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Numerical Simulation of Soil Temperature With Sand Mulching During the Growing Season of Spring Wheat

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ABSTRACT

The thermal conditions of soil are important in practical agricultural production. The characteristics of heat flux, moisture content, thermal conductivity, and other soil parameters vary with temperature. This study uses VADOSE/W to create a model of heat transmission between soil and atmosphere, simulating daily changes in soil temperature using sand mulching. By using the published data to verify the model, the results show that the fitting effect is good and the reliability of the model is verified. We also used this model to determine the temporal and spatial distributions of soil temperature, temperature differences, and a temperature gradient for sand mulching and bare soil during the growing season of spring wheat. These results indicated that the sand mulching preserved heat at night. The difference in temperature at each depth and the temperature gradient became negative with the gradual increase in solar altitude. The difference in soil temperature at each depth and the temperature gradient tended to become positive by 22:00. These results indicated that the sand mulch effectively maintained the soil temperature in the morning and night during the growing season and impeded the transfer of heat at mid-day. This study provides a new method for determining the transfer of heat in sand-mulched soil, which can guide the effective regulation of soil temperature.

INTRODUCTION

The thermal conditions of soil have had a wide-ranging impact on various aspects of Earth sciences, including the growth of surface crops, the production of carbon dioxide, and the evaporation of water from the soil (Votrubová et al. 2012, Timlin et al. 2002, Buchner et al. 2008, Sakai et al. 2011). The thermal changes of soil affect the characteristics of heat flux, moisture content, thermal conductivity (Hsieh et al. 2009, Matsushima et al. 2010, Lu & Dong 2015), and other parameters. Soil temperature is critical to agricultural production and is an important physical indicator. Many scholars have investigated the effects of soil temperature on the growth and development of crops, the thermal status of the soil, and the evaporation of soil water.

Füllner et al. (2012) reported that biomass yield and root structure differed significantly among 30-day-old plants due to the effects of a gradient of soil temperature on plant growth and development, but Lahti et al. (2005) found that a reduction in temperature did not significantly affect biomass or nutrient uptake in seedlings. Nabi & Mullins (2008) reported that cotton roots and shoots during emergence were shortest and biomass was highest at 38°C. The sizes and proportions of sandstone particles can affect soil temperature, transpiration, water-use efficiency, and yield in watermelon with mulching. Bu et al. (2013) found that both gravel and plastic-film mulching increased the cumulative soil thermal time by 150-220°C over the growing season relative to bare soil. Mulching with gravel or plastic film is an effective strategy for increasing soil temperature, soil moisture content, and crop yield. Plastic films, however, can cause environmental pollution.

Farmers in the arid regions of northwestern China developed a method of conservation tillage with sand and gravel mulching to survive, which has been practiced for more than 300 years (Li et al. 2000, Lü et al. 2011). A cover of gravel and sand on the soil surface can improve soil conditions by retaining water, increasing and maintaining soil temperature, reducing surface salt accumulation, increasing infiltration, and effectively reducing evaporation and runoff (Yang et al. 2019, Li 2003, Ma & Li 2011). Numerical simulation has recently been widely used in various disciplines, with many studies simulating the flux of soil heat and evaporation. VADOSE/W modeling has typically been applied to obtain the pore pressure of natural or artificially covered slopes under controlled climates using stability analysis and to determine infiltration, evaporation, and plant transpiration for projects of agricultural irrigation. Argunhan-Atalay & Yazicigil (2018) used VADOSE/W to simulate fluxes in unsaturated and saturated regions and evaluated the performance of various overlay systems. Zhao et al. (2017a) used VADOSE/W to determine that cumulative soil evaporation was independent of mulch thickness and depended only on the depth of the inclusion: the deeper the inclusion, the higher the evaporation. Li et al. (2016) used VADOSE/W to simulate the characteristics of fluxes in unsaturated loess under the influence of environmental factors.

We used VADOSE/W to simulate the daily variation in the temperature of soil containing sandstone particles 0.3-1 cm in size and covered by 7 cm of sand at depths of 5 and 10 cm. We also used published data for the ground temperature of a cornfield at 14:00 and 20:00 in an irrigated area in Xinjiang, China. The simulated and measured temperatures were compared to verify the reliability of the model. The temporal and spatial distributions of temperature at different growth stages of spring wheat and the distribution of temperature differences and a temperature gradient over time were then simulated and predicted. This study clarifies the mechanism of soil heat transfer, which is important for agricultural production.

