Construction and Evaluation of Transfer Function of Marginal Soil Temperature on the South Side of Greenhouse under Different Linings

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Abstract. The marginal soil temperature on the south side of a greenhouse remains at low temperatures in winter for long periods, which affects crop growth and land-use efficiency, it is of great significance to grasp the influencing factors of soil temperature change to improve the marginal soil temperature on the south side of the greenhouse. This study was conducted in at typical greenhouse in the cold and arid area of northern China and used the Grey Relational Analysis (GRA) method, the relational degree between the marginal soil temperature on the south side of the greenhouse and environmental factors under different lining structures was analyzed, and established the soil temperature transfer function. The results show that soil temperature had the greatest correlation with the soil humidity and air humidity inside and outside the greenhouse, and the second greatest correlation was the relation with the air temperature inside and outside the greenhouse and the outdoor soil temperature; the lining structure could effectively reduce the relation between soil temperature and humidity inside and outside the greenhouse. Polystyrene extruded board (PEB) had a greater degree of relational reduction than other lining materials in the test. Through verification analysis, the mean absolute error of soil temperature of 5 cm was less than 0.85 °C, the average absolute error of soil temperature at 15 cm was less than 0.57 °C, and the average absolute error of soil temperature at 25 and 55 cm was less than 0.2 °C. In conclusion, the constructed soil temperature transfer function could be used to predict the variation trend of soil temperature, and the PEB material lining structure had good thermal insulation.

Soil temperature affects the growth and development of crops (Sun, 2005). Studies have shown that a 1 °C difference in soil temperature will seriously affect crop growth and development (Sarkar et al., 2007; Sypka et al., 2016). Soil temperature has a time lag and is directly related to air temperature and groundcover (Roxy et al., 2014). Ta et al. (2014) used the peak fitting method to fit the soil temperature change curve under different water content; it concluded that as long as the relevant parameter values of the extreme function were determined, the change function of soil temperature to time could be obtained. Saiyin et al. (2019) used Gaussian function multipeak fitting and linear fitting methods to analyze the relationship between soil temperature and moisture content, and the results showed that the relationship

between soil temperature and soil moisture content was linear: the closer to the surface, the more obvious the linearity. Some scholars have established the soil temperature transfer function through multiple linear regression methods, nonlinear regression methods, artificial neural network methods, classification regression trees, and typing mechanisms; they have all been well applied (Liu et al., 2007; Minasny and McBratney, 2002; Schaap et al., 1998). The soil on the south side of a greenhouse in winter was often affected by marginal effects, resulting in lower soil temperature that directly affected the growth of crops on the south side (Sun, 2008; Sun et al., 2009). Researchers have suggested various improvements to the southern boundary of greenhouses, such as sinking the greenhouse (Wang, 2012; Wang et al., 2012), adding a cold-proof ditch outside a greenhouse (Shang, 2016), and adopting an internal arch (Zhang, 2017; Zhang et al., 2017). It reduced the distance of the greenhouse boundary and increased the soil temperature at the southern boundary of the greenhouse.

On the basis of this research, scholars have conducted an in-depth analysis of the changes in soil temperature through different methods for many years, but there are few studies on the changes in soil temperature at

the southern boundary of the greenhouse in winter in cold and arid regions. In this study, by testing the internal and external environmental changes of the greenhouse in cold and arid regions, the GRA method was used to establish the soil temperature transfer function for the soil at different linings and depths on the southern margin of a greenhouse. Therefore, the law of soil temperature changed on the southern boundary of the greenhouse and effective cold protection measures on the southern boundary of the greenhouse were obtained.

Materials and Methods

Test area. The test area was located in Hohhot, Inner Mongolia, the test base of Hailiutu Science and Technology Park of Inner Mongolia Agricultural University (lat. 40.69°N, long. 111.38°E). The experimental greenhouse was a new type of greenhouse with inner and outer double-layer covering film. Compared with other types of the greenhouse, its thermal insulation performance is better, and it is suitable for the cold, dry areas of northern China. The greenhouse faced south with a length of 70 m in the east–west direction and a span of 8.5 m in the north–south direction.

Test method. Inner Mongolia is located in a cold and arid area, the winter is as long as 5–6 months, and the annual sunshine time is 2863 h. The experiment started on 11 Nov. 2020 and selected data from 7 through 10 Dec. 2020 for analysis, with a total of 131 data points, 96 data points were selected for analysis and modeling, and the remaining 31 data points were selected for model verification. To reduce the influence of the boundary effect around the greenhouse on the experiment, the experiment selected the central area of the greenhouse as the experiment area, and divided it into five areas: no lining structure group (CK), PEB buried 30 cm deep (PEB30), PEB buried 60 cm deep (PEB60), and cement brick buried 30 cm deep (CB30). Each test area was 2.4 m long from east to west. According to the preliminary analysis of the test data, it was found that the soil temperature and humidity changes in the unlined IV and unlined V areas were similar, so this article only analyzes the IV area. The lining structure was buried outside the foundation on the south side of the greenhouse, the soil temperature and humidity sensors inside and outside the greenhouse were buried at soil depths of 5, 15, 25, and 55 cm. The outdoor soil temperature and humidity sensor was 20 cm away from the lining structure, and the indoor soil temperature and humidity sensor were 10 cm away from the foundation on the south side of the greenhouse (Fig. 1).

