African Journal of Biotechnology Vol. 10(63), pp. 13729-13734, 17 October, 2011
Available online at http://www.academicjournals.org/AJB
DOI: 10.5897/AJB10.2447
ISSN 1684–5315 © 2011 Academic Journals

Full Length Research Paper

Hysteresis of soil temperature under different soil moisture and fertilizer in solar greenhouse conditions

Xing-jun Lin[1], Yin-li Liang[1,2]* and Ze-xiu Wei[2]

[1]Research Center of Soil and Water Conservation and Ecological Environment, Chinese Academy of Sciences and Ministry of Education, Shaanxi Yangling, 712100, China.
[2]Institute of Soil and Water Conservation, Northwest A & F University, Shaanxi Yangling, 712100, China.

Accepted 9 September, 2011

Soil temperature is one of the important variables in spatial prediction of soil energy balance in a solar greenhouse. The objective of this study was to find a simple method to estimate the hysteresis of soil temperature under three soil moisture and two fertilizer levels in solar greenhouse conditions with tomato crop (*Lycopersicon esculentum Mill*). The results show that the soil moisture had no significant effects on the soil mean temperature and had significant effects on the soil hysteresis. The mean soil temperature could not express the relationship between the soil temperature and the air temperature accurately due to the soil hysteresis existence, while the correlation between the diurnal variations, air temperature and soil temperature could describe the soil hysteresis. We applied the phase of sinusoidal curve $T_i = \overline{T_i} + A_i \sin(\omega t - \varphi_i)$ to best approximate the hysteresis effect of soil temperatures. The soil hysteresis increased with the increase of soil depth, and the hysteresis effect of soil temperature was more and more obvious with the increase of soil moisture and the amount of fertilizer. When forecasting the soil hysteresis, we need to take into account, the change of the diurnal variations, soil temperature, the amplitude of soil temperature and initial phase.

Key words: Soil moisture, fertilizer, soil temperature, solar greenhouse.

INTRODUCTION

Soil temperature fluctuates annually and daily as a complex function of many parameters, some of them pertains to the soil itself (thermal properties, moisture content, type of soil, local vegetation cover and depth in the earth), others being related to atmospheric behavior (incident solar radiation and air temperature) (Idso, 1975; Pratt and Ellyett, 1979; Price, 1980; Carlson et al., 1981). During the last few years, investigators have shown increasing interest in the model description of soil temperature (Kang et al., 2000; Plauborg, 2002; Timlin, 2002; Gehrig-Fasel et al., 2008; Tyagi and Satyanarayana, 2010). These models estimate daily soil temperatures and display these values as functions of time or depth for user defined input parameters. Being functions of both soil and atmosphere, the surface temperature can be expected to have spatial structures characteristics of both soil and atmosphere (Al-Kayssi, 2002). Under greenhouse conditions, the atmosphere plays an important role in governing the soil temperature rather than the soil properties (Al-Kayssi et al., 1990). Mathematical models have been developed to describe heat and mass transport processes in the greenhouse microclimate (Kindelam, 1980; Chandra et al., 1981; Trigui et al., 2001; Yang et al., 1990). Due to the much higher heat capacity of soil relative to air and the thermal insulation provided by vegetation and surface soil layers, daily changes in soil temperature deep in the ground are much less than and lag significantly behind daily changes in overlying air temperature. Hysteresis refers to systems where the effects of the current input (or stimulus) to the system are experienced with a certain delay in time. The term "hysteresis" is sometimes used in soil fields where it describes a lagging effect. Hysteresis is a source of soil temperature measurement error. In soil temperature system with hysteresis, it is not possible to predict the

*Corresponding author. E-mail: liangyl@ms.iswc.ac.cn. Tel: +86-29-87012227. Fax: +86-29-87012210.

heat output at an instant, given only heat input at that instant. For this reason, it is difficult to realistically predict soil temperature if not take into consideration, the hysteresis of soil temperature under the different soil moisture and fertilizer, especially in the solar greenhouse. The objective of this study was to find a simple method to estimate the hysteresis of soil temperature under different soil moisture and fertilizer in solar greenhouse conditions.