MATERIALS AND METHODS

Experimental Materials

The sandstone particles ranged in size from 0.3 to 1 cm, and the sand mulch was 7 cm thick. We used data from Xie et al. (2010) to simulate the changes in soil temperature over the time at depths of 5 and 10 cm. We also used data from Li et al. (2003) for the ground temperature at 08:00 on 25 April in a cornfield in an irrigated district in Xinjiang as the initial data for verification, and the ground temperature at 14:00 and 20:00 was simulated. Experimental data (Zhao et al. 2016) from an experimental base (Zhao et al. 2017b) (Table 1) were used for simulating the temporal and spatial distributions of temperature at various stages of growth of spring wheat and for determining the distribution of temperature differences and a temperature gradient over time, and the sand mulch was 15 cm thick.

Model Composition

Experimental design: All experiments were field experiments. Temperatures on sunny days from local meteorological data were used as the thermal boundary to analyze the influence of heat.

Model construction: The first model represented a volume of soil 25 cm in depth and 50 cm in width, including bare soil, a sand mulch 7 cm thick, and a sand mulch 15 cm thick (Fig. 1a, b, and c).

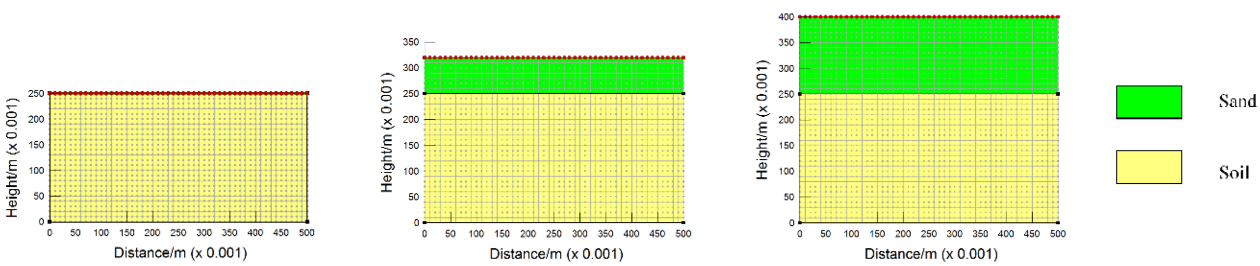
Boundary conditions: Information for the temperature in a soil profile is necessary to solve the equations for moisture content and heat flux. The surface temperature of snow-free soil can be estimated using the relationship (Wilson 1990):

$$T_s = T_a + \frac{1}{vf(u)}(Q - E) \quad ...(1)$$

where T_s is the temperature of the soil surface (°C), T_a is the air temperature above the soil surface (°C), v is the constant humidity and Q is the net radiant energy available on the surface (minus transpiration) (mm.d^{-1}).

Table 1: Particle composition of the soil and sand.

Particle size [mm]	<2.00	<1.00	<0.05	<0.01	<0.001
Soil [%]	100.00	99.46	80.26	23.13	10.06
Sandstone composition [mm]	<10.00	<5.00	<2.50	<1.25	<0.63
Sand stone [%]	100.00	94.51	79.58	59.70	34.62



(a) (b) (c)

Fig. 1: Geometric model. (a) Bare soil (CK); (b) Sand mulching, 7 cm; (c) Sand mulching, 15 cm.

RESULTS AND DISCUSSION

Model Verification

Example 1

The soil temperature was simulated at depths of 5 and 10 cm and compared to the temperature measured for soil with a 7 cm thick layer of sand. The correlation coefficient, R, with mulching was 0.987 and 0.979, respectively (Fig. 2). The simulation accuracy was thus high, indicating that VADOSE/W could be reliably used to simulate the soil temperature. Sand mulching thickness is 7cm.

