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Research Article

Heliogreenhouse Ground Temperature Forecasting Technology Research

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Abstract: According to internal and external meteorological observation data of the heliogreenhouse from the Shandong Laiwu 2007-2010 winter (December to February), under different weather conditions such as sunny, cloudy and overcast sky, the variation characteristics of the ground temperature as well as its relationship with the internal and external meteorological elements were analyzed. By considering the internal and external meteorological elements of the greenhouse as the triggering factors, a forecast model was constructed to predict the 10 cm hourly ground temperature for the next three days. The results showed that due to the impact of heat exchange between air and the soil surface near the greenhouse, during the day, the temperature gradually reduced with the deepening of the soil, while the opposite trend was observed at night; for shallow soil, the diurnal range of the ground temperature was greater than that of the deep soil layer. The daily maximum temperature showed a gradually decreasing trend from the soil surface to the deep layer, while the daily minimum ground temperature showed an increasing trend. According to the forecast model's prediction results of the 10 cm ground temperature for three weather conditions (sunny, cloudy and overcast sky), the overall forecast accuracy was relatively high, among which the forecast accuracy on overcast days was greater than on sunny or cloudy days. Among the three periods of the day, the forecast accuracy for the time periods 00:00-07:00 and 18:00-23:00 was better than that of 08:00-17:00. The RMSE average values of the 10 cm ground temperature for the next first, second and third day were 0.5, 0.6 and 0.8°C, respectively and with the increasing prediction time, the forecast accuracy gradually decreased.

Keywords: Forecast, ground temperature, heliogreenhouse, model

INTRODUCTION

The main role of the heliogreenhouses in China is horticultural crops, especially the anti-season production of vegetables in winter. In this production process, the ground temperature is one of the main meteorological factors that have a direct impact on vegetable development. The research conducted by Walker (1969) has shown that if the ground temperature is lower than the temperature required for physiological activities of crop roots, the root growth will be blocked, resulting in poor growth and even death. Numerous reports have been published about the relationships of heligreenhouse at home and abroad. Kurpaska and Slipek (1996) identified greenhouse thermal environment parameters through observation of the different soil temperature variations under the heating conditions. Salomez and Hofman (2007) considered the 10cm ground temperature in the greenhouse as input values of lettuce growth model. Based on experimental observations, Bai *et al*. (1998) explored the variation characteristics of the air temperature and ground temperature of the heliogreenhouse in winter. Zhao *et al*. (2008) investigated the diurnal variations characteristics of the ground temperature of each layer in the heliogreenhouse under different weather conditions. Tong *et al*. (2010) revealed the characteristics of marginal effect of ground temperature within the heliogreenhouse using computational fluid simulation technology. According to the relationship of the solar elevation angle and the greenhouse air-ground temperature, Yun and Zhang (1992) constructed a ground temperature forecast model with the solar elevation angle as the independent variable. The study conducted by Zhang *et al*. (2009) showed the significant correlation between the greenhouse temperature and the 5cm ground temperature after two hours and thus, they constructed a ground temperature prediction model based on temperature values from early adjacent time level. Using the theory of heat conduction, He *et al*. (2005) constructed a theoretical model about the effect of the internal and external weather conditions on indoor ground temperature of a heliogreenhouses within 30 min. The abovementioned

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studies of the foreign scholars mainly focus on the modern greenhouse, while most of the domestic research involves simple analysis of variation characteristics of the heliogreenhouses ground temperature. However, the ground temperature model construction, a single initiation factor, the limited forecast accuracy and the short forecast effectiveness are all unable to meet the demands of the greenhouse production management for meteorological support services.

Until now, the research related to using the internal and external meteorological factors of the heliogreenhouses as the driving factors to forecast heliogreenhouses ground temperature for next three days has not yet been reported. In this research, through experimental observation, the dynamic forecast model was constructed to predict the 10 cm ground temperature of the heliogreenhouses in winter for the next 3 days, in order to provide the basis for scientific production management of the heliogreenhouse.