MATERIALS AND METHODS

Site description

The experiments were conducted from spring to autumn seasons of 2007 and 2008 in the greenhouse at Ansai Experiment Research Station of the Chinese Academy of Sciences, located at Ansai (36°48'N and 109°18' E), Shaanxi Province of China. In the tomato growing season, during 2007 and 2008, minimum and maximum daily average temperature were 11.1 and 27.6℃ in the greenhouse, and 8.2 and 25.6℃ outside the greenhouse, respectively. Solar radiation averaged 2834 $w/m^2/h$ in the greenhouse and 4462 $w/m^2/h$ outside the greenhouse from June to October. The soil was typical loess, with a bulk density of 1.35 $g.cm^{-3}$ and field water holding capacity of 27%. The greenhouse was covered with transparent polyethylene film and planted with tomato plants. Trickle system was used for irrigation.

Experiment design

Tomato seeds were sown in the month of April on seed beds. The seedlings were transplanted in the month of May after completing initial growth stage (that is, 30 days). The water was pumped using a water supply system into an elevated tank of 2000 L capacity, at a height of 1.5 m. Water was applied to the crops using a gravity drip system.

The experimental design was three soil moisture levels: deficit irrigation (W_l, 50 to 60% of soil moisture holding capacity), moderate irrigation (W_m, 70 to 80% of soil moisture holding capacity), high irrigation (W_h, 90 to 100% of soil moisture holding capacity) and two levels of fertilizer application: deficit fertilizer (F_l, 195 kg $N{\cdot}ha^{-1}$ + 47 kg $P_2O_5{\cdot}ha^{-1}$) and moderate fertilizer (F_m, 278 kg $N{\cdot}ha^{-1}$ + 67 kg $P_2O_5{\cdot}ha^{-1}$). Tomatos (Tianfu 501) were transplanted with spacing of 0.5 m between plants and 0.6 m between rows to plots of 2.50 x 2.40 m. A total of six treatments were randomly designed with three repetitions. Two plots at either end comprised of guard rows to eliminate the surrounding effect.

Observational data

Four thermometers (Thermo Recorder TR-52, accuracy ±0.1℃ in the range of -60 to 155℃) were buried in 5, 10, 20 and 35 cm depths of soil to automatically record data once an hour at each plot. Air temperature and relative humidity (HOBO Pro v2 Temperature/RH Data Logger accuracy ±0.2 over 0 to 50℃ and 0.02 at 25℃ in range of -40 to 70℃; ±2.5% from 10 to 90% in range of 0 to 100% RH) was measure at the center of solar greenhouse from a height of 1.5 m. The Profile Probe Type (PR2/4, accuracy ±0.04 $m^3{\cdot}m^{-3}$ in a range of 0 to 0.4 $m^3{\cdot}m^{-3}$) was used to measure the soil moisture of 5, 10, 20 and 35 cm of soil depth and the date was collected every day using HH2 Moisture Meter. With the HH2 and PR2 combination, a probe can be moved from access tube to access tube. After the transplant, all the apparatus were immediately recorded.

Methodology

Phase means a particular appearance or state in a regularly recurring cycle of changes with respect to time.The initial phases of a sinusoidal curve is the fraction of a complete cycle corresponding to an offset in the displacement from a specified reference point at time.

Soil temperatures changed diurnally, and the pattern of soil temperature which changed with respect to time was similar to a sinusoidal curve, so in our analysis, we assumed the soil temperature is governed by the one-dimensional heat conduction equation in the soil, and the soil temperature varied sinusoidally. We applied the sine function (Gao, 2003); $T_i = \overline{T_i} + A_i \sin(\omega t - \varphi_i)$, i=1, 2, 3, 4, 5 to best approximate the curves of soil temperatures collected at the depths of 5, 10, 20 and 35 cm, respectively. $\overline{Ti}$ is the mean temperature at depth Z_i and the amplitude (A_i) of the soil temperature is half of the difference between the daytime maximum value and the night time minimum value. ω is the angular velocity of the Earth's rotation, ω =2π/τ, here τ = 24h. t is the elapsed time, φ_i is the initial phases of soil temperatures at the surface and depths of Z_i.