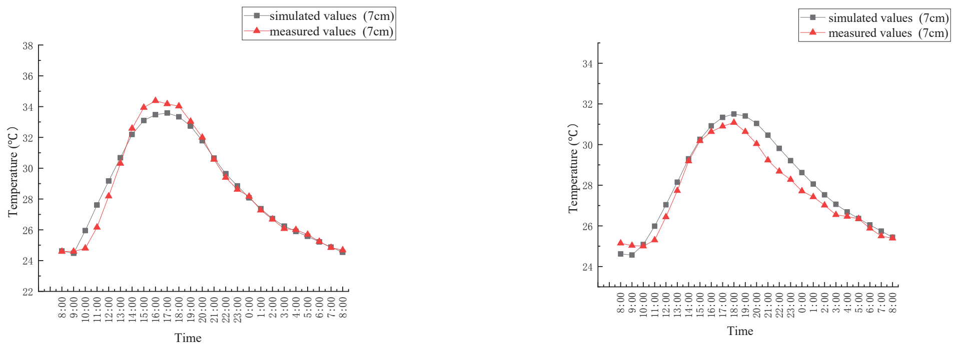
Example 2

The ground temperature of the cornfield was numerically simulated to verify the reliability of the software. The ground temperature at 08:00 on 25 April during the corn growing season was used as the simulated initial temperature, and the temperatures at 14:00 and 20:00 were used to compare the simulated and measured temperatures (Fig. 3). R between the simulated and measured temperatures for 14:00 and 20:00 was 0.9980 and 0.9906, respectively.

Model Application

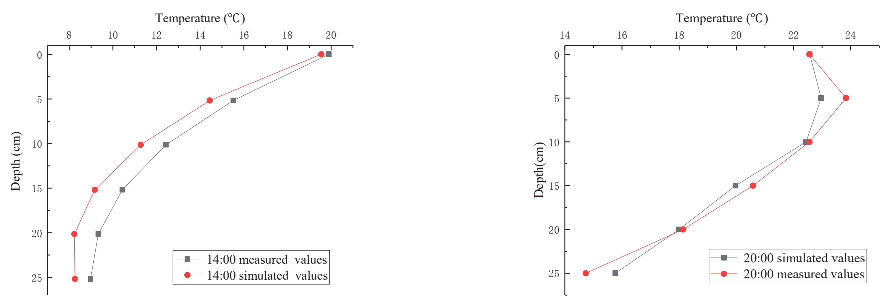
The start and end of each stage of growth of the wheat (Zhou et al. 2016) are presented in Table 2

Temporal and spatial distributions of soil temperature during the growing season of spring wheat: The research object was a field in the experimental region, which was used to simulate and assess the temporal and spatial distributions of soil temperature. Sand mulching thickness is 15 cm. The simulated ground temperature at each depth at 7:00



(a) (b)

Fig. 2: Soil temperature at depths of 5 and 10 cm. (a) Soil temperature at 5 cm; (b) Soil temperature at 10 cm.



(a) (b)

Fig. 3: Simulated and measured ground temperatures at each depth. (a) Simulated and measured ground temperatures at 14:00;(b) Simulated and measured ground temperatures at 20:00.

Table 2: Stages of growth of the spring wheat.

Growth period	Sow-emerge	Emerge-tiller	Tiller-jointing	Jointing-heading	Heading-maturity
Number of days/d	16	20	14	22	52
Date	03-24 to 04-09	04-09 to 04-28	04-28 to 05-12	05-12 to 06-03	06-03 to 07-25

during the growing season was higher with than without sand mulching (Fig. 4), and the temperature increased linearly with depth both with and without mulching. The simulated ground temperature at each depth at 14:00 during the growing season was lower with than without sand mulching, and the temperature decreased with depth both with and without mulching. Ground temperature and depth were not linearly correlated at 14:00, consistent with the results reported by Li et al. (2003). Determining the relationship between soil temperature and depth at 20:00 and 00:00 will require further study. The fitted functions of the simulated and measured temperatures at 7:00 and 14:00 are presented in Table 3. In each fitting equation, x represents temperature (°C) and y represents depth (cm).

Distribution of difference in soil temperature (ΔT) over time during the growing season of spring wheat: The difference in temperature between sand mulching and bare ground at each depth of soil was used as the research object. The range of variation of the temperature difference during the growing season was in the order 0>5>10>15>20>25 cm, indicating that the thermal influence was stronger in shallower soil (Fig. 5). The range of the temperature difference was within ±3°C. The temperature difference at each depth in each stage was positive from 01:00 to 08:00. The temperature at each depth was higher with than without mulching, indicating that the sand mulch effectively preserved heat at night. The temperature difference during the daytime until 18:00 at each depth during the growing season was negative. The temperature during this period was lower with than without mulching, indicating that the sand mulch impeded the transfer of heat at mid-day. The temperature difference at each depth during the growing season tended to become positive by 22:00, indicating that evening was a transitional period of heat transfer.

