NM$_{22.5}$. There were higher $T_v$ fluctuations under BM$_{22.5}$ than PM$_{22.5}$ because water vapor exchange between the soil surface and atmosphere was more intensive due to a higher disintegration area in the filling and maturation stages. The $SD$, $DV$, and $K$ under BM$_{22.5}$ were 6.7 %, 32.6 %, and 19.3 % higher than under PM$_{22.5}$.

Additionally, the apparent difference in $T_v$ values between BM$_{22.5}$ and PM$_{22.5}$ mainly occurred in the soil surface layer (5 cm), and the area with “optimal $T_v$” under BM$_{22.5}$ increased by 33.5 % compared with PM$_{22.5}$. The order of $T_v$ for different irrigation treatments was BM$_{15}$, BM$_{22.5}$, and BM$_{30}$, while the maximum size of the “optimal $T_v$” area occurred in BM$_{22.5}$. Generally, BM effectively regulated soil temperature within a suitable range for crop growth. The biodegradable film can thus be recommended as an alternative material to replace the traditional polyethylene film.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgments

This research was jointly supported by the National Natural Science Foundation of China (52079064, 51969024, and 51469022), the Local Science and Technology Development Fund Projects Guided by the Central Government (2020ZY0023), the Major science and technology projects of Inner Mongolia (dzdx2018059), Inner Mongolia autonomous region graduate education innovation plan subsidize project (S20191167Z). Additionally, we are sincerely appreciating the careful and precise reviews by the anonymous reviewers, editors.

References