Test instrument. The soil temperature and humidity sensor produced by China He Bei Ousu Electronic Technology Co., Ltd. was used: soil temperature measurement ranged from –30 to 70 °C, measurement accuracy was ±0.2 °C; soil moisture ranged from 0% to 50%, measurement accuracy was ±2% (m³/m³). The air temperature and humidity sensor used was produced by China Dalian Zheqin Electronic Technology Co., Ltd. The

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Fig. 1. Overview of the test area and test plan design. The upper left picture is a flat map of the test area, the geographic location of the test area is lat. 40.69°N and long. 111.38°E. The upper right picture shows the experimental greenhouse, the double-layer solar greenhouse. The picture in the lower left corner is the top view of the test of different linings. The picture in the lower right corner shows the position of the soil temperature and humidity sensor in the soil. The longitudinal depth is based on the soil surface and the horizontal distance. The interior of the greenhouse is based on the inner surface of the foundation on the south side, and the outside of the greenhouse is based on the lining structure.

air temperature and humidity sensor was arranged in the middle of the greenhouse, 110 cm from the south and 50 cm from the ground. For sensor accuracy, temperature measurement range was -40 to 80°C , with an accuracy of $\pm 0.2^{\circ}\text{C}$; for humidity, the range was 0% to 100% , with a measurement accuracy of $\pm 3\%$ (m^3/m^3). The weather station used the U.S. Onset HOBO small weather station provided by Beijing Tiannuo Foundation Technology Co., Ltd (Bourne, MA) and was arranged outside the greenhouse to measure the environmental changes outside the greenhouse. Test data include outdoor temperature, humidity, water content, wind speed, wind direction, and pressure solar radiation (Fig. 2).

Methods. GRA, proposed by Professor Julong Deng in the early 1980s, has been widely used in agriculture, social economy, and other fields and has led to remarkable achievements (Deng, 1990; Liu, 1999). In recent years, it had been widely used in the correlation analysis of soil temperature, humidity, and environmental factors. The so-called degree of correlation was essentially the degree of

difference between the geometric shapes of the curves. The theoretical basis was as follows (Deng, 1990; Fu et al., 2018; Ma, 2018):

1. Due to the different physical meanings of the representative factors of each data sequence, the data in the sequence has different

Fig. 2. Soil temperature and humidity sensor, air temperature and humidity sensor, small weather station test location. (A) Soil temperature and humidity sensor, after the sensor is buried, and the soil is backfilled and compacted. (B) Air temperature and humidity sensor: the sensor was arranged in the middle of the greenhouse, 110 cm from the south and 50 cm from the ground. (C) Outdoor weather stations, located in an open area outside the greenhouse.

Table 1. Relational degree between soil temperature and environmental factors at 5-cm soil depth.

Environ. factor	CK group		PEB60 group		PEB30 group		CB30 group	
	GRA coeff.	RR	GRA coeff.	RR	GRA coeff.	RR	GRA coeff.	RR
ISMC	0.6890	2	0.7186	1	0.7421	1	0.7065	2
OSMC	0.7490	1	0.7017	2	0.7052	2	0.7369	1
OST	0.5339	6	0.4910	6	0.4905	7	0.4983	7
IRH	0.6624	3	0.6213	3	0.7017	3	0.6801	3
IAT	0.5545	5	0.5672	5	0.5192	6	0.5523	5
OAT	0.4934	7	0.4794	7	0.5958	5	0.5070	6
ORH	0.6084	4	0.6166	4	0.7003	4	0.6268	4
SR	0.3544	8	0.3542	8	0.3500	8	0.3542	8

Coeff. = coefficient; environ = environmental; PEB60 = PEB buried 60 cm deep; PEB30 = PEB buried 30 cm deep; CB30 = cement brick buried 30 cm deep; RR = relevance ranking; ISMC = indoor soil moisture content; OSMC = outdoor soil moisture content; OST = outdoor soil temperature; IRH = indoor relative humidity; IAT = indoor ambient temperature; OAT = outdoor ambient temperature; ORH = outdoor relative humidity; SR = sun radiation.

Table 2. Relational degree between soil temperature and environmental factors at 15-cm soil depth.

