Simulation of temperature distribution in double-row potato ridges mulched with plastic film covered with soil

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Abstract: In Northwest China, potatoes are cultivated on double-rows of each ridge which is mulched with plastic film, and the film is covered with some of soil. While effective in retaining soil moisture, this technique can render the potato seedlings prone to be burned if they are not released from the plastic film in time. In this study, the model of convective heat transfer of potato ridge under solar radiation and atmospheric radiation is established by the Fluent software. The processes of the heat transfer of potato ridge was simulated for a certain day, and the temperature distribution in the potato ridge was monitored over time. The temperature distribution of soil in the growth layer of potato plants was analyzed under different thickness and widths of the covering soil on the film. The results showed that with the increase of covering soil thickness and width, the time for soil at different depth to reach the peak-temperature was delayed, and the daily temperature change of soil where the different depths layer of potato plants growth was reduced. At that time, a binary regression equation of offset temperature was constructed by using the Response Surface Method. The best parameter combination for covering soil on the plastic film is a thickness of 50 mm and a width of 280 mm in the cold and arid areas of Northwest China. However, the offset temperature (PT) first decreased and then almost remained unchanged with the increase of covering soil thickness. Considering the operational efficiency and power consumption of soil covering devices in the field, the unchanged width of the covering soil is 200 mm. The field experiments have shown that a 50 mm thick of soil covering is beneficial for the growth of potato plants and a 200 mm width of soil covering is beneficial for the growth of potato plants. The height of potato plants was 21 cm, and the natural emergence rate of potatoes was 95.8% on June 9, 2024. The environment of soil covered could provide theoretical support for the mechanized planting of potatoes.

Keywords: potato growth, plastic mulching, soil covered with film, temperature distribution, natural emergence rate
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1 Introduction

The cold and arid region of the Loess Plateau in Northwest China is a vast area with low, unevenly distributed rainfall and a fragile ecology. Therefore, it is very difficult for cereal crops to grow. As the potato plants is resistant to the environment of drought and cold, it can not only grow normally, but also can help reduce the soil erosion and preserve moisture[1]. Therefore, it has become one of the dominant crops in the cold and arid region of Northwest China. The northwest arid region is located on the edge of China's inland and dominant monsoon regions, with an annual precipitation of less than 200 mm (about 47% of the national average precipitation), and an annual evaporation of over 1000 mm. The water resources per unit area are only 1/6 of the national average[2]. Plastic film mulching is an effective mean of improving the efficiency of water resources utilization[3]. In recent years, traditional drought-resistant measures have been combined with modern research in the cold and arid region of Northwest China and a cultivation mode with furrows and ridges mulched with plastic film was created[4]. Compared with the traditional cultivation methods, this has increased potato yield by more than 20%[5].

Currently, there are two methods of potato cultivation with plastic film mulched on furrows and ridges: One is to sow first, then mulch with plastic film, and then release the seedlings manually after emergence. The advantage of this method is that seedlings can grow rapidly and moisture can be well-preserved. The disadvantage is that releasing the seedling manually requires extra labor. If the potato seedlings are not released in time, they can be burned due to high temperature between the plastic film and soil gas occurring during sunny days. The other method is to mulch the plastic film first and then punch holes in the film for sowing. The advantage is that films can be mulched in advance to improve the ground temperature, and seedlings are not easy to be burned. The disadvantage is that the film must be perforated for planting the seeds, which is time-consuming if done manually. If the hole perforated in the plastic film is too wide, the loss of moisture from the soil is increased, and winds can blow away the film, or harden the soil around the hole and hence reduce the rate of seedling

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emergence. The soil temperature becomes higher after mulching, which is not conducive for seedlings to germinate and grow. At the same time, it is difficult to weed under the film, and the potato tubers become green easily[6]. Studies have shown[7-10] that potato sprouts can break the plastic film if the film is covered with some of soil after sowing. The sprouts will not open if they are not exposed to the sun light during germination, and the seedlings will break the film to emerge naturally, under the soil layer pressure and by the natural upward action of the sprouts (see Figure 1). Sun et al.[11] integrated this into a high-yield potato cultivation technology with film mulching, and put forward a cultivation mode of single ridge with double-row mulched with film and covered with some soil on the film.

Figure 1 Process of potato seedlings breaking through the plastic film and growing

When the plastic film is covered with soil, it becomes the physical barrier for water-vapor exchange between soil and the atmosphere, which alters infiltration and evaporation, and significantly increases the ground temperature. Potatoes can grow better when the soil temperature is not high, as the high soil temperature caused by film mulching will induce stress to their growth[12-13], the buds and seedlings can be easily burned during sunny days, and the emergence rate diminishes. Therefore, the temperature distribution characteristics of plastic film covered with soil, and the soil system under the film are important topics of research. Wang et al.[14] and Tang et al[15] studied the soil hydrothermal effect and yield for different mulching methods of potato on dry land, and determined the daily average ground temperature changes under film during the growth period. Li et al.[16] determined the soil temperature variation under wide plastic film mulching in an irrigation area in Xinjiang, China, through continuous dynamic monitoring of ground temperature. Wang et al.[17] studied the characteristics of ridge temperature distribution under white film coverage. However, the existing research do not involve the influence of the width and thickness of the covering soil upon the temperature distribution under the plastic film.

This study continues the research on potato cultivation on furrows and ridges mulched with full-film plastic and seed-row covered with soil (see Figure 2). Specifically, it simulates the daily variation of potato ridge temperature distribution using the Computational Fluid Dynamics simulation software that is Fluent (ANSYS Inc, USA) and explores the effect of thickness and width of covering soil upon the most favorable growing conditions of potato seedlings. The study ultimately provides a theoretical background for the construction of adequate film-soil mulching systems.

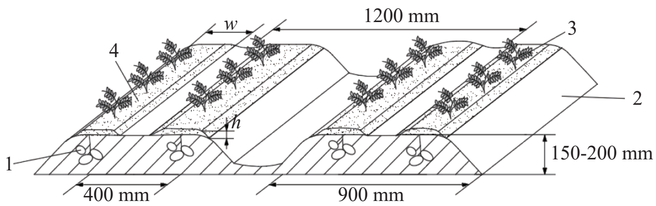
Note: The thickness of film is 0.01 mm; The thickness of covering soil is 50 mm; The spacing between holes is 400 mm.

Figure 2 Mechanized mode of potato cultivation with plastic film mulched on furrow and ridge

2 Materials and methods

2.1 Radiation heat transfer analysis of potato ridge

Figure 3 shows the potato cultivation mode of single ridge with double-row mulched with full-film and seed-row covered with soil, as it is done in the cold and arid areas of Northwest China. The soil, air, solar radiation, and black plastic film are the main factors determining the temperature distribution in the potato ridge.



Note: 1. potato; 2. ridge body; 3. seed row; 4. covering soil on the seed row. w is the covering width; h is the covering thickness.

Figure 3 Potato planting with plastic film mulching and covering soil on the plastic film

Much of the solar radiation energy is transmitted in the form of visible light. The earth's surface temperature increases after the solar radiation is reflected and scattered through the atmosphere[18]. At night, the soil temperature emits heat mainly in the form of long-wave radiation[19]. Mulching film is the physical barrier between potato ridge and the environment, so plastic film mulching can effectively reduce heat and water loss[20]. The density and moisture content of the potato ridge change with depth[4]. There is no solar radiation on the side face of the ridge, and a shielding wall is added to block the solar radiation. To sum up (see Figure 4), the heat transfer system of potato ridge-air-film was constructed, and the three-dimensional modeling of the solar radiation heat exchange system was done with the help of the 3D modeling software SolidWorks (Dassault Systemes, USA). The intersection of the potato-ridge plane, potato-ridge strike profile and the potato-ridge transverse symmetry plane was regarded as the center point of this 3D model.