MATERIALS AND METHODS

Experimental design: The experiment was carried out during the winter of 2007-2010 (December-February) in Shandong Laiwu Daxia Farm 10th Heliogreenhouse. The heliogreenhouses faced south, with east to west length of 60 m, north-south span of 10 m and ridge height of 3 m. The three sides facing east, west and north were solid walls with thickness of 1m. The heliogreenhouses roof covering films were polyethylene anti-fogging films. There was cultivation of vegetables such as tomatoes in the heliogreenhouses.

The heliogreenhouses microclimate observation elements included indoor air temperature, humidity, radiation and ground temperature (0, 5, 10, 20, 40 cm). The ZQZ-A automatic weather station was used as the observation instrument and the data acquisition frequency was once per hour. The external meteorological data of the heliogreenhouses originated from the Meteorological Bureau of Laiwu City.

Data processing and analysis: Solar radiation is the main source of energy for the production of the heliogreenhouse. The microclimate within the heliogreenhouses was quite different under different weather conditions; therefore, three types of forecast models were constructed according to the three weather conditions namely sunny, cloudy and overcast sky, respectively. The division method of weather type is sunshine percentage method (p = sunshine hours/ duration of possible sunshine), among which, $p \geq 0.6$ is considered as sunny days, $0.2 \leq p < 0.6$ as cloudy days, $p < 0.2$ as overcast days. The forecast method mainly uses linear and nonlinear statistical methods.

Model verification: The accuracy of the model was verified by using the Root Mean Squared Error (RMSE) between the observed and predicted values; the smaller the RMSE value, the higher the prediction accuracy of the model. The RMSE values are calculated as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(O_i - S_i)^2}{N}} \quad (1)$$

where, O_i, S_i and N indicate the observed value, predicted value and sample size, respectively.

RESULTS AND ANALYSIS

Variation characteristics of ground temperature of the heliogreenhouse in winter: Figure 1 shows the graph of the daily changes in ground temperature at varying depths of the heliogreenhouse under different weather types in Laiwu winter. The figure shows that there was a consistent trend between the ground temperatures at different depths in the heliogreenhouse. It was evident that the temperature in the daytime was higher than that at night. During the day, the temperature gradually decreased as soil depth increased, while the opposite trend was observed at

Table 1: The maximum, minimum values and diurnal range of ground temperature at varying depths of the heliogreenhouse in winter (Laiwu)

		Soil depth (cm)				
Weather type		0	5	10	20	40
Sunny	Maximum temperature (°C)	26.3	21.9	18.9	17.0	16.7
	Minimum temperature (°C)	12.0	13.2	14.3	15.2	16.4
	Diurnal range (°C)	14.3	8.70	4.60	1.70	0.30
Cloudy	Maximum temperature (°C)	23.3	19.6	17.8	16.7	16.8
	Minimum temperature (°C)	12.6	13.7	14.6	15.5	16.6
	Diurnal range (°C)	10.7	5.90	3.20	1.20	0.20
Overcast sky	Maximum temperature (°C)	17.9	16.4	16.0	16.5	16.6
	Minimum temperature (°C)	12.6	13.5	14.3	15.2	16.4
	Diurnal range (°C)	5.30	2.90	1.60	1.30	0.20