Environ. factor	CK group		PEB60 group		PEB30 group		CB30 group	
	GRA coeff.	RR	GRA coeff.	RR	GRA coeff.	RR	GRA coeff.	GRA coeff.
ISMC	0.8848	1	0.8773	1	0.8297	2	0.8842	1
OSMC	0.8569	2	0.8440	2	0.8402	1	0.8468	2
OST	0.8029	3	0.7650	5	0.7561	3	0.7962	4
IRH	0.7999	4	0.7820	3	0.7266	4	0.8011	3
IAT	0.5150	7	0.5138	7	0.5138	7	0.5110	7
OAT	0.5864	6	0.5943	6	0.6109	6	0.5988	6
ORH	0.7749	5	0.7678	4	0.8181	5	0.7840	5
SR	0.3470	8	0.3516	8	0.3504	8	0.3500	8

Coeff. = coefficient; environ = environmental; PEB60 = PEB buried 60 cm deep; PEB30 = PEB buried 30 cm deep; CB30 = cement brick buried 30 cm deep; RR = relevance ranking; ISMC = indoor soil moisture content; OSMC = outdoor soil moisture content; OST = outdoor soil temperature; IRH = indoor relative humidity; IAT = indoor ambient temperature; OAT = outdoor ambient temperature; ORH = outdoor relative humidity; SR = sun radiation.

Table 3. Relational degree between soil temperature and environmental factors at 25-cm soil depth.

Environ. factor	CK group		PEB60 group		PEB30 group		CB30 group	
	GRA coeff.	RR	GRA coeff.	RR	GRA coeff.	RR	GRA coeff.	GRA coeff.
ISMC	0.9381	2	0.9385	1	0.9464	1	0.9253	2
OSMC	0.9402	1	0.9083	2	0.9060	2	0.9263	1
OST	0.8037	5	0.7497	5	0.7486	5	0.7501	5
IRH	0.8262	3	0.8078	4	0.8487	3	0.9173	3
IAT	0.5089	7	0.5074	7	0.5029	7	0.5032	7
OAT	0.6040	6	0.6061	6	0.6049	6	0.6176	6
ORH	0.8122	4	0.8214	3	0.8114	4	0.8858	4
SR	0.3488	8	0.3493	8	0.3515	8	0.3774	8

Coeff. = coefficient; environ = environmental; PEB60 = PEB buried 60 cm deep; PEB30 = PEB buried 30 cm deep; CB30 = cement brick buried 30 cm deep; RR = relevance ranking; ISMC = indoor soil moisture content; OSMC = outdoor soil moisture content; OST = outdoor soil temperature; IRH = indoor relative humidity; IAT = indoor ambient temperature; OAT = outdoor ambient temperature; ORH = outdoor relative humidity; SR = sun radiation.

Table 4. Relational degree between soil temperature and environmental factors at 55-cm soil depth.

Environ. factor	CK group		PEB60 group		PEB30 group		CB30 group	
	GRA coeff.	RR	GRA coeff.	RR	GRA coeff.	RR	GRA coeff.	RR
ISMC	0.9576	1	0.9602	1	0.9429	2	0.9565	1
OSMC	0.9569	2	0.9522	2	0.9571	1	0.9530	2
OST	0.8605	3	0.8352	5	0.8370	3	0.8365	3
IRH	0.8390	4	0.8384	4	0.8369	4	0.8339	4
IAT	0.4785	7	0.4695	7	0.4837	7	0.5008	7
OAT	0.6050	6	0.6015	6	0.5967	6	0.6006	6
ORH	0.8011	5	0.8390	3	0.8098	5	0.8023	5
SR	0.3490	8	0.3495	8	0.3516	8	0.3512	8

Coeff. = coefficient; environ = environmental; PEB60 = PEB buried 60 cm deep; PEB30 = PEB buried 30 cm deep; CB30 = cement brick buried 30 cm deep; RR = relevance ranking; ISMC = indoor soil moisture content; OSMC = outdoor soil moisture content; OST = outdoor soil temperature; IRH = indoor relative humidity; IAT = indoor ambient temperature; OAT = outdoor ambient temperature; ORH = outdoor relative humidity; SR = sun radiation.

dimensions and therefore needs to be processed without dimension

$$X'_0(k) = X_0(k)/X_0(1)$$

$$= \{X'_0(1), X'_0(2), X'_0(3), \dots, X'_0(n)\}$$

$$X'_i(k) = X_i(k)/X_i(1)$$

$$= \{X'_i(1), X'_i(2), X'_i(3), \dots, X'_i(n)\},$$

where $X_0(k)$ is the standard sequence, $X_i(k)$ is the comparison sequence, i is the number of sequences, $i = 1, 2, 3, \dots, m$, k is the number of variables in the sequence, $k = 1, 2, 3, \dots, n$.

This study used the method of averaging to make the data dimensionless; averaging method transformation was mostly used for correlation analysis of periodic changes of natural factors (Deng 1990). This study was also a correlation analysis of greenhouse soil temperature and periodic changes of environmental factors, so the mean value method was used for dimensionless processing of the data.

2. After the reference and comparison sequences were dimensionless processed, each variable in the reference sequence was compared with each variable in the sequence, and the absolute value was taken to obtain the difference sequence:

$$\Delta_i(k) = |X'_0(k) - X'_i(k)|$$

$$= \{\Delta_i(1), \Delta_i(2), \Delta_i(3), \dots, \Delta_i(n)\}$$

3. The maximum and minimum difference between the two poles of the elements in each sequence were calculated:

$$M = \max_i \max_k \Delta_i(k)$$

$$m = \min_i \min_k \Delta_i(k)$$

4. By screening the largest and smallest differences in the sequences, the correlation coefficient between each variable in the reference sequence and the comparison sequence was calculated:

$$\varepsilon_{0i}(k) = \frac{m + \varepsilon M}{\Delta_i(k) + \varepsilon M},$$

where ε is the resolution coefficient, the value is between 0 and 1. This study used the recommended value of 0.1.