Distribution of temperature gradient with time in different periods of spring wheat during the growing season: The temperature gradient represents the vertical change in temperature and thus the intensity of heat transfer in the vertical direction (Ao et al. 2015). The temperature gradient from 01:00 to 9:00 was positive both with and without

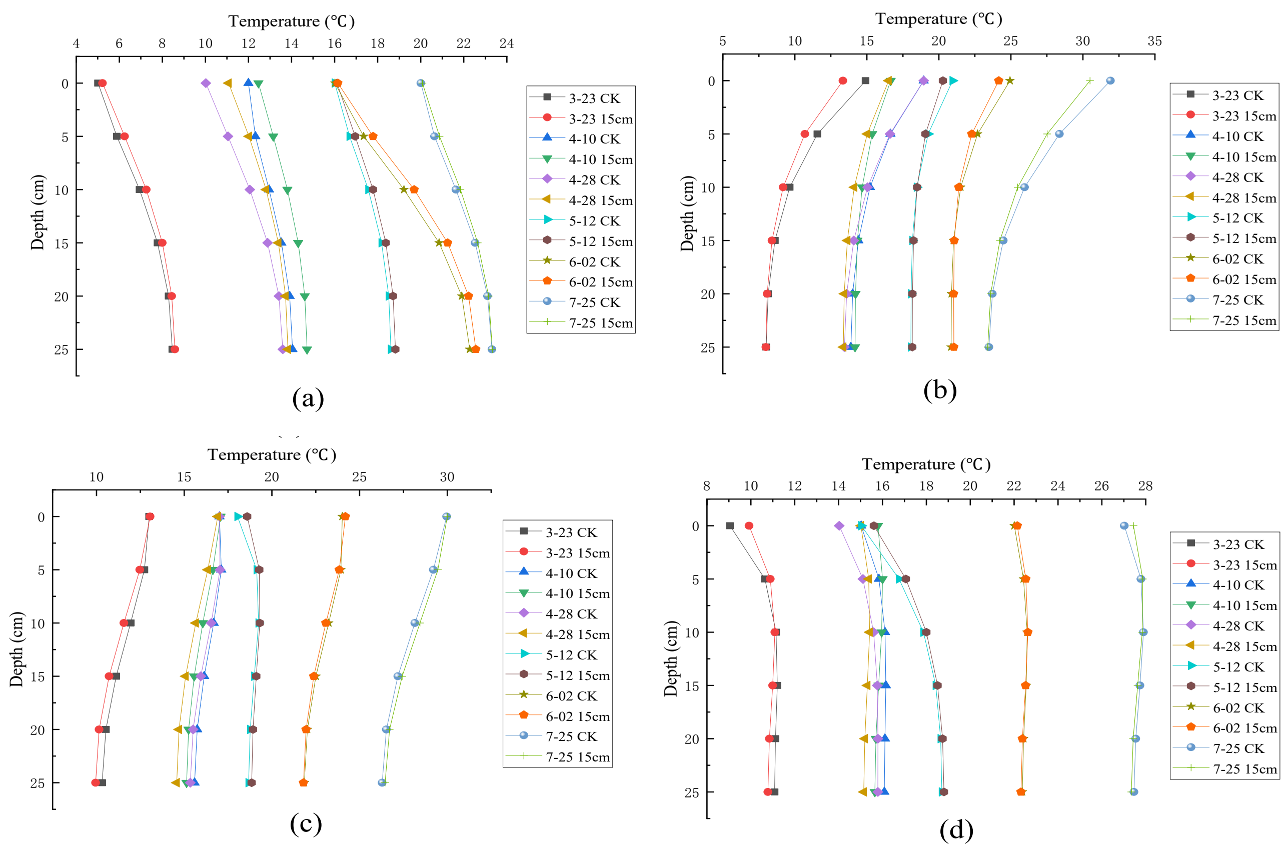


Fig. 4: Simulated ground temperatures at the various stages of growth of the spring wheat. (a) Ground Temperature at 07:00 during the growing season; (b) Ground temperature at 14:00 during the growing season; (c) Ground temperature at 20:00 during the growing season; (d) Ground temperature at 00:00 during the growing season.

Table 3: Fitting of the simulated temperature and depth during the growing season of the spring wheat.