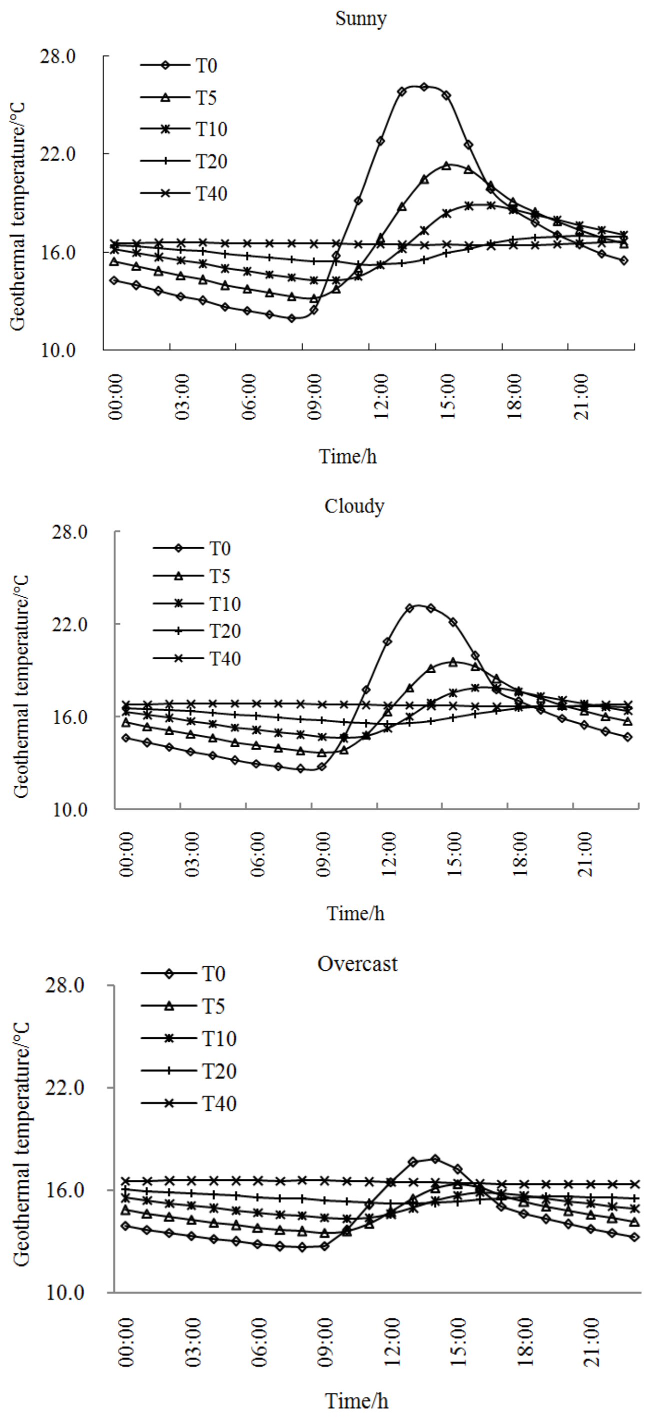


Fig. 1: Figure of daily changes in ground temperature at varying depths of the heliogreenhouse in winter under different weather types (Laiwu); (a): shows the data for sunny days, (b): for cloudy days and (c): for overcast sky. The data is plotted with ground temperature (°C) on the vertical axis and time (h) on the horizontal axis; (T0: ground temperature, T5: 5 cm ground temperature, T10: 10 cm ground temperature, T20: 20 cm ground temperature, T40: 40 cm ground temperature)

night; the shallower the soil, the greater the diurnal range of the ground temperature. As shown in Table 1, under each type of weather condition, as the soil depth increased, the maximum temperature tended to decrease gradually and the minimum daily temperature showed an increasing trend. For 0, 5, 10, 20, 40 cm depths, the average diurnal ranges of ground temperature were 10.1, 5.9, 3.2, 1.4 and 0.2°C, respectively. With increasing depth of the soil, especially below 20 cm, the diurnal variation of the temperature tended to stable. In addition, the weather type greatly affected the diurnal range of the ground temperature; sunny weather had the greatest impact, followed by cloudy weather and overcast sky had the smallest impact. The effect of weather types on shallow ground temperature was particularly evident. Under sunny conditions, the average diurnal range of ground temperature at the three layers 0, 5, 10 cm was 9.2°C and was 2.6, 6.0°C higher than the cloudy and overcast days, respectively. The diurnal range of the deep ground temperature gradually reduced after being influenced by weather type.

Construction of heliogreenhouses ground temperature forecast model: According to the classification model of three weather types namely sunny, cloudy and overcast sky as mentioned in above section, the observation data of indoor ground temperature and the internal and external meteorological elements of the greenhouse in winter of 2007 and 2008 was analyzed and the forecast model was constructed to predict the hourly ground temperature in the heliogreenhouses for the next three days. Table 2 to 5 show the hourly 10 cm ground temperature forecast model for the next three days in heliogreenhouses under sunny conditions in winter. As shown in these Tables, the 10 cm hourly ground temperature on one day was influenced by the outdoor maximum and minimum ground temperatures of the same day and the day before as well as the indoor 10 cm ground temperature on the day before. For the hourly 10 cm ground temperature forecast model for the next two days and three days, the forecast factors were selected mainly from the maximum and minimum ground temperatures on previous one and two days as well as the hourly 10 cm ground temperature from previous different time periods, among which the latter were the predicted values for the indoor hourly 10 cm ground temperature. Since the hourly ground temperature forecast model was being constructed in this experiment, during the construction of the model, time was introduced as the triggering factor, the values were the time series data for the next 24 h, such that x = 0, 1, 2...23.