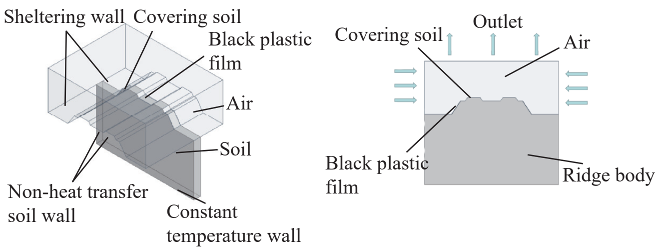


Figure 4 Three-dimensional model of the potato ridge

2.2 Mathematical model

2.2.1 Control equation of air convection and heat transfer

The continuity equation of an ideal gas in space rectangular coordinate system is[21]

$$\frac{\partial \rho_{\rm air}}{\partial t}+\frac{\partial(\rho_{\rm air}u)}{\partial x}+\frac{\partial(\rho_{\rm air}v)}{\partial y}+\frac{\partial(\rho_{\rm air}w)}{\partial z}=0 \tag{1}$$

The Navier-Stokes equation describes the conservation of momentum of fluid micelle in the space rectangular coordinate system, which can be expressed as followings[21]:

$$\frac{\partial(\rho_{\rm air}u)}{\partial t}+\frac{\partial(\rho_{\rm air}uu)}{\partial x}+\frac{\partial(\rho_{\rm air}uv)}{\partial y}+\frac{\partial(\rho_{\rm air}uw)}{\partial z}=\frac{\partial}{\partial x}\left(\mu_{\rm air}\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_{\rm air}\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu_{\rm air}\frac{\partial u}{\partial z}\right)-\frac{\partial P}{\partial x} \tag{2}$$

$$\frac{\partial(\rho_{\rm air}v)}{\partial t}+\frac{\partial(\rho_{\rm air}uv)}{\partial x}+\frac{\partial(\rho_{\rm air}vv)}{\partial y}+\frac{\partial(\rho_{\rm air}vw)}{\partial z}=\frac{\partial}{\partial x}\left(\mu_{\rm air}\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_{\rm air}\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu_{\rm air}\frac{\partial v}{\partial z}\right)-\frac{\partial P}{\partial y} \tag{3}$$

$$\frac{\partial(\rho_{\rm air}w)}{\partial t}+\frac{\partial(\rho_{\rm air}uw)}{\partial x}+\frac{\partial(\rho_{\rm air}wv)}{\partial y}+\frac{\partial(\rho_{\rm air}ww)}{\partial z}=\frac{\partial}{\partial x}\left(\mu_{\rm air}\frac{\partial w}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_{\rm air}\frac{\partial w}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu_{\rm air}\frac{\partial w}{\partial z}\right)-\frac{\partial P}{\partial z} \tag{4}$$

The heat convection and heat transfer system must meet the conservation law of energy equation[22]:

$$\frac{\partial(\rho_{\rm air}T)}{\partial t}+\frac{\partial(\rho_{\rm air}uT)}{\partial x}+\frac{\partial(\rho_{\rm air}vT)}{\partial y}+\frac{\partial(\rho_{\rm air}wT)}{\partial z}=\frac{\partial}{\partial x}\left(\frac{k_{\rm air}}{c_{\rm air}}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial x}\left(\frac{k_{\rm air}}{c_{\rm air}}\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial x}\left(\frac{k_{\rm air}}{c_{\rm air}}\frac{\partial T}{\partial z}\right) \tag{5}$$

where, $\rho_{\rm air}$ represents air density; $\mu_{\rm air}$ represents aerodynamic viscosity; P represents pressure on micro element; $k_{\rm air}$ represents thermal conductivity of air; $c_{\rm air}$ represents specific heat capacity of air.

2.2.2 Temperature field of soil

The temperature field of the potato ridge is due to solar radiation and natural convection of the air. In addition, assuming that the soil inside the potato ridge does not flow, there is no convection heat transfer inside the potato ridge. Therefore, the heat conduction equation of potato ridge is[23]:

$$\rho_s c_s\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(\lambda_s\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_s\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_s\frac{\partial T}{\partial z}\right) \tag{6}$$

where, ρ_s represents air density, c_s represents specific heat capacity of soil, T represents soil temperature, λ_s represents thermal conductivity of soil.

2.3 Boundary conditions

2.3.1 Boundary conditions of soil on potato ridge

There is almost no heat transfer on the side face of the ridge by setting the heat flow boundary around the potato ridge to zero (see Figure 4). Studies have shown[24] that there is essentially no significant diurnal variation in the ground temperature at the depths of 500 and 800 mm of the soil layer in Dingxi area and the temperature at the depth of 800 mm of the soil is set to be 283.1225 K or 9.973°C, so the temperature at the depth of 800 mm of the soil is set to be 283.1225 K or 9.973°C (the boundary conditions should be far from the computational domain.). The soil absorption rates of direct visible and direct infrared (IR) were set to 0.83 and 0.86 respectively, and the black-film absorption rates of the direct visible and direct IR were set to be 0.93 and 0.88 respectively[25]. To prevent sunlight from shining onto the side face of potato ridge, the internal emissivity of the shielding wall was set to zero, and the direct visible and direct IR were set to 1.0 (the shielding wall absorbs all the sun rays and does not radiate heat outward).

2.3.2 Boundary conditions of air above potato ridge

The diurnal variation of air temperature above the potato ridge can be approximated to a sinusoidal curve[26]. The maximum temperature of the simulated day is 21.6°C and the minimum temperature is 6°C, and then the change curve of atmospheric temperature with time during a day is calculated with Equation (7). The temperature variation with time above potato ridge can be described by DEFINE_PROFILE combined with CURRENT_TIME function as follows[17].

$$T=0.5(t_{\max}-t_{\min})\sin((\pi/12)(t-9))+t_{\min}+0.5(t_{\max}+t_{\min})+273.15 \tag{7}$$

where, $t_{\max}$ represents maximum temperature of the day, $t_{\min}$ represents minimum temperature of the day.

2.4 Initial conditions of soil temperature

When calculating the transient problem, the initial conditions must be specified. The soil temperature values at the depths of 0, 5, 10, 20, 30, 50 and 80 cm are obtained from the data collected in the Loess Plateau by Zhang et al.[24]. By fitting the functional relationship between the temperature of each coordinate in the center of the potato ridge grid unit and the shortest distance from this coordinate to the potato ridge surface, and using the interval search method combined with the DEFINE_INIT function to write a User Defined Function (UDF) to set the local initial temperature of the soil. See literature[17] for specific UDF.

$$\begin{aligned}T=&13.072\,811\,245\,074\,3+75.139\,982\,753\,391\,2rp-\\&257.687\,566\,682\,656rp^2+309.798\,255\,069\,971rp^3-\\&70.244\,596\,542\,140\,8rp^4-65.945\,567\,249\,271\,4rp^5-\\&6.527\,756\,611\,202\,812+273.15\end{aligned}$$

where, rp is the shortest distance between the internal space location of the soil layer and the surface of the potato ridge, and it ranges from 0 to 0.8 m. It is obtained by compiling the corresponding computer program with the interval search method.

2.5 Physical parameters

Wang et al.[27] found that when the density of soil is constant, the thermal conductivity and specific heat capacity of loess soil increase with the moisture-content increase. When the soil moisture content is constant, the thermal conductivity and specific heat capacity of loess increase with the increase of dry density of soil, according to the Equations (8) and (9):

$$c_s=\gamma_s(1.27+0.021w_s)\times10^3 \tag{8}$$

$$\lambda_s=\left(4.17w_s^2+1540\right)\times10^{0.25\gamma_s-3.9} \tag{9}$$

where c_s represents specific heat capacity of soil, γ_s represents dry density of soil, λ_s represents thermal conductivity of soil, and w_s represents moisture content of soil.

The moisture content and density of soil are obtained from literature[17], and then the soil thermal conductivity and specific heat capacity are determined. Table 1 lists the main physical parameters of both the soil and the plastic film.

Table 1 Physical parameters of soil and black plastic film

Material	Density/ kg·m⁻³	Specific heat/ J·kg⁻¹·K⁻¹	Thermal conductivity/ W·kg⁻¹·K⁻¹
Soil	1400.000	1778.00	0.4239
	1596.172	2260.16	0.7400
	1618.020	2304.26	0.8000
Plastic film	920.000	2301.00	0.3200

2.6 Loading of solar payloads

The solar load is loaded by tracing solar ray which is updated regularly. The solar altitude angle and ridge orientation are set through the solar calculator panel. The specific longitude is set to be 104.2133°, the latitude is 35.298 33°and the time zone is 8+GMT. The fraction of solar spectrum is set to be 0.547[17].