Time	Growth period and coverage	Fitting equation	Decision coefficient （R2）	Time	Growth period and coverage	Fitting equation	Decision coefficient （R2）
7:00	3-23 CK	y = 6.598x - 34.097	$R^2 = 0.9547$	7:00	3-23 15cm	y = 6.8114x - 37.159	$R^2 = 0.9388$
	4-10 CK	y = 10.895x - 130.53	$R^2 = 0.9705$		4-10 15cm	y = 10.2x - 128.72	$R^2 = 0.9422$
	4-28 CK	y = 6.458x - 66.106	$R^2 = 0.9521$		4-28 15cm	y = 33.132x - 430.74	$R^2 = 0.9030$
	5-12 CK	y = 8.5895x - 138.64	$R^2 = 0.9382$		5-12 15cm	y = 8.3987x - 136.95	$R^2 = 0.9327$
	6-02 CK	y = 3.6291x - 58.642	$R^2 = 0.9664$		6-02 15cm	y = 3.5707x - 58.712	$R^2 = 0.9570$
	7-25 CK	y = 6.8357x - 136.99	$R^2 = 0.9685$		7-25 15cm	y = 7.0335x - 142.14	$R^2 = 0.9596$
14:00	3-23 CK	y = 0.6358x2 - 17.68x + 122.64	$R^2 = 0.9500$	14:00	3-23 15cm	y = 1.0814x2 - 27.03x + 168.52	$R^2 = 0.9434$
	4-10 CK	y = 1.1037x2 - 40.536x + 372.23	$R^2 = 0.9574$		4-10 15cm	y = 5.3214x2 - 172.5x + 1397.4	$R^2 = 0.9322$
	4-28 CK	y = 0.8509x2 - 31.543x + 292.62	$R^2 = 0.9646$		4-28 15cm	y = 0.7797x2 - 30.362x + 295.78	$R^2 = 0.9627$
	5-12 CK	y = 4.4317x2 - 179.81x + 1822.1	$R^2 = 0.8936$		5-12 15cm	y = 7.9327x2 - 314.41x + 3114	$R^2 = 0.9065$
	6-02 CK	y = 2.027x2 - 97.748x + 1177.4	$R^2 = 0.9030$		6-02 15cm	y = 3.6048x2 - 169.05x + 1980.4	$R^2 = 0.8513$
	7-25 CK	y = 0.3574x2 - 22.393x + 351.05	$R^2 = 0.9644$		7-25 15cm	y = 0.5058x2 - 30.34x + 455.32	$R^2 = 0.9641$

mulching, indicating that heat was transferred from deep soil to the surface during this period (Fig. 6). The changes in the temperature gradient became negative as the sun continued to rise, and deeper soil gained heat from the surface. The change in the gradient on May 12 was again positive at 20:00 and remained positive at 22:00 for the remainder of the growing season. The range of the variation in the temperature gradient was smaller with than without mulching, mainly because the sandstone effectively reduced the amount of solar radiation received by the surface, consistent with the results reported by Ao et al. (2015).

CONCLUSION

We used VADOSE/W to study the temporal and spatial distributions of soil temperature, the differences in temperature, and the temperature gradient of sand-mulched and bare soil.

(1) We established a model for the transfer of heat within the soil and between soil and the atmosphere using VADOSE/W. The correlation coefficients between the simulated and measured temperatures were >0.97, indicating that the accuracy of the simulation was high, verifying the reliability of the model.

(2) The temporal and spatial distributions of the soil temperature at 7:00 and 14:00 at the various stages of growth of the spring wheat for both mulched and bare soil had linear nonlinear relationships. The relationship between soil temperature and depth for 20:00 and 00:00 requires further study.

(3) The difference in soil temperature at each depth and the temperature gradient were positive from 01:00 to 08:00 at each stage of growth, and the heat was transferred from deep soil to the surface, indicating that sand mulching effectively preserved heat at night. The difference in soil temperature and the temperature gradient during the growing season became negative at all depths as the sun rose, with deeper soil gaining heat from the surface, indicating that sand mulch impeded the transfer of heat at mid-day. The difference in temperature at each depth and the temperature gradient tended to become positive by 22:00, and heat began to transfer from deep soil to the surface. The range of the temperature difference was within ±3°C, and the thermal influence was stronger in shallower soil.