Model verification: The observational data from winter 2009 as mentioned in above section was used for the construction of the hourly 10 cm ground temperature forecast model of the next one, two and three days and the predicted values were obtained. Compared to the measured values, the average values of absolute error for the next one, two and three days were 0.4, 0.5 and 0.8°C, respectively. With the prolongation of the forecast period, the error showed an increasing trend. The average error values for the three types of weather conditions, namely sunny, cloudy and

Table 2: The forecast model for 10cm ground temperature for one day in the heliogreenhouse on sunny days

Time period	Forecast model	Variable name
00:00-07:00	$Y = 13.15-0.13X_1+0.25X_2-0.0758X_3-0.0156X_2^2+0.027X_3^2$ (SE = 0.48, $R^2 = 0.90^{**}$)	X_1: Time X_2: Minimum indoor 10 cm ground temperature on the previous day (°C) X_3: Minimum outdoor air temperature on the previous day(°C)
08:00-17:00	$Y = 11.3+0.64X_1+0.075X_2+0.28X_3-0.9X_4-0.03X_3X_4+0.042X_4^2$ (SE = 0.70, $R^2 = 0.86^{**}$)	X_1: Time X_2: Minimum outdoor air temperature on the same day (°C) X_3: Maximum outdoor air temperature on the previous day (°C) X_4: Maximum indoor 10 cm ground temperature on the previous day (°C)
18:00-23:00	$Y = 9.6-0.16X_1+0.65X_2+0.54X_4+0.011X_2X_3-0.06X_2X_4-0.018X_4^2$ (SE = 0.44, $R^2 = 0.92^{**}$)	X_1: Time X_2: Maximum outdoor air temperature on the same day (°C) X_3: Maximum outdoor air temperature on the previous day (°C) X_4: Maximum indoor 10 cm ground temperature on the previous day (°C)

Table 3: The forecast model for 10cm ground temperature for the next two days in the heliogreenhouse on sunny days

Time	Forecast model	Variable name
00:00-7:00	$Y = 1.73+0.8X_2+1.4X_4-1.6X_5-0.028X_1X_4-0.015X_2X_3-0.07X_2X_4+0.09X_2X_5-0.076X_3X_5+0.033X_4X_5+0.04X_1^2-0.089X_4^2+0.011X_5^2$ (SE = 0.69, $R^2 = 0.85^{**}$)	X_1: Time X_2: Hourly indoor 10 cm ground temperature in the time period 18:00-23:00 on the previous day (°C) X_3: Minimum outdoor air temperature on the previous day (°C) X_4: Minimum indoor air temperature before two days (°C) X_5: Minimum outdoor air temperature before two days (°C)
08:00-17:00	$Y = 8.18+0.5X_1+0.56X_3-0.069X_4+0.0268X_5-0.009X_1X_3+0.015X_1X_4+0.005X_1X_5+0.013X_2X_3+0.024X_2X_4-0.025X_2X_5-0.009X_1^2-0.02X_3^2-0.01X_4^2$ (SE = 1.3, $R^2 = 0.80^{**}$)	X_1: Time X_2: Hourly indoor 10 cm ground temperature in the time period 00:00-7:00 on the same day (°C) X_3: Minimum outdoor air temperature on the previous day (°C) X_4: Maximum indoor air temperature before two days (°C) X_5: Minimum outdoor air temperature before two days (°C)
18:00-23:00	$Y = 6.9+1.01X_1+0.35X_2+0.2X_3-0.04X_4-0.009X_1X_2-0.009X_1X_4+0.0022X_1X_5+0.017X_2X_4+0.02X_3X_4-0.007X_4X_5-0.023X_1^2-0.01X_2^2-0.02X_4^2$ (SE = 0.72, R2=0.83^{**})	X_1: Time X_2: Minimum outdoor air temperature on the same day (°C) X_3: Hourly indoor 10 cm ground temperature in the time period 08:00-17:00 on the same day (°C) X_4: Minimum outdoor air temperature on the previous day (°C) X_5: Minimum indoor air temperature before two days (°C)