The influence of clouds on the atmospheric direct radiation transmittance is not considered in the HOTTEL model[28], only the solar zenith angle, climate-related parameters and altitude are used to describe the atmospheric direct radiation transmittance through the following Equations (11)-(14):

$$a_0^* = 0.4237 - 0.008\,21(6 - A)^2 \tag{10}$$

$$a_1^* = 0.5055 - 0.009\,59(6.5 - A)^2 \tag{11}$$

$$k^* = 0.2711 - 0.018\,58(2.5 - A)^2 \tag{12}$$

$$r_0 = \frac{a_0}{a_0^*},\ \ r_1 = \frac{a_1}{a_1^*},\ \ r_k = \frac{a_k}{a_k^*} \tag{13}$$

$$t_b = a_0 + a_1 \exp\left(-\frac{k}{\cos\vartheta_z}\right) \tag{14}$$

where, A represents the altitude (A<25 km); r_0, r_1, r_k represents climate correction coefficients; a_0, a_1, k represents atmospheric physical constants with 20 km visibility.

The scattering transmittance can be determined by the direct transmittance through the following Equation (15):

$$t_d = 0.271 - 0.294 t_b \tag{15}$$

Therefore, the intensity of direct radiation on the horizontal plane is:

$$G_h = G_s t_b \cos\vartheta_z \tag{16}$$

The intensity of scattered radiation is:

$$G_v = G_s t_d \cos\vartheta_z \tag{17}$$

The DEFINE function in Fluent returns to altitude angle of solar radiation. Based on this, according to the intensity of solar diffuse radiation and direct solar radiation, the DEFINE_SOLAR_INTENSITY function in Fluent is used to write UDF loading. See literature[17] for specific UDF.

2.7 Numerical simulation

The finite volume method is used to solve the governing equation, the SIMPLE algorithm is used to deal with the relationship between pressure and velocity and the second-order upwind scheme is used to discretize the convection term. The simulation time of solar radiation on potato ridge began at 5:10 on June 10, and the time range was set at 300 s, lasting for one day.

In order to study the influence of covering soil environment on the temperature field distribution of potato ridge, the simulation tests were summarized in Table 2. The w is the covering width and h is the covering thickness.

2.7.1 Temperature time ratio

The temperature that potato can grow normally range from 291.15 K to 298.15 K[9,29], so the evaluation criteria for optimal growth environment that potato can grow are established as:

$$\begin{cases} HT = \dfrac{m_{t>298.15}}{m} \times 100\% \\ LT = \dfrac{m_{t<291.15}}{m} \times 100\% \\ GT = \dfrac{m_{291.15\le t\le 298.15}}{m} \times 100\% \end{cases} \tag{18}$$

The total simulation time is divided into m shares on average. In equation (18), $m_{t>298.15}$ is the number of shares with a temperature higher than 298.15 K, $m_{t<291.15}$ is the number of shares with a temperature lower than 291.15 K, $m_{291.15\le t\le 298.15}$ is the number of shares with a temperature between 291.15 K and 298.15 K, HT is the temperature time ratio that high temperature inhibits potato growth, LT is the temperature time ratio that low temperature inhibits potato growth, and GT is the temperature time ratio that potato can grow normally.

Table 2 Schedule of simulation experiments

Simulation experiment No.	Simulation test label	w×h/mm×mm
1	WH100	100×40
2	WH150	150×40
3	WH200(DH40)	200×40
4	WH250	250×40
5	WH300	300×40
6	DH30	200×30
7	DH20	200×20
8	DH50	200×40
9	DH60	200×60

Note: WH refers to different covering widths under 40 mm covering thickness, and the following number is the value of covering width; DH refers to different covering thicknesses under 200 mm covering width, and the following number is the value of covering thicknesses.

2.7.2 Offset temperature

In order to estimate the deviation degree between the optimal growth temperature of potato[29] and soil temperature, a offset temperature (PT) was constructed

$$PT = \sum_{i=5}^{n} \left| \left(T_{(\max,i)} + T_{(\min,i)}\right) - 2\times 294.15 \right| \tag{19}$$

where, PT is the offset temperature between ridge temperature and optimal growth temperature of potato, n is 15, The i is 50, 100, and 150 respectively, $T_{(\max,50)}$ is the maximum temperature at the depth of 50 mm soil layer, $T_{(\min,50)}$ is the minimum temperature at the depth of 50 mm soil layer, $T_{(\max,100)}$ is the maximum temperature at the depth of 100 mm soil layer, $T_{(\min,100)}$ is the minimum temperature at the depth of 100 mm soil layer, $T_{(\max,150)}$ is the maximum temperature at the depth of 150 mm soil layer, $T_{(\min,150)}$ is the minimum temperature at the depth of 150 mm soil layer.

3 Results

3.1 Simulation results and analysis

3.1.1 Effect of covering soil's width on temperature distribution of potato ridge

Under WH100, WH200 (DH40) and WH300 (Table 2) of covering soil's width treatments at 8:11, as shown in Figure 5, the density of temperature isolines on the east side of potato ridge is higher than that on the west side, indicating that solar radiation has forced the temperature of surface layer on the east side of potato ridge to rise. At this time, the soil temperature at the longitudinal position (from –570 mm to –120 mm) of potato ridge is about 1-3K higher than the upper soil temperature, the soil heat inside the potato ridge flows from bottom to top. Due to the low density of the covered soil and the weak thermal conductivity, the low temperature area on the upper layer of the potato ridge is forced to shift to the west, forming a circular area, which causes the temperature on the east side of the potato ridge to be about 1K-3K higher than that on the west side. When the width of the covered soil changes from WH100 to WH300 (Table 2) the circular area gradually becomes smaller, indicating that the width of the covered soil can weaken the heat dissipation capacity of the potato ridge.

The temperature distribution of potato ridge varies from different thickness of covering soil and changes with time. As shown in Figure 5, at 8:11 and 13:11, under the condition of WH200 (DH40) mulching, the temperature isoline of potato ridge presents a M-shaped, while the temperature isoline under WH100 and WH300 mulching treatments presents a N-shaped. This is mainly because the mulching retards the transfer of heat, resulting in the temperature of potato ridge at 0 mm vertical position being slightly higher than the surrounding temperature, causing uneven distribution of potato temperature. At 19:11, the solar radiation capacity becomes weak, according to the principle of entropy increase, the temperature isoline of potato growth layer becomes more uniform, and the M-shaped temperature isoline changed to N-shaped.