5. The degree of association between sequences was calculated:

$$\gamma_{0i} = \frac{1}{n} \sum_{k=1}^n \varepsilon_{0i}(k)$$

The GRA method was combined with linear regression (Fu et al., 2015; Wang et al., 2019; Yao et al., 2014) to construct the transfer function of soil temperature. First, GRA was used to analyze the relation between different test areas and soil temperature at different depths as well as various environmental factors; then, the transfer function between soil temperature and major environmental factors was constructed by linear programming with the environmental factor of relational

degree >0.6. Further, the multiple regression model of environmental factor and soil temperature was established, and the two models were verified.

Model accuracy evaluation. Selected mean square error (MSE) and the coefficient of determination (R^2) (Li et al., 2007) were used to evaluate model accuracy. The MSE reflected the overall error between the measured value and the simulated value: the smaller the MSE, the higher the measurement accuracy. R^2 evaluated the accuracy of the constructed transfer function, reflecting the degree of agreement between the measured value and the simulated value.

$$MSE = \frac{\sum_{i=1}^N (y_{mi} - y_{pi})^2}{N}$$

$$R^2 = 1 - \frac{SSE}{SSQ} = \frac{\sum_{i=1}^N (y_{pi} - \bar{y}_m)^2}{\sum_{i=1}^N (y_{mi} - \bar{y}_m)^2},$$

where y_{mi} is the measured value of the model, y_{pi} is the estimated value of the model, $\bar{y}_m$ is the average of the measured values, and N is the total number of samples.

Results

Selection of main environmental factors.

The change in soil temperature was mainly due to the energy exchange between the soil

and atmosphere (Tang, 2019). Hu and Feng (2005) studied soil temperature, surface temperature, and precipitation data and found that surface temperature had a significant impact on soil temperature throughout the entire continent. Zhao et al. (2016) found that the meteorological factors affecting soil temperature were arranged according to the degree of influence—namely, solar radiation, precipitation, air temperature, water vapor pressure, relative humidity, and wind speed—based on field experiments. The coefficients of determination of the multiple linear regression equations of soil depth and soil temperature were all greater than 0.93. Liu et al. (2018) analyzed the change characteristics of soil water and heat in Daqingshan area of Guangxi and its relationship with meteorological elements. The results showed that air temperature was the main element that affects soil temperature, followed by soil moisture. Ma (2018) and Tang et al. (2019) used the GRA to analyze the relation between soil temperature and environmental factors. Our research group (Saiyin et al., 2019; Ta et al., 2014) had tested the soil temperature and humidity in greenhouses for many years and found that there was a functional relationship between soil temperature and soil moisture content. Our study was intended to explore the relationship between the soil temperature at different depths in a

greenhouse and the environmental factors inside and outside a greenhouse under different lining conditions, combined with years of discussion in the literature on the relation between soil temperature changes and meteorological factors. The following environmental factors and the soil temperature in the greenhouse were selected: outdoor ambient temperature (OAT), outdoor relative humidity (ORH), sun radiation (SR), outdoor soil temperature (OST), outdoor soil moisture content (OSMC), indoor ambient temperature (IAT), indoor relative humidity (IRH), indoor soil temperature (IST), and indoor soil moisture content (ISMC).

Because the test area was in the cold and dry area of northern Inner Mongolia, there was less rainfall in winter; thus, this study mainly analyzed the test data on sunny days. According to weather station data, the wind speed in winter was mostly gusty, with a wind speed of 0 m/s most of the time, so this study did not consider the influence of wind speed. The test area was mainly the marginal soil on the south side of the greenhouse. Because of the low soil temperature in winter and lack of crop growth in this area, the influence of soil organic matter and humus on soil temperature was ignored.

GRA of soil temperature. The size of the grey correlation reflects the closeness of each

Table 5. Grey relational soil temperature transfer function.