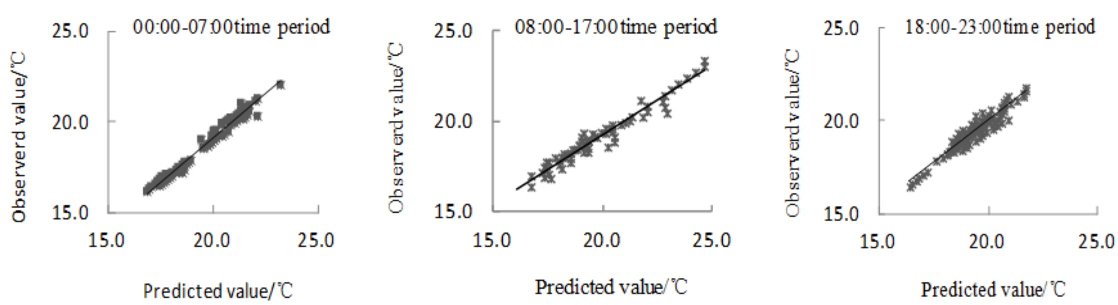
Table 4: The forecast model for 10cm ground temperature for the next three days in the heliogreenhouse on sunny days

Time	Forecast model	Variable name
00:00-7:00	$Y = 4.7+1.17X_1+0.075X_2+0.22X_3-0.097X_4-0.22X_5+0.005X_1X_3+0.017X_1X_5-0.019X_2X_3-0.03X_2X_4+0.044X_3X_4-0.005X_3X_5-0.03X_1^2-0.006X_4^2+0.004X_5^2$ ($SE = 0.71$, $R^2 = 0.85^{**}$)	X_1: Time X_2: Hourly indoor 10 cm ground temperature in the time period 18:00-23:00 on the previous day (°C) X_4: Maximum outdoor air temperature on the previous day (°C) X_5: Minimum outdoor air temperature before two days (°C)
08:00-17:00	$Y = 10.38+0.7X_1+0.023X_2-0.06X_4+0.027X_1X_3+0.013X_2X_3-0.019X_2X_4+0.02X_2X_5-0.13X_3X_5-0.002X_2^2+0.017X_3^2-0.017X_4^2-0.01X_5^2$ ($SE = 1.7$, $R^2 = 0.78^{**}$)	X_1: Time X_2: Hourly indoor 10 cm ground temperature in the time period 00:00-7:00 on the same day (°C) X_3: Minimum outdoor air temperature on the same day (°C) X_4: Maximum outdoor air temperature on the previous day (°C) X_5: Minimum outdoor air temperature before two days (°C)
18:00-23:00	$Y = 3.65+1.3X_1+0.44X_2-0.5X_3+0.7X_4-0.03X_1X_2+0.03X_1X_3-0.04X_1X_4+0.043X_2X_3-0.051X_2X_4+0.06X_2X_5-0.03X_1^2-0.007X_2^2+0.011X_3^2-0.014X_4^2-0.01X_5^2$ ($SE = 1.4$, $R^2 = 0.80^{**}$)	X_1: Time X_2: Hourly indoor 10 cm ground temperature in the time period 08:00-17:00 on the same day (°C) X_3: Maximum outdoor air temperature on the same day (°C) X_4: Maximum outdoor air temperature on the previous day (°C) X_5: Maximum outdoor air temperature before two days (°C)