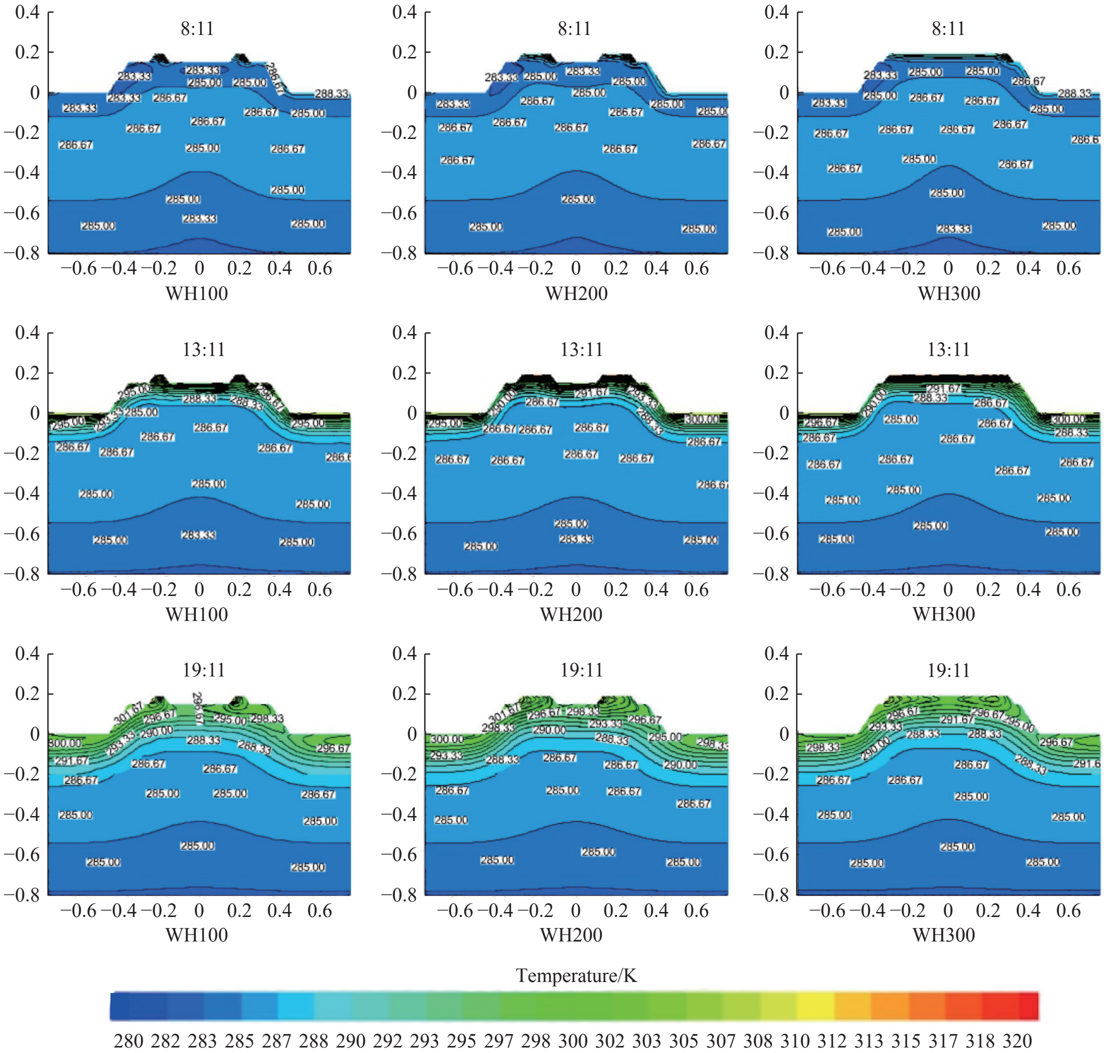


Figure 5 Cloud temperature at 8:11, 13:11 and 19:11 under different covering widths as defined in Table 2

3.1.2 Effect of covering soil's width on diurnal variation of potato ridge temperature

The soil temperature at the depth of 0, 50 mm, 100 mm, 150 mm soil layers under the film of potato ridge obviously follow daily changes, while the temperature at the depth of 200 mm do not change obviously, which indicates that the temperature active layer of potato ridge is mainly distributed at the depth of 0-100 mm soil layer under the film (see Figure 6).

As shown in Figure 6, the depth of 0-100 mm soil layer under the film is greatly affected by the covering width, while the temperature of 100-200 mm soil layer is almost not affected by the covering width. The width of covering soil has different effects on the temperature at the depth of 0-100 mm of the potato ridge in different time periods. During the time period from 7:11 to 20:11, when the covering soil treatment changes from WH100 to WH250, the soil temperature at the depth of 0 mm and 50 mm under the plastic film was decreasing, but under the WH250 and WH300 covering soil treatment, the temperature changes almost the same. Outside this time period, when the covering soil treatment changes from WH100 to WH200, the temperature of soil at the depth of 0-100 mm below the plastic film keeps rising and the temperature differences are almost the same when the covering soil treatment changes from WH200 to WH300. With the increase of the width of the covering soil, it can inhibit the temperature rise of the potato ridge at the depth of 0-100 mm soil layer in the daytime, and reduce the heat loss at the depth of 0-100 mm soil layer of the potato ridge at night. Although the width of covering soil can weaken the temperature change of potato ridge, this effect will not increase all the time.

3.1.3 Effect of covering soil's width on the peak time of potato ridge temperature

The time of soil temperature peak at different depths is different due to covering soil. According to Figure 7, under the DH200 soil covering treatment, the time when the temperature reaches its peak at the depth of 0 mm, 50 mm, 100 mm, 150 mm and 200 mm soil layers under the film is at about 17:11, 19:41,

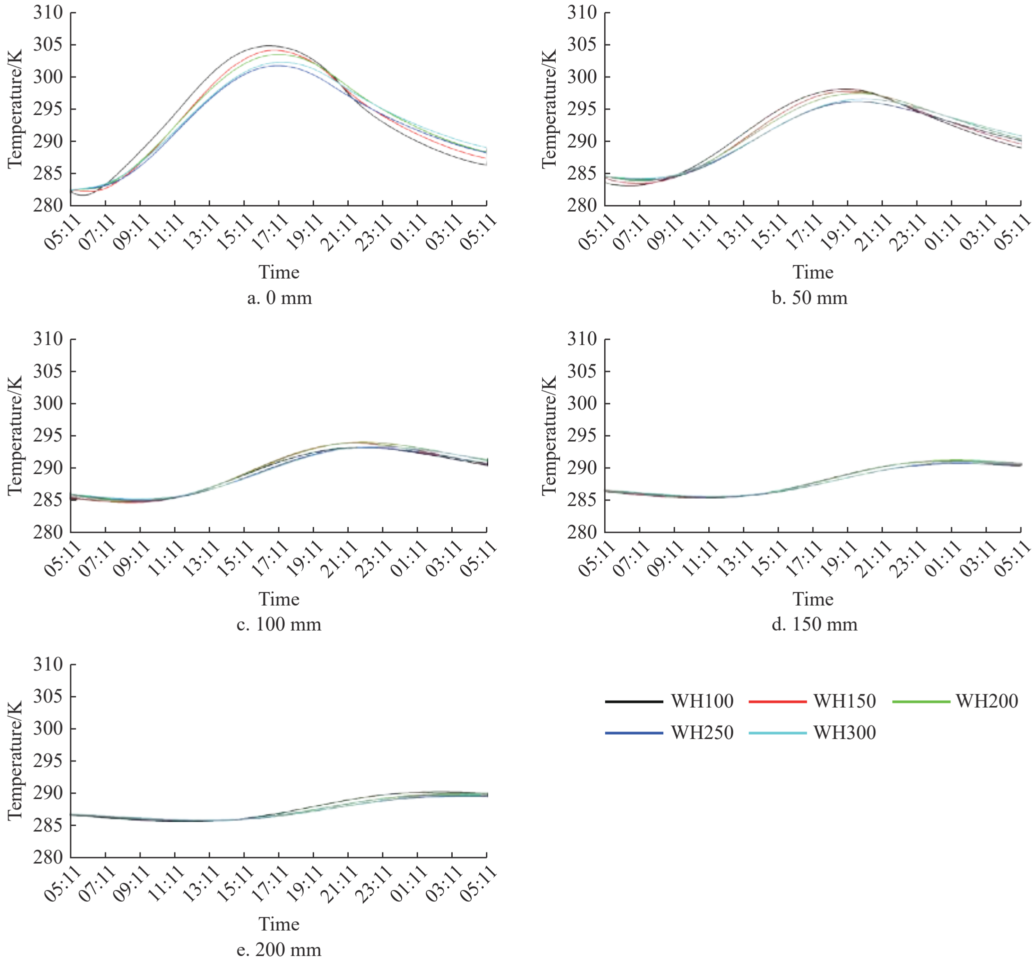


Figure 6 Daily variation of temperature field at the depth of 0, 50, 100, 150 and 200 mm under the film with different covering width at 5:11 on one day and 5:11 on the next day

22:01, 01:26 and 03:51 of the next day respectively. The time when the temperature reaches its peak is gradually delayed with the increase of the soil depth. At the depth of 0-100 mm soil layer, the time when the temperature reaches its peak extends about 5 h for every 100 mm increase of the soil depth. At the depth of 100-200 mm soil layer, when the soil depth increases by 100 mm, the time of reaching the peak temperature is delayed by 3.5 h. The time of reaching the peak temperature will be delayed by 1.5 h for every 100 mm of soil depth, which may be caused by the inconsistency of soil layer density and water content of potato ridge.