Soil depth	Lining structure	Soil temp transfer function	R^2
5 cm	CK	$Y = 58.707 - 380.589X_1 + 123.863X_2 - 3.55X_4 - 4.609X_7$	0.727
	PEB60	$Y = 0.978 + 98.073X_1 - 98.472X_2 - 5.632X_4 - 7.448 X_7$	0.902
	PEB30	$Y = 68.785 - 278.37X_1 + 8.621X_2 - 2.02X_4 - 0.127X_7$	0.897
	CB30	$Y = 48.012 - 243.06X_1 + 76.546X_2 - 4.693X_4 - 5.002X_7$	0.865
15 cm	CK	$Y = 24.17 - 80.817X_1 + 14.452X_2 + 0.399X_3 - 2.414X_4 - 1.627X_7$	0.679
	PEB60	$Y = 8.936 - 49.149X_1 + 83.559X_2 + 0.635X_3 + 0.097X_4 + 0.287X_7$	0.787
	PEB30	$Y = 25.284 - 78.092X_1 + 22.286X_2 + 0.147X_3 - 0.533X_4 - 0.001X_6 + 0.067X_7$	0.776
	CB30	$Y = 25.112 - 103.427X_1 - 29.044X_2 + 0.052X_3 - 1.378X_4 - 3.491X_7$	0.741
25 cm	CK	$Y = 33.261 - 118X_1 - 3.747X_2 - 0.048X_3 - 1.132X_4 - 0.042X_6 - 1.109X_7$	0.736
	PEB60	$Y = 18.303 - 69.77X_1 + 48.244X_2 + 0.258X_3 - 0.384X_4 - 0.038X_6 - 0.533X_7$	0.835
	PEB30	$Y = 27.834 - 75.597X_1 - 3.227X_2 - 0.067X_3 + 0.045X_4 - 0.026X_6 - 0.049X_7$	0.814
	CB30	$Y = 31.848 - 99.71X_1 - 14.553X_2 + 0.05X_3 - 0.752X_4 - 0.04X_6 - 0.879X_7$	0.748
55 cm	CK	$Y = 25.192 - 54.324X_1 + 1.643X_2 + 0.117X_3 + 0.442X_4 - 0.023X_6 - 0.658X_7$	0.739
	PEB60	$Y = 26.58 - 40.08X_1 - 6.848X_2 + 0.176X_3 + 0.737X_4 - 0.027X_6 - 0.793X_7$	0.792
	PEB30	$Y = 19.39 - 52.154X_1 + 11.468X_2 + 0.193X_3 + 0.893X_4 - 0.793X_7$	0.789
	CB30	$Y = 25.301 - 73.914X_1 + 0.799X_2 + 0.15X_3 + 0.547X_4 - 0.025X_6 - 0.645X_7$	0.757

PEB60 = PEB buried 60 cm deep; PEB30 = PEB buried 30 cm deep; CB30 = cement brick buried 30 cm deep.

Table 6. Multiple regression transfer function.

Soil depth	Lining structure	Multiple regression transfer function	R^2
5 cm	CK	$Y = 36.308 - 199.684X_1 + 19.946X_2 - 0.412X_3 - 0.439X_4 + 0.174X_5 + 0.243X_6 - 2.404X_7 - 0.008X_8$	0.796
	PEB60	$Y = 7.033 + 22.663X_1 - 76.29X_2 - 0.51X_3 + 0.2X_4 + 0.171X_5 + 0.426X_6 - 2.454X_7 - 0.002X_8$	0.920
	PEB30	$Y = 36.537 - 132.082X_1 + 2.34X_2 - 0.009X_3 - 0.818X_4 + 0.008X_5 + 0.068X_6 + 1.948X_7 - 0.001X_8$	0.854
	CB30	$Y = 36.959 - 181.428X_1 + 28X_2 - 0.155X_3 + 0.222X_4 + 0.134X_5 + 0.161X_6 - 1.068X_7 - 0.009X_8$	0.823
15 cm	CK	$Y = 100.972X_1 + 18.585X_2 - 0.183X_3 - 0.784X_4 + 0.008X_5 + 0.054X_6 + 0.088X_7 - 0.003X_8$	0.666
	PEB60	$Y = 13.353 - 53.049X_1 + 59.412X_2 + 0.482X_3 + 0.283X_4 + 0.022X_5 + 0.01X_6 + 0.807X_7 - 0.003X_8$	0.850
	PEB30	$Y = 24.935 - 76.235X_1 + 17.693X_2 + 0.122X_3 - 0.406X_4 + 0.009X_5 - 0.009X_6 + 0.241X_7 - 0.001X_8$	0.697
	CB30	$Y = 29.002 - 104.503X_1 - 5.139X_2 + 0.055X_3 - 1.172X_4 + 0.018X_5 - 0.013X_6 + 1.273X_7 - 0.003X_8$	0.686
25 cm	CK	$Y = 32.832 - 120.358X_1 + 0.161X_2 - 0.03X_3 - 0.777X_4 - 0.01X_5 - 0.028X_6 - 1.02X_7 - 5.839E - 5X_8$	0.635
	PEB60	$Y = 18.585 - 49.931X_1 + 18.041X_2 + 0.26X_3 - 0.252X_4 + 0.013X_5 - 0.031X_6 + 0.053X_7 - 0.001X_8$	0.769
	PEB30	$Y = 27.396 - 77.742X_1 + 1.269X_2 - 0.038X_3 + 0.14X_4 - 0.001X_5 - 0.032X_6 - 0.297X_7 - 0.000X_8$	0.824
	CB30	$Y = 31.717 - 94.751X_1 - 18.05X_2 + 0.052X_3 - 0.706X_4 - 0.002X_5 - 0.039X_6 - 0.934X_7 - 6.495E - 5X_8$	0.748
55 cm	CK	$Y = 27.051 - 60.286X_1 + 3.58X_2 + 0.053X_3 + 0.207X_4 - 0.008X_5 - 0.027X_6 - 1.028X_7 + 0.001X_8$	0.721
	PEB60	$Y = 28.201 - 40.913X_1 - 9.355X_2 + 0.121X_3 + 0.436X_4 - 0.006X_5 - 0.033X_6 - 1.165X_7 - 0.001X_8$	0.817
	PEB30	$Y = 25.25 - 55.376X_1 - 3.706X_2 + 0.021X_3 + 0.478X_4 - 0.009X_5 - 0.021X_6 - 0.823X_7 + 0.001X_8$	0.865
	CB30	$Y = 25.522 - 74.175X_1 - 0.48X_2 + 0.14X_3 + 0.473X_4 - 0.001X_5 - 0.027X_6 - 0.708X_7 - 0.000X_8$	0.759