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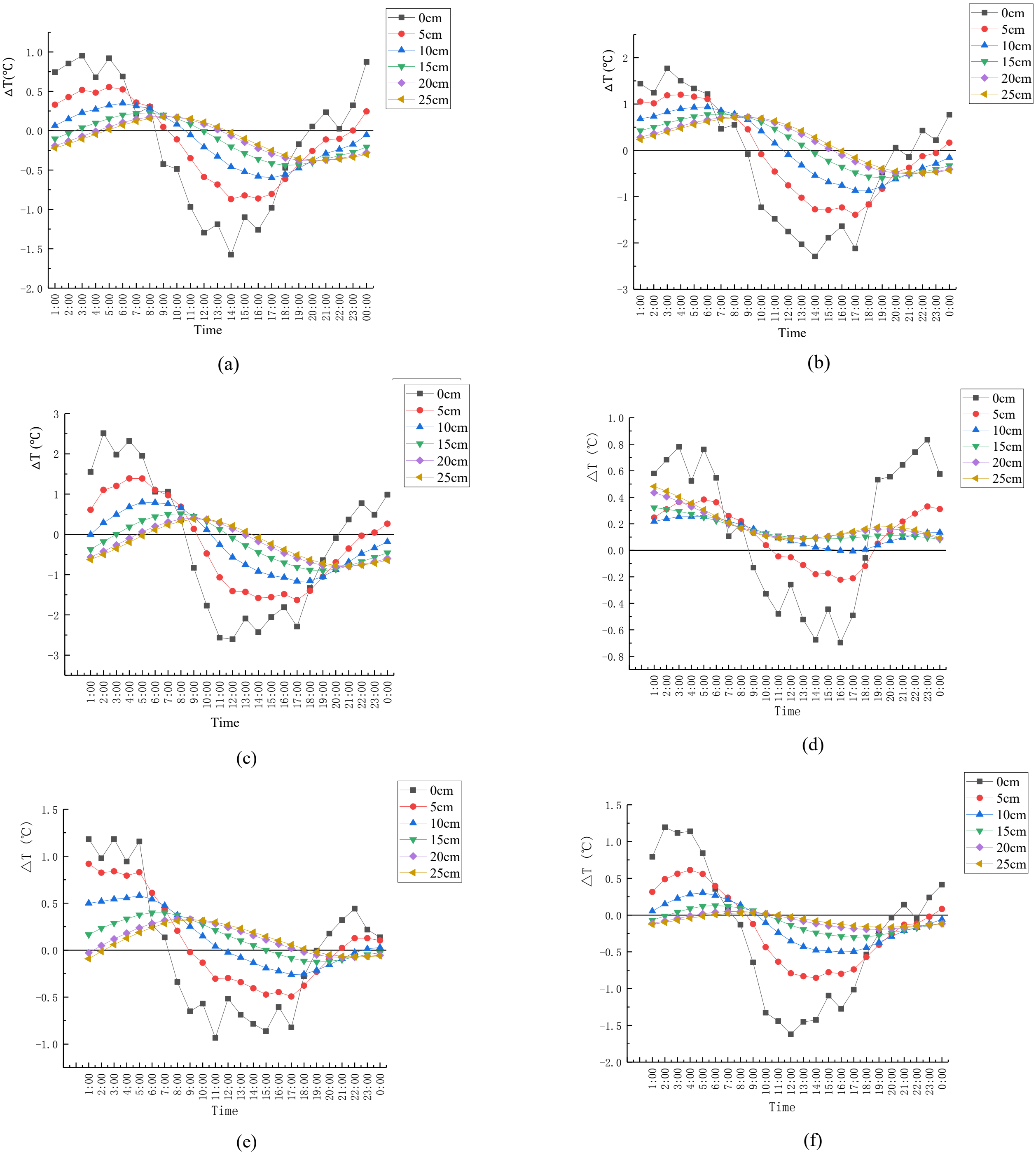
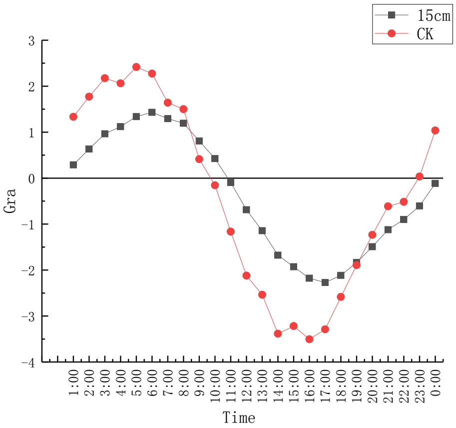


Fig. 5: Distribution of the differences in soil temperature (△T in the various stages of growth of the spring wheat. (a) Distribution of △T over time on 23 March; (b) Distribution of △T over time on 10 April; (c) Distribution of △T over time on 28 April;(d) Distribution of △T over time on 12 May; (e) Distribution of △T over time on 2 June;(f) Distribution of △T over time on 25 July.