With the increase of soil depth, the average temperature and maximum temperature of potato ridge decreases, and the minimum temperature increases under different soil covering widths. Comparing the time when the temperature of each layer under the WH100, DH100 and WH300 mulching treatments reaches the peak value, as shown in Figure 7, with the increase of the mulching width, the time when the temperature of each layer of the potato ridge reaches its peak value is delayed. For every 100 mm increase in the mulching width, the time when the temperature at the depth of 0 mm, 50 mm, 100 mm, 150 mm, and 200 mm of soil layers reaching the peak value is delayed by 0.375, 0.510, 0.500, 0.625 and 1.080 h, respectively, showing that the width of covering soil can delay the time when the temperature at different soil layers reaches its peak.

3.1.4 Effect of covering soil thickness on temperature distribution of potato ridge

At 8:11, as shown in Figure 8, the temperature of potato ridge at 40-140 mm of the longitudinal position under WH20 mulching treatment is about (1-2)K higher than that of DH40 mulching treatment and DH60 mulching treatment at –400 mm of the transverse position, while the temperature of potato ridge at the longitudinal depth in 40-140 mm is about 1 K higher than that of DH40 mulching treatment and DH60 mulching treatment at the transverse position 0 mm. In addition, the low temperature area at 40-80 mm in longitudinal position under WH20 mulching treatment is much larger than that under DH40 and DH60 mulching treatment, which indicates that under DH20 mulching treatment, potato ridge is more affected by solar radiation and external environment than DH40 and DH60 mulching treatment.

The increase of the thickness of the soil mulch will also delay the temperature change of the soil under the mulch, resulting in uneven distribution of the potato ridge temperature. As shown in Figure 8, at 8:11 and 13:11, with the increase of coverage thickness, the high-density temperature contour moved upward, and the deformation of the M-shaped contour increased. The soil temperature below the planting rows was lower than that between the planting rows. Compared with the coverage width, the coverage thickness has a more significant effect on the formation of M-shaped isolines. But at 19:11, the deformation of M-shaped temperature profile becomes a N-shaped.

3.1.5 Effect of covering soil thickness on diurnal variation of potato ridge temperature

As shown in Figure 9, the depth of 0-150 mm soil layer under the film is greatly affected by the covering thickness, while the

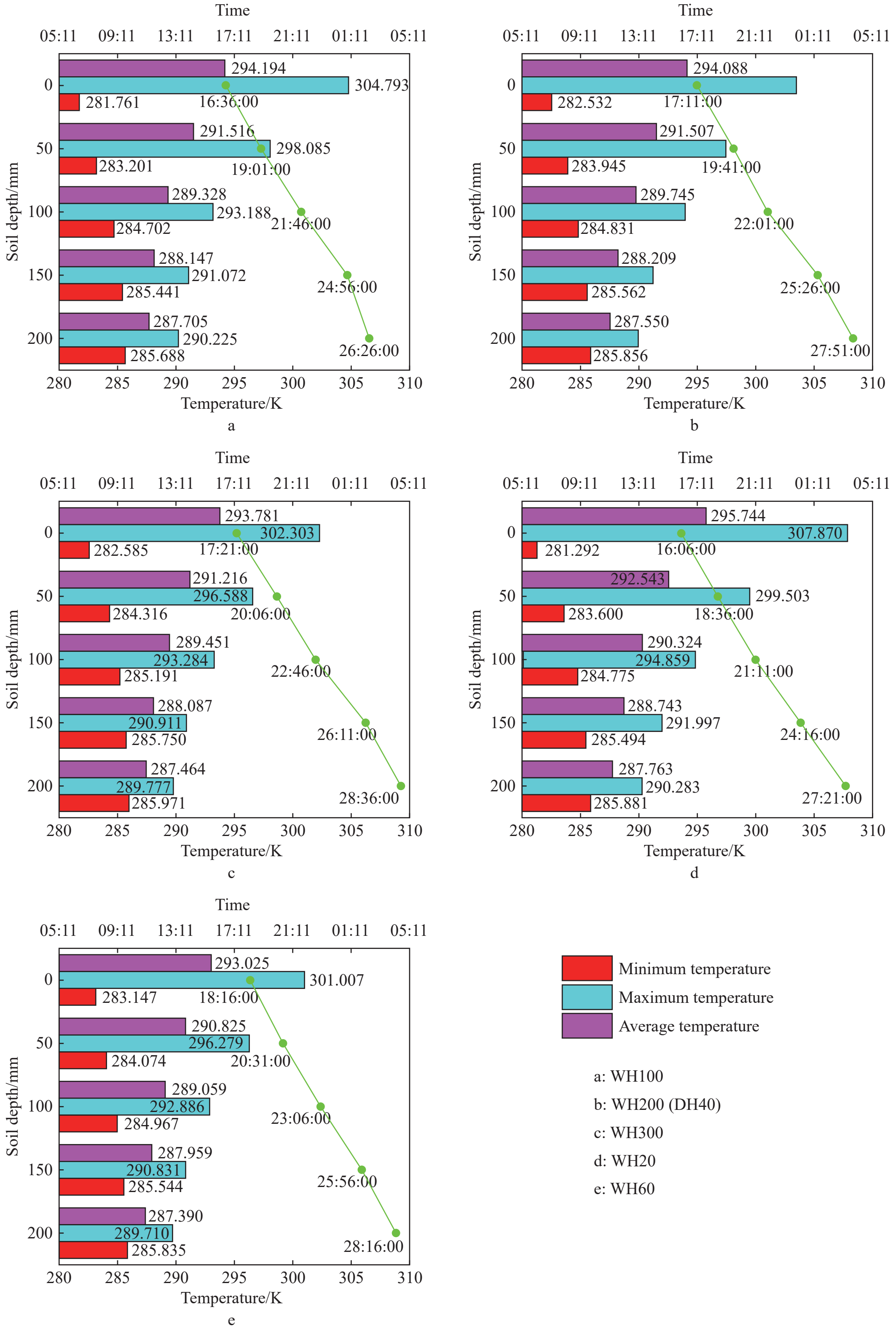


Figure 7 Effects of different soil covering treatments on the maximum temperature, minimum temperature, average temperature, and time of temperature peak of potato ridge at 5:11 on one day and 5:11 on the next day

temperature of 150-200 mm soil layer under the film is almost not affected by the covering thickness. The thickness of covering soil also has different effects on the temperature at the depth of 0-150 mm under the film of potato ridge in different time periods. During the time period 6:11-20:11, when the thickness of covering soil changes from DH20 to DH60, the temperature at 0 mm under the film of potato ridge has been decreasing, which is called Time Period I. During the time period 20:11-5:11, when the thickness of covering soil changes from DH20 to DH60, the temperature at 0 mm of potato ridge has been increasing, which is called Time Period II. With the increase of soil depth, Time Periods I and II are delayed backward, and the influence of covering soil thickness on the temperature of potato ridge is weakened. The temperature changes corresponding to Time Period I is almost not affected by the thickness of covering soil at the depth of 150 mm of soil layer, while the temperature change corresponding to Time Period II is