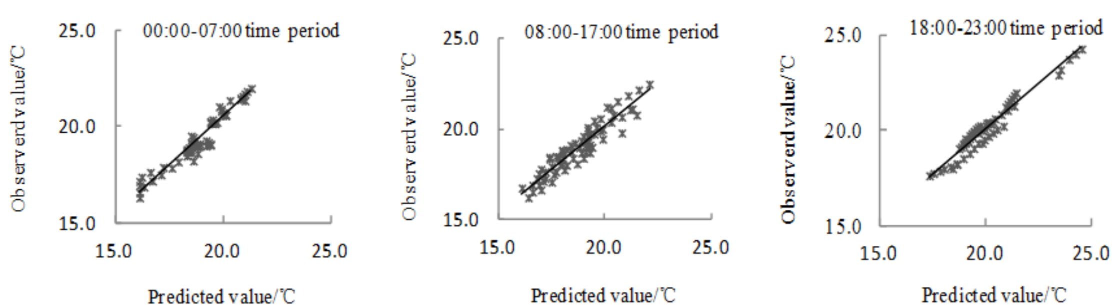
R^2 is the coefficient of determination, SE is standard error

Table 5: Prediction error values of the hourly 10cm ground temperature within the heliogreenhouse for the next one, two and three days under varying weather conditions in winter

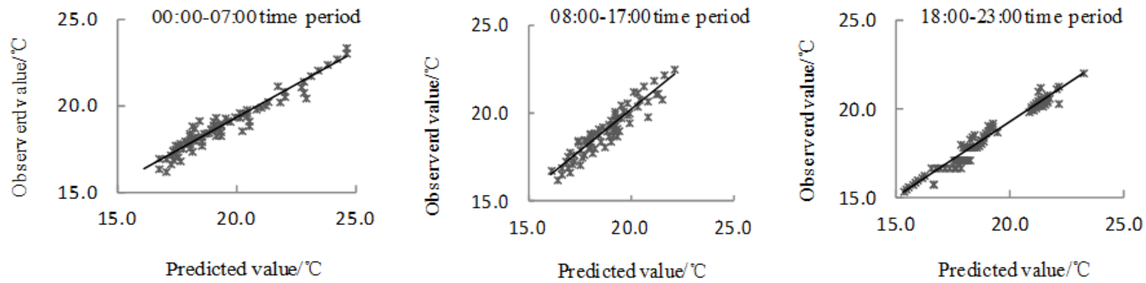
		Average absolute error(°C)		
Prediction time	Time period	Sunny	Cloudy	Overcast sky
The first day	00:00-07:00	0.31	0.42	0.43
	08:00-17:00	0.48	0.49	0.44
	18:00-23:00	0.37	0.39	0.30
The second day	00:00-07:00	0.45	0.49	0.37
	08:00-17:00	0.5	0.54	0.47
	18:00-23:00	0.47	0.68	0.43
The third day	00:00-07:00	0.66	1.19	0.66
	08:00-17:00	0.85	1.28	0.70
	18:00-23:00	0.63	0.98	0.61



(a) The 1:1 comparison chart of the prediction and measured values of hourly 10 cm ground temperature under sunny conditions in the heliogreenhouse on the first day in winter



(b) The 1:1 comparison chart of the prediction and measured values of hourly 10 cm ground temperature under sunny conditions in the heliogreenhouse on the second day in winter



(c) The 1:1 comparison chart of the prediction and measured values of hourly 10 cm ground temperature under sunny conditions in the heliogreenhouse on the third day in winter

Fig. 2: The 1:1 comparison chart of the predicted and measured values of hourly 10 cm ground temperature under sunny conditions in the heliogreenhouses on the next one, two and three days

overcast sky were respectively as follows: 0.5, 0.7 and 0.5°C; the prediction error for cloudy conditions was greater than that for other weather types. According to the calculations of formula (1), the average RMSE values for the three weather types, namely sunny, cloudy and overcast sky were respectively 0.7, 0.8 and 0.6°C. The average RMSE values for the three time periods, namely 00:00-07:00, 08:00-17:00 and 18:00-23:00 were respectively 0.6, 0.7 and 0.6°C. The average RMSE values for hourly 10cm ground temperature on the next one, two and three days were 0.5, 0.6 and 0.8°C, respectively. From the absolute error and RMSE values of the predicted and measured values, it is evident that the forecast model had high prediction accuracy. Figure 2 is a comparison chart of the predicted and measured values of hourly 10cm ground temperature under sunny conditions in the heliogreenhouses on the next one, two and three days.