PEB60 = PEB buried 60 cm deep; PEB30 = PEB buried 30 cm deep; CB30 = cement brick buried 30 cm deep.

influencing factor to the soil temperature: the larger the grey correlation degree and the closer to 1: the closer the connection between the reference sequence and the comparison sequence, the greater the influence of the comparison sequence on the reference sequence; conversely, the more distant the connection, the smaller the impact (Tang et al., 2019).

Table 1 shows the correlation between soil temperature and environmental factors at a depth of 5 cm compared with the PEB60, PEB30, and CB30 lining structure test groups. Further, the relation between soil temperature and OSMC in the CK group increased by 6.32%, 5.85%, and 1.62%, respectively, the correlation between soil temperature and OST increased by 8.04%, 8.13%, and 6.67%, respectively, in the PEB60, PEB30, and CB30 groups.

Table 2 shows the correlation between soil temperature and environmental factors at a depth of 15 cm, compared with the PEB60, PEB30, CB30 lining structure test group, the

relational degree between soil temperature and OSMC in the CK group increased by 1.51%, 1.95%, and 1.18%, respectively, the correlation between soil temperature and OST increased by 4.72%, 5.83%, and 3.08%, respectively.

Table 3 showed the correlation between soil temperature and environmental factors at a depth of 25 cm compared with the PEB60, PEB30, and CB30 lining structure test groups; the correlation between soil temperature and OSMC in the CK group increased by 3.39%, 3.22%, and 1.48%, respectively. The relational degree between soil temperature and OST increased by 6.72%, 6.86%, and 6.67%, respectively.

Table 4 shows the correlation between soil temperature and environmental factors at a soil depth of 55 cm; at this depth, only the PEB60 group still had a lining structure, and the relational degree between the soil temperature of the PEB60 group and OSMC and OST was lower than that of other test groups. In summary, the correlation between soil

temperature and humidity outside the greenhouse showed that the lining structure could reduce the relational degree between the soil temperature in the greenhouse and the external soil water and heat, and to a certain extent affect the energy transfer between the soil outside and inside the greenhouse. By comparing the same test groups in Tables 1–4, it was found that the relation among ISMC, OSMC, IRH, ORH, and OAT and soil temperature was $55 > 25 > 15 > 5$ cm. This shows that as the depth increases, the relation between the five environmental factors and soil temperature became stronger. The relation between IAT and soil temperature was $5 > 15 > 25 > 55$ cm, indicating that the influence of air temperature in the greenhouse on soil temperature weakens with increased depth. SR had the weakest correlation with soil temperature. The main reason was that amount sunshine time in the winter greenhouse was 6 to 7 h, and the heat preservation roller blind was covered during the rest of a 24-h period.

Fig. 3. The 5-cm soil model test comparison. The points in the figure and the X- and Y-axes are temperature values ($^{\circ}\text{C}$).

Three different lining forms (PEB60, PEB30, CB30) were studied; in 5-cm soil, the relation between OSMC and soil temperature was $CB30 > PEB30 > PEB60$. The relation between OST and soil temperature was $CB30 > PEB60 > PEB30$. In 15- and 25-cm soil, the relation between OSMC and OST and soil temperature was $CB30 > PEB60 > PEB30$. In summary, among the soils above 25 cm, OSMC and OST had the strongest relation to greenhouse soil temperature among the CB30 lining methods, and their influence on the soil energy transfer inside and outside the greenhouse was greater than that of PEB30/60 lining. In the 55-cm soil, for the PEB60 test group, OSMC, OST, and the soil temperature relational degree were slightly lower than in the PEB30 and CB30 groups, indicating that in 55-cm-deep soil, deep lining buried to 60 cm could affect soil energy transfer.