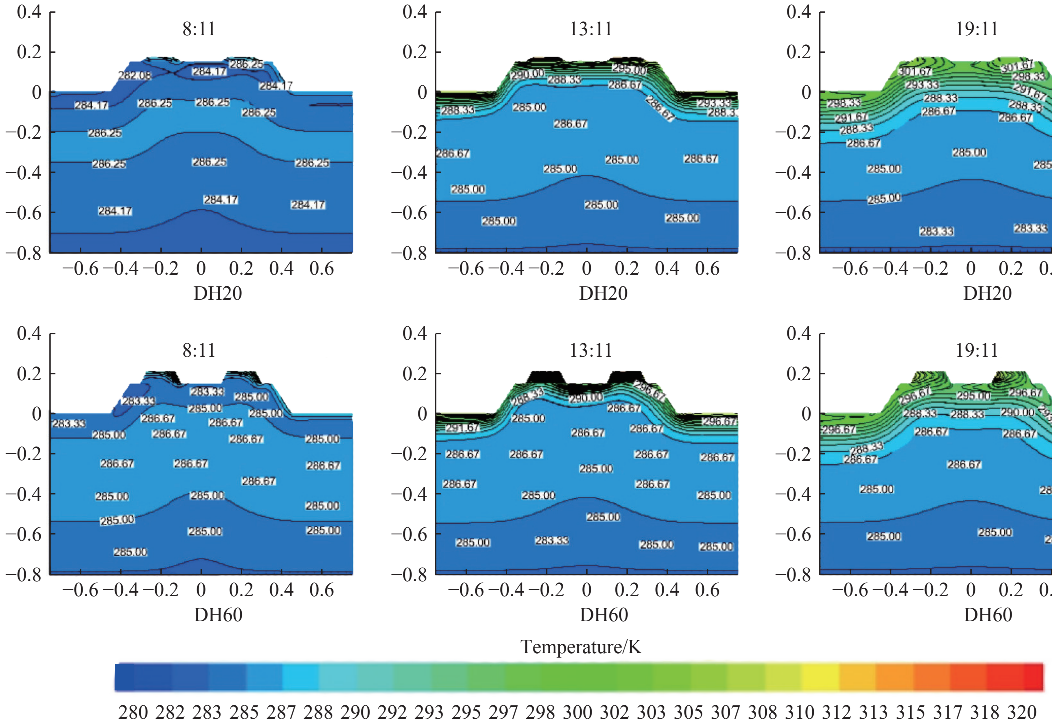


Figure 8 Cloud temperature at 8:11, 13:11 and 19:11under different covering thickness

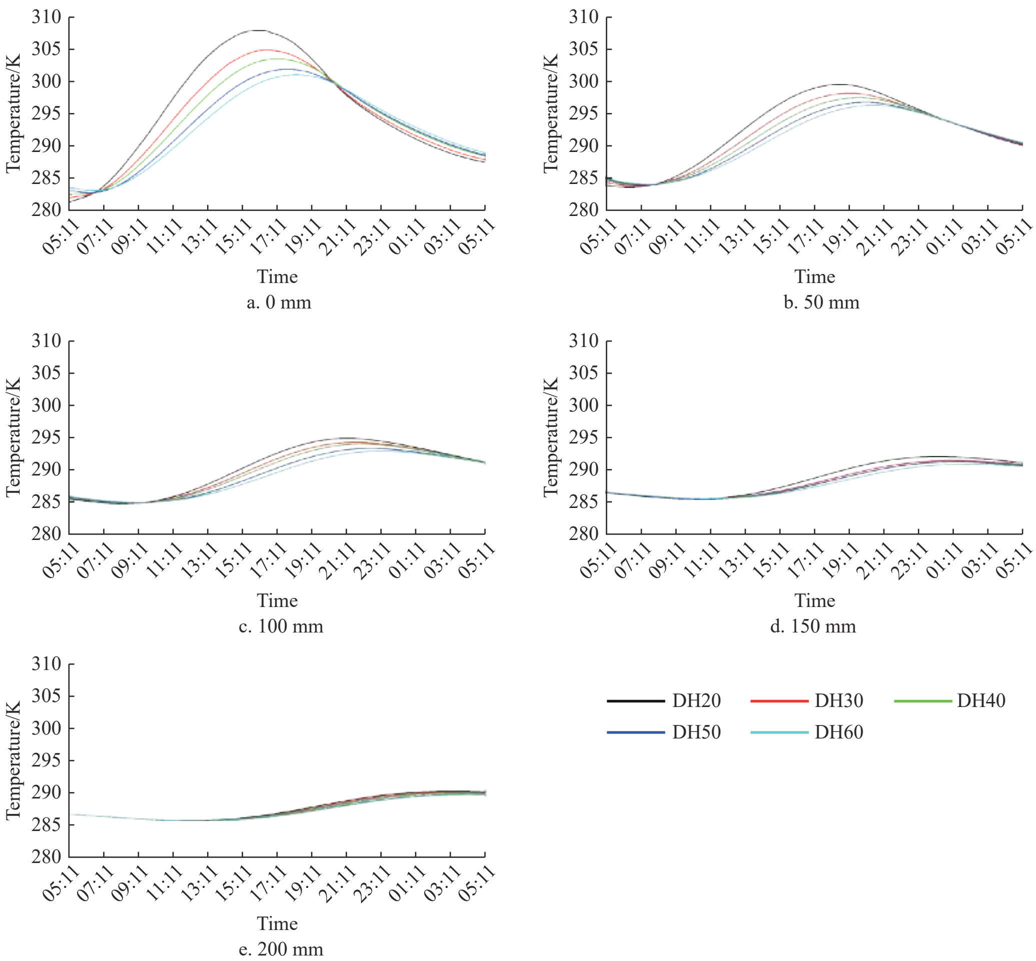


Figure 9 Daily variation of temperature field at the depth of 0, 50, 100, 150 and 200 mm under the film covered with different soil thickness at 5:11 on one day and 5:11 on the next day

almost not affected by the thickness of covering soil at the depth of 50 mm of soil layer, indicating that the increase of covering soil thickness can inhibit the temperature rise at the depth of 0-150 mm of soil layer of potato ridge during daytime. In the evening, it can reduce the heat loss at the depth of 0-50 mm soil layer of the potato ridge. The increase of covering thickness can reduce the temperature change of the potato ridge.

3.1.6 Effect of covering soil thickness on the peak time of potato ridge temperature

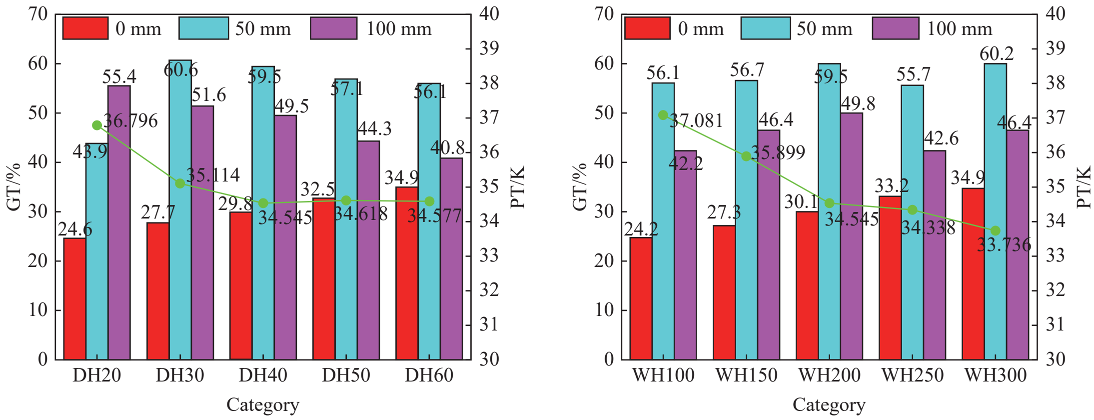
With the increase of soil depth, the average temperature and maximum temperature of potato ridge soil decreased, and the minimum temperature increased under different thickness of covering soil. By comparing the peak temperature time of each layer under DH20, DH40 and DH60 soil covering treatment, as shown in Figure 7, with the increase of covering soil thickness, the peak temperature time of each soil layer of potato ridge is delayed, indicating that the increase of covering soil thickness can also delay the peak temperature time of different soil layers.

3.1.7 Study on the optimal growth temperature of potato buds

1) Impact of covering soil environment on GT

When the thickness of covering soil changes from DH20 to DH60, as shown in Figure 10a, the GT at the depth of 0 mm soil layer of potato ridge has been increasing, and the GT of DH60 soil coverage treatment reach the highest and is equal to 35%. The GT at the depth of 50 mm soil layer of potato ridge first increased and then decreased, and the highest values were DH30 and DH40, which were 61% and 60% respectively. The GT at the depth of 100 mm soil layer of potato ridge has been increasing, and the highest value is DH20, which is 41%.

As shown in Figure 10b, when the thickness of covering soil changes from WH100 to WH300, the GT at the depth of 0 mm soil layer of potato ridge has been increasing, of which the WH300 soil cover treatment has the highest GT, which is 35%, while the change trend of the GT at the depth of 50 mm and 100 mm soil layers of the potato ridge is consistent, of which the WH200 has the highest GT, which is 60% and 50% respectively.



a. Soil covering thickness b. Soil covering width

Figure 10 Effects of different soil covering treatments on the GT and PT of potato ridges

2) Impact of covering soil environment on PT

The width and thickness of the covering soil on the film will affect the growth of potatoes. As shown in Figure 10, with the increase of covering soil's width, the PT first decreased significantly and then decreased slowly. With the increase of covering soil thickness, the PT first decreased and then almost remained unchanged.