CONCLUSION AND DISCUSSION

Variation characteristics of heliogreenhouses ground temperature: Under all types of weather conditions, the diurnal range of temperature of different soil layers gradually decreased with increasing soil depth. The temperature variation of the soil below 20 cm was relatively stable. The diurnal amplitude of the ground temperature on the surface, 5 and 10 cm was significantly influenced by weather types because there was greater heat exchange between the atmosphere near the surface layer of the heliogreenhouses and the shallow soil. The soil is the storage of the heat. During the day, it absorbs the solar radiation and carries out the heat exchange with the atmosphere near the surface layer. The temperature increases rapidly and the ground temperature of the shallow layer is significantly greater than that of the deep soil layer. At night, the stored heat is released to improve the heliogreenhouses air temperature, often presented as air temperature being less than ground temperature of deep soil layer. In addition, on sunny days, the shallow soil layer absorbs more solar radiation for heat storage, thus heating up faster. On cloudy days, there is no solar radiation during the day and the external temperature is low and the heliogreenhouses temperature is relatively low; therefore, the ground temperature of the shallow soil layer increases slowly and the diurnal amplitude is relatively small.

Heliogreenhouses ground temperature forecast model: In the case of assimilation products of plants roots and leaves, there is not only a relationship between the sink and the source but also between the supply and demand of water and nutrients. The soil temperature directly influences the root activity, thus affects the absorption of water and mineral nutrition (Walker, 1969); therefore, the levels of ground temperature have some restriction on the production of vegetables and their quality. The accurate prediction of variations in ground temperature is especially important for taking reasonable production management measures. Taking into account that most of the physiological activities of vegetable roots occur about below 0-40 cm of the soil surface layer in the heliogreenhouses; the area where the roots are largely concentrated is 0-20 cm (Fang *et al*., 2010; Liu *et al*., 2012; Wu *et al*., 1994) and the ground temperature below 20 cm is relatively stable. Therefore, this study mainly constructed the 10 cm ground temperature forecast model, taking into account the relationships between the different weather types, different time periods within the heliogreenhouse, external meteorological factors as well and the ground temperature.

In addition, taking into consideration the heliogreenhouse energy from the solar radiation, there were many differences between magnitude of energy input for varying time periods during each day as well as the production management and other factors; the variation characteristics of the ground temperature were also significantly different; therefore, the forecast model was constructed for three time periods, namely 00:00-07:00, 08:00-17:00, 18:00-23:00 in order to improve the prediction accuracy of the forecast model.

Forecast model accuracy: The results showed that the prediction accuracy was greater on overcast days than on sunny or cloudy days because in the absence of solar radiation, the heliogreenhouses does not obtain enough energy supplements and thus the internal air temperature is low. In such cases, producers often reduce the heliogreenhouses ventilation or even do not ventilate in order to avoid excessive human interference. Similarly, in the three time periods of the day, the forecasting effectiveness of the time periods 00:00-07:00, 18:00-23:00 was better than that of 08:00-17:00, mainly due to the interference caused by daytime ventilation and production management activities; while during the time period between covering sheet at night and taken off early in the morning, the heliogreenhouses is in a closed state and the factors affecting the change in indoor ground temperature are relatively few; therefore, the prediction accuracy is higher. The 10 cm ground temperature forecast model for the next one day under all weather types had the highest prediction accuracy, however, as the forecast time was prolonged, the forecast accuracy gradually reduced. Some input factors of the forecast model for the next one, two and three days were considered as the predicted values. There were certain differences in these predicted values and the observed values; therefore, the prediction accuracy decreased.

In this study, the model was constructed using statistical methods but the soil thermal conductivity and other physical processes in different soil layers were not considered, which had a certain impact on the prediction accuracy of the forecast model.

Moreover, the variation in heliogreenhouses ground temperature is influenced by several factors, such as film materials, light transmittance, ventilation management and vegetable species. These factors directly or indirectly affect the amount of solar radiation received by the ground as well as the degree of the heat exchange between ground and air. The quantitative influence of the above-mentioned factors on the ground temperature is to be further studied.

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