In summary, the lining structure on the southern margin of the greenhouse could

effectively reduce the correlation between the soil temperature and humidity inside and outside the greenhouse. Among the same buried depth and different lining structures, the relation of PEB lining structure was lower than that of CB lining structure, indicating that PEB lining structure could effectively prevent the movement of soil water and heat. Among the PEB lining structures at different burial depths, at 55 cm, the relational degree of soil temperature inside and outside the greenhouse was close. The main reason was that the variation range of soil temperature at 55-cm depth inside and outside the greenhouse was relatively weak. Considering the material cost and construction difficulty, it was suggested to adopt FEB30 lining structure

Construction of soil temperature transfer function. The marginal soil temperature on the south side of the greenhouse was considered as dependent variable Y and the eight

environmental factors as independent variable X. ISMC was recorded as X_1 , OSMC as X_2 , OST as X_3 , IRH as X_4 , IAT as X_5 , OAT as X_6 , ORH as X_7 , and SR as X_8 .

Construction of soil temperature transfer function based on GRA. The above relational analysis showed that environmental factors have different influences on soil temperature at different depths on the southern margin of different lining greenhouses. As shown in Tables 1–4, the environmental factors with relational degrees greater than 0.7, 0.6, 0.5, and 0.4 were used for modeling; according to the model's fit R^2 and model testing, it was found that the model with a relational coefficient greater than 0.6 was better than the others (only the model with a relational degree greater than 0.6 is explained here), established a soil temperature transfer function with a relational degree greater than 0.6, as shown in Table 5.

It can be seen from Table 5 that at different soil depths, the transfer function R^2 was

Fig. 4. The 15-cm soil model test comparison. The points in the figure and the X- and Y-axes are temperature values ($^{\circ}\text{C}$).

expressed as $PEB60 > PEB30 > CB30 > CK$; in the case of the same environmental factors, the experimental group with lining could better explain the relationship between environmental factors and soil temperature. Among them, PEB lining was better than CB lining. At the 55-cm soil layer, because the PEB30, CB30, and CK groups had no lining structure and the PEB60 group still had a lining structure, the PEB60 group could better explain the changes in soil temperature through environmental factors. For different soil depths, the coefficient of determination of the transfer function was $R^2_{5cm} > R^2_{55cm} > R^2_{25cm} > R^2_{15cm}$, showing that the integrity of the lining structure in the middle layer of soil (15 to 25 cm) was better than that of the surface layer (5 cm) and the deep layer (55 cm), so the existence of the lining structure reduced the energy transfer between the middle layer of soil and environmental factors, thereby reducing the coefficient of determination of the regression equation.

Multiple regression transfer function. The multiple regression model for eight environmental factors and soil temperature at different depths was established (Table 6). At different soil depths, the R^2 of the lining structure was greater than that of the CK group, indicating that the eight environmental factors had a greater effect of the marginal soil temperature on the south side of the greenhouse than the CK group. It was shown that more independent variables in the CK group affected soil temperature changes than in the lining test group and that the lining structure could reduce the influence of other environmental factors on soil temperature in the greenhouse. At different soil depths, the coefficient of determination of the multiple regression model was $R^2_{5cm} > R^2_{55cm} > R^2_{25cm} > R^2_{15cm}$, and further that the existence of the lining structure reduced the energy transfer between the middle soil and environmental factors, thereby reducing the coefficient of determination of the regression equation.

As shown in Tables 5 and 6, it could be seen that the two ways to build a transfer function model had a small difference in model fit, but the multivariate transfer function model used more environmental factors, and the test workload was relatively large.

Test and comparison of two soil temperature transfer functions. Using to the established soil temperature transfer function, this study used the remaining data to verify the transfer function; by adjusting the standard error values of the respective variable coefficients of the transfer function, the model simulation value of the soil temperature was calculated. Establishing a linear equation between the measured value (X-axis) and the simulated value (Y-axis), the slope of the fixed equation was $K = 1$. According to the vertical distance between the two transfer function fitting lines and the 1:1 line, the accuracy of the transfer function estimation was judged. The function fitting line was close to the 1:1 line perpendicularly, and the larger the R^2 value, the smaller the MSE value. This

Fig. 5. The 25-cm soil model test comparison. The points in the figure and the X- and Y-axes are temperature values ($^{\circ}C$).

indicates that the model prediction accuracy was higher.

As shown in Fig. 3, for the soil temperature transfer function simulation at a depth of 5 cm, the scattered points of soil temperature were basically distributed on both sides of the 1:1 line, and the fitting line of the grey relational transfer function (GRTF) of the CK group and the PEB60 group was closer to the 1:1 line. R^2 was also better than the multiple regression transfer function (MRTF), the fitted line of the MRTF of the PEB30 group and the CB30 group was closer to the 1:1 line, and the GRTF was smaller than the MRTF MSE value; further, the number of environmental factors in GRTF was small, and the model was simple. In sum, at the 5-cm deep soil, GRTF was selected as the prediction model, and the absolute errors of each regional model were 0.24, 0.35, 0.25, and 0.55 °C, respectively.

As shown in Fig. 4, the measured and simulated values of the two soil temperature transfer functions at a depth of 15 cm were verified by the CK group, PEB60 group, and CB30

group. The fitting line of the GRTF was closer to the 1:1 line, and the two transfer functions of the PEB30 group the simulation results were similar, but the GRTF could express soil temperature with fewer environmental factors, so the GRTF was selected. The absolute errors of each region model were 0.19, 0.18, 0.21, and 0.22 °C, respectively.