3) Simulation experiment design

With the help of Design-Expert data analysis software (Stat-Ease, Inc, USA), the soil width (100-300 mm), soil thickness (20-60 mm) and the thickness of film (0.010-0.014 mm) being used as the experimental factors and test levels, and taking the PT calculated according to Equation (20) as the test indicators to establish an analysis model with three factors and three levels[25]. The specific test scheme is listed in Table 3 and the test results are listed in Table 4.

Table 3 Test factors and levels

Code	Factor		
	A: Covering width /mm	*B*: Covering thickness /mm	*C*: Film thickness /mm
–1	100	20	0.010
0	200	40	0.012
1	300	60	0.014

4) Simulation results and analysis

As listed in Table 5, the thickness and width of the covering soil have a significant impact on the deviation of the temperature field of the ridge directly below the potato seedling belt, while the thickness of the plastic film has no significant impact on the deviation of the temperature field. The primary and secondary influencing shadows are the width, thickness of the covering soil, and the thickness of the plastic film.

Table 4 Results of the quadratic orthogonal rotation regression test

Test No.	*A*: Covering width/mm	*B*: Covering thickness/mm	*C*: Film thickness/mm	*PT*: Offset temperature/K
1	200	40	0.012	34.545
2	200	40	0.012	34.545
3	300	20	0.012	36.653
4	200	40	0.012	34.545
5	200	40	0.012	34.545
6	100	20	0.012	39.200
7	100	60	0.012	36.633
8	300	40	0.014	33.807
9	200	20	0.010	36.918
10	300	40	0.010	32.699
11	100	40	0.014	37.147
12	100	40	0.010	37.257
13	200	20	0.014	35.545
14	300	60	0.012	33.134
15	200	40	0.012	34.545
16	200	60	0.010	34.463
17	200	60	0.014	34.694

Table 5 Results of the quadratic orthogonal rotation regression test

Source	Sum of squares	df	Mean square	*F*-value	*p*-value	
Model	44.34	9	4.93	17.53	0.0005	* *
A	24.30	1	24.30	86.48	< 0.0001	* *
B	11.03	1	11.03	39.23	0.0004	* *
C	0.0026	1	0.0026	0.0092	0.9262	
AB	0.2266	1	0.2266	0.8062	0.3991	
AC	0.3709	1	0.3709	1.32	0.2884	
BC	0.6432	1	0.6432	2.29	0.1741	
A^2	2.98	1	2.98	10.60	0.0139	*
B^2	4.37	1	4.37	15.55	0.0056	*
C^2	0.1061	1	0.1061	0.3776	0.5583	
Residual	1.97	7	0.2810			
Lack of fit	1.97	3	0.6557			
Pure error	0.0000	4	0.0000			
Cor total	46.31	16				

Note: $0.01<p<0.05$ means significant *, $p<0.01$ means extremely significant * *, and $p>0.05$ means not significant.

With the help of Design-Expert data analysis software, a binary regression equation for the deviation degree of the temperature field was established, and the optimal parameter combination was obtained through optimization, namely, the covering soil thickness was 50 mm, the width was 280 mm, the thickness of film was 0.010 mm and the *PT* is 32.67 K.

$$PT = 34.55 - 1.74A - 1.17B - 0.018C - 0.2380AB + 0.3045AC + 0.401BC + 0.8412A^2 + 1.02B^2 - 0.1588C^2$$

Figure 11 shows the influence of the interaction between coverage width and coverage thickness on *PT*. When the covering width is less than 200 mm and the covering thickness is less than 40 mm, the *PT* changes greatly. When the covering width is more than 200 mm and the covering thickness is more than 40 mm, the *PT* changes slightly.

4 Potato field planting experiment

In order to further seek suitable soil covering for potato growth and development, as shown in Figure 12, the monitoring experiment of temperature field of potato ridge seedlings covered with soil was carried out in Lianda village, Yuzhong County, Lanzhou on April 20th, 2024. The field test was arranged as T0 (100×50, No soil covering), T1 (100×50), T2 (200×50) and T3 (280×50), (covering width×covering thickness). Manual seeding and planting was performed. The plastic film was a black plastic film with a thickness of 0.012 mm. The variety of potatoes used Atlantic varieties. The sowing period was April 28, 2024. The emergence rate was calculated on June 9, 2024, and the growth of potato was measured on June 10. The experiment was conducted in a random arrangement with 3 replicates. The area of each community is 30 m^2. The natural emergence rate is expressed as the percentage of the number of seedlings that naturally break through the plastic film to the number of seeds sown. Using the the height of potato plants to represent their growth potential and using the SPSS for significance analysis.

As shown in Figure 12, as the soil cover width changed from T0 treatment to T2 treatment, the growth of potatoes showed a significant improvement trend with the increase of soil cover width, and the emergence rate also significantly increased with the increase of soil cover width. But when the width of the soil cover changed from T2 treatment to T3 treatment, there was no significant change in the growth and natural emergence rate.