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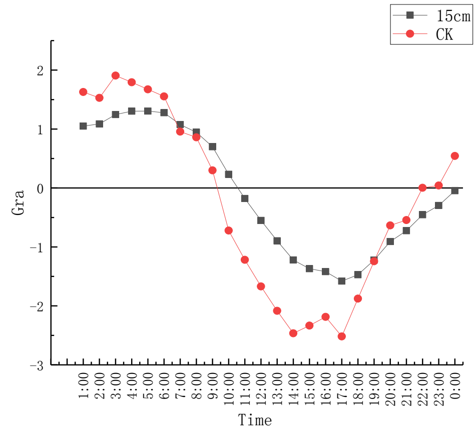

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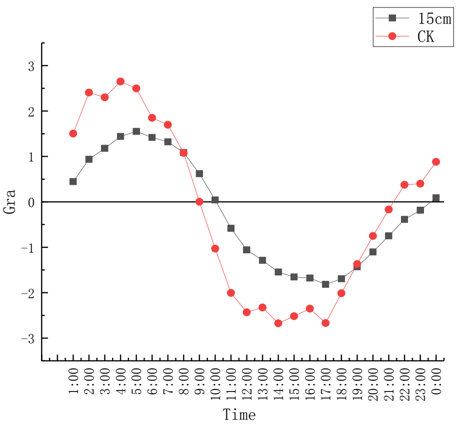

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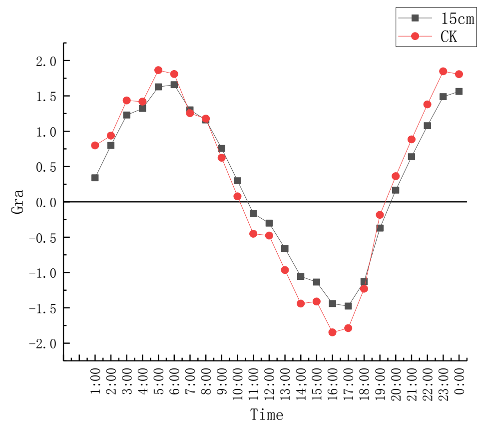

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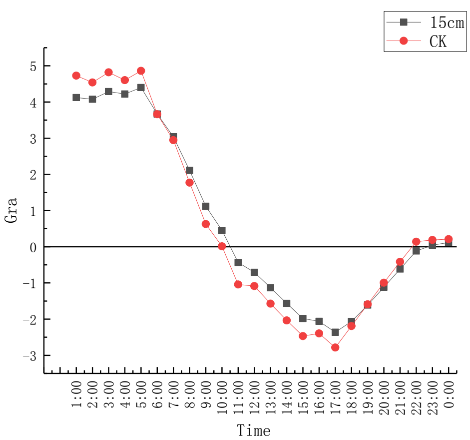

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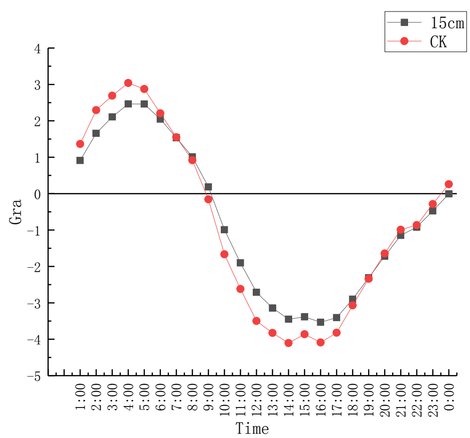

(f)

Fig. 6: Distribution of the temperature gradient (Gra) of the tilled layer during the growing season of the spring wheat. (a) Distribution of Gra over time on 23 March;(b) Distribution of Gra over time on 10 April; (c) Distribution of Gra over time on 28 April; (d) Distribution of Gra over time on 12 May; (e) Distribution of Gra over time on 2 June;(f) Distribution of Gra over time on 25 July.

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