As shown in Fig. 5, the 25-cm-deep soil temperature transfer function was verified. It was found that the distance between the two transfer functions was almost equal to the 1:1 line. The measured and simulated values of the two transfer functions were poorly fitted, mainly due to the 25-cm soil and soil temperature. The magnitude of change was small, and both transfer functions could simulate soil temperature changes well, but GRTF used fewer environmental factors and the model was simple. The absolute errors of each region model were 0.12, 0.16, 0.12, and 0.14 °C, respectively.

As shown in Fig. 6, 55-cm-deep soil temperature transfer function simulation, the MRTF fitting lines of CK, PEB60, and

PEB30 groups were closer to the 1:1 line, and the degree of fit R^2 was also higher than the GRTF. However, by comparing the absolute value of the Y-axis intercept, it was found that the average error of the Y-axis intercept of the two transfer functions was 0.05 °C, and the error was small; the GRTF had fewer variables, and the model was simple. In the CB30 group, the GRTF coincided with the 1:1 line, and the fit R^2 was 0.729, which was a good fit. In summary, the soil temperature transfer function constructed based on grey correlation had higher estimation longitude, a simple model, and better effect.

GRTF verification. The verification of the two transfer functions (Fig. 4–6) showed that the transfer function model of the correlation degree was simple to express and could be used to predict soil temperature with fewer environmental factors. In the 25- and 55-cm deep soil, the absolute error of the correlation transfer function was smaller than that of 5- and 15-cm-deep soils. To verify the feasibility of the correlation transfer function, the test

Fig. 6. The 55-cm soil model test comparison. The points in the figure and the X- and Y-axes are temperature values (°C).

data from 16–18 Dec. 2020 and 3–4 Jan. 2021 were selected, where the outdoor temperature was relatively low (approximately -20°C), to verify the transfer function of the 5- and 15-cm soil temperature correlation (Figs. 7 and 8). The results show that the average absolute error between the predicted value and the measured value of the 5-cm soil temperature correlation degree transfer function was less than 0.85°C ; the average absolute error of 15-cm soil temperature was less than 0.57°C . The GRTF prediction was more accurate, and the soil temperature could be predicted based on environmental factors.

Discussion

Through the foregoing analysis of the correlation between soil and environmental

factors, it could be seen that the change of soil temperature had the greatest correlation with soil and environmental moisture content, with the increase of depth, the correlation between ambient temperature and soil temperature gradually weakens. This was consistent with the results of Tang et al. (2019). Ma's (2018) research demonstrated a multivariate regression transfer function model of soil temperature to achieve a quantitative description of soil temperature migration and transformation. In our study, by establishing a simpler grey correlation transfer function model, the quantitative description of soil temperature migration and changes under different lining conditions between the soil inside and outside the greenhouse was realized. However, the established soil temperature transfer function still had a certain error. For

example, the mechanical components of the soil were different at different depths and different test areas. These components were closely related to the bulk density of the soil, change of bulk density directly affected the change of porosity, and porosity affects the soil moisture content (Li et al., 2007; Zheng et al., 2012; Zhu et al., 2003). The humus of the soil, such as dead plant matter and root system, was a poor heat conductor and could block heat transmission. In winter, the temperature inside and outside the greenhouse was quite different. The temperature at the plastic film of the greenhouse decreases rapidly in the evening, while the relative humidity of the inner air rises quickly, leading to condensation and frost on the film. With the increase of solar radiation during the day, after the frost melts, part of it would flow down the arc of the greenhouse

Fig. 7. Verification of grey relational transfer function of soil temperature at 5-cm depth. The points in the figure and the X- and Y-axes are temperature values ($^{\circ}\text{C}$).

Fig. 8. Verification of grey relational transfer function of soil temperature at 15-cm depth. The points in the figure and the X- and Y-axes are temperature values ($^{\circ}\text{C}$).

and infiltrate to bottom corner of the south side, which had a greater impact on the temperature transfer function of the soil surface (5 cm). This phenomenon affected the accuracy of the soil temperature transfer function to a certain extent, which also led to the regional characteristics of the soil temperature transfer function and the existence of errors between the simulated and measured values.

Conclusion

Soil moisture, environmental humidity, and environmental temperature had an impact on soil temperature. As the soil depth increases, the correlation between soil moisture and soil temperature also increases; the lining structure could effectively reduce the correlation between soil temperature and humidity inside and

outside the greenhouse. The GRTF could use fewer environmental factors and more accurately predict the change trend of soil temperature. Under the same buried depth of 30 cm, the correlation of the polystyrene extruded board lining was lower than that of the cement brick lining, indicating that the PEB lining could effectively prevent the movement of soil water and heat. When planting crops with root length less than 30 cm in the greenhouse, it is recommended to use PEB lining buried to a 30-cm depth. When planting crops with roots longer than 30 cm in the greenhouse, it is recommended to use PEB buried to a depth of 60 cm.

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