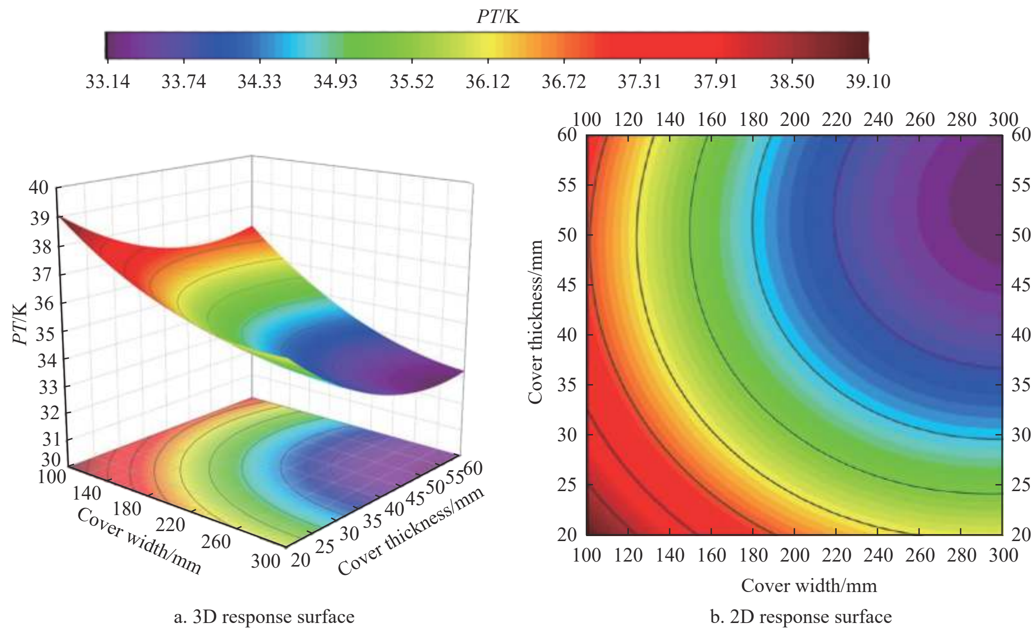
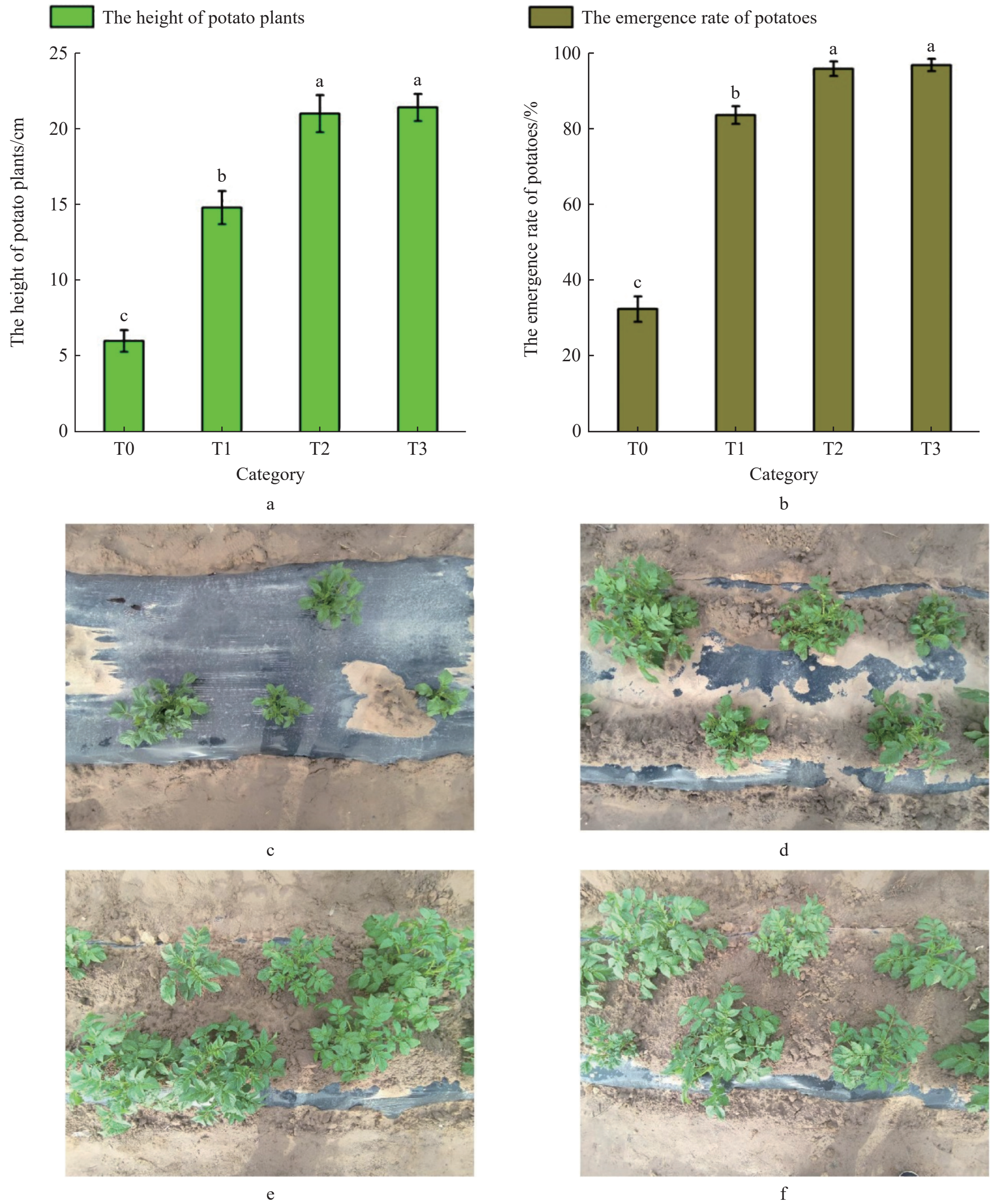


Figure 11 Influence of interaction between covering width and covering thickness on *PT*

5 Discussion

The convective heat transfer of potato ridge under solar radiation and atmospheric radiation is modeled numerically by using Fluent software. The heat transfer and the temperature distribution in the potato ridge are simulated over time. The temperature distribution in the growing layer of potato mulched with film was analyzed for different thickness and widths of the covering soil layer.

As crop of liking cool environment[9,30], when the temperature of the potato growth layer exceeds 298.15 K, the growth of potatoes will be slowed down. Unfortunately, the plastic film is a physical barrier between soil and the external environment, which can effectively increase soil temperature. The temperature of the potato



Note: a. Growth of potatoes under different treatments b.Emergence rate of potatoes under different treatments c. Growth of potato plants under T0 treatment d. Growth of potato plants under T1 treatment e. Growth of potato plants under T2 treatment f. Growth of potato plants under T3 treatment

Figure 12 Field experiment of potato seedlings breaking film and emerging

growth layer could be much higher than 298.15 K[9], slowing down the growth of potatoes. In this study, the width and thickness of soil covering the plastic film significantly affect the soil temperature of potato growth layer. With the increase of the thickness and width of the covering soil, the time of reaching the peak temperature at different soil layers is delayed, and the daily temperature change of potato growth layer decreases. This may be due to the ability of the covering material to reflect and transmit solar energy, resulting in a decrease in the soil temperature of the potato growth layer[31]. Similarly, Li et al.[32] found that plastic film mulching and ridge morphologies reduced heat fluctuations, which was more conducive to crop growth. Therefore, the covering soil with plastic film can effectively reduce the temperature rise of potato ridges, making the temperature of potato ridges more and more suitable for potato growth[10].

The soil temperature should not be too low, as it can also slow down the growth of potato plants[9]. Therefore, the width and thickness of the soil cover on the plastic film should not be too large. In this paper, through the response surface method, the optimal parameters of soil covering on the film were determined as follows: the soil covering thickness was 50 mm, the soil covering width was 280 mm and the PT was 32.67 K. With the increase of covering soil's width, the PT first decreased significantly and then decreased slowly. Therefore, the emergence rate of natural potatoes increases significantly with the increase of soil cover thickness and then decreased slowly. However, when the thickness of the covered soil exceeds 40 mm, the natural emergence rate of potatoes is not significant with the increase of soil cover thickness. Considering the strong wind and sand forces in the northwest arid agricultural area[33], which will cause the covered soil to be blown away by the wind, the optimal soil covering width of 50 mm is selected to resist wind and sand. At that time, considering the operational efficiency and power consumption of soil covering devices in the field and optimization result for the thickness of the soil covering, a 50 mm thick soil covering is beneficial for the growth of potato plants. The optimized optimal cover width is 280 mm, however the PT first decreased and then almost remained unchanged with the increase of covering soil thickness. Considering the operational efficiency and power consumption of soil covering devices in the field, the unchanged width of the covering soil is 200 mm. Therefore, a 200 mm width of soil covering is beneficial for the growth of potato plants.

The field tests showed that as the soil cover width changed from T0 treatment to T2 treatment, the growth of potatoes showed a significant improvement trend with the increase of soil cover width, and the emergence rate also significantly increased with the increase of soil cover width. But when the width of the soil cover changed from T2 treatment to T3 treatment, there was no significant change in the growth and natural emergence rate. Considering the operational efficiency and power consumption of soil covering devices in the field, a 200 mm width soil covering is beneficial for the growth of potato plants. Yang et al.[6] found through experiments that the treatment of 30 mm and 50 mm soil covering thickness is more conducive to the emergence of potato seedlings, with the emergence rates of 95.2% and 98% respectively, which is consistent with the conclusion obtained in this study, that is, the treatment of 50 mm soil covering thickness is more conducive to the growth of potatoes. Therefore, a 50 mm soil covering thickness is beneficial for the growth of potato plants.

6 Conclusions

A model of solar radiation potato ridges was constructed by using Fluent software and obtained some conclusions. The width and thickness of soil covering on the plastic film significantly affect the soil temperature of potato growth layer. With the increase of the thickness and width of the covering soil, the time of reaching the peak temperature at different soil layers is delayed, and the daily temperature change of potato growth layer decreases. In this study, through the response surface method, the optimal parameters of potato mulching were determined as follows: the soil covering thickness was 50 mm, the soil covering width was 280 mm and the *PT* was 32.67K. Considering the operational efficiency and power consumption of soil covering devices in the field, the 50 mm thick of soil covering is beneficial for the growth of potato plants and the 200 mm width of soil covering is beneficial for the growth of potato plants.

Field experiments have shown that when the width of the soil covering the film changes from 0 to 200 mm, the width of the soil covering has a significant impact on the growth and natural emergence rate of potatoes and when the width of the soil covering the film changes from 200 to 280 mm, the width of the soil covering has an insignificant impact on the growth and natural emergence rate of potatoes. The 50 mm thick of soil covering is beneficial for the growth of potato plants and the 200 mm width of soil covering is beneficial for the growth of potato plants. The height of potato plants was 21 cm, and the natural emergence rate of potatoes was 95.8% on June 9, 2024.

Acknowledgements

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