Analysis software SAS was used to conduct variance analysis and correlation analysis of soil temperature and air temperature.

RESULTS AND DISCUSSION

The effects of soil moisture and fertilizer on the correlation between the average daily soil temperature and air temperature

Mean soil temperature, a standard index for the thermal climates of soil, is necessary for accurate soil resource inventory and for climate studies. It has been universally used as an independent variable relating the average reaction rates of physical and biological processes occurring in soil environment (Lee, 1969).

The inside air temperature and solar radiation are considered to be the same in solar greenhouse. Soil temperature fluctuated daily and was affected mainly by variations of air temperature and solar radiation as shown in Figure 1. The soil temperature had the same change trend with air temperature. The scale of the diurnal soil temperature wave at top slab was large, and the substrate remained at a fixed temperature. Table 1 show that there was a significantly positive correlation between soil temperature and air temperature during the tomato growth stage. The correlation coefficient (r) between soil temperature and air temperature reached the statistical significant level (p = 0.01), and r decreased with the increase of soil depth, but could not show significant difference among the soil depth. At low fertility level, r increased with the increase of soil moisture; the tendency was more obvious with the increase of soil depth. But at high fertility level, r was $W_h > W_m > W_l$ in 5 and 10 cm of soil depth and $W_h < W_m < W_l$ in 20 and 35 cm of soil depth. Because the thermal conductivity and heat

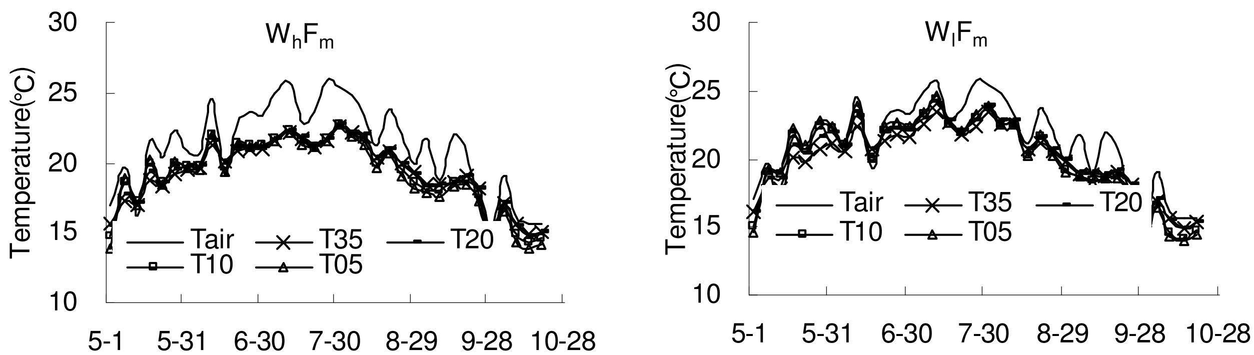

Figure 1. The dynamic change of soil temperature in W_hF_m and W_lF_m treatments during tomato growth in 2008. Tair, air temperature; T35, the soil temperature in 35 cm of soil depth; W_l, deficit irrigation; W_h, high irrigation; F_m, moderate fertilizer.

Table 1. The correlation coefficient (r) between the average daily air temperature and soil temperature.

Soil depth (cm)	Treatment					
	W_hF_m	W_mF_m	W_lF_m	W_hF_l	W_mF_l	W_lF_l
35	0.82**	0.82**	0.83**	0.84**	0.80**	0.80**
20	0.84**	0.85**	0.85**	0.85**	0.84**	0.83**
10	0.89**	0.88**	0.86**	0.88**	0.86**	0.85**
5c	0.91**	0.88**	0.87**	0.89**	0.87**	0.86**

** Shows that the correlation coefficient (r) reached the statistical significant levels at 0.01. W_l, deficit irrigation; W_m, moderate irrigation; W_h, high irrigation; F_l, deficit fertilizer; F_m, moderate fertilizer.

capacity of water is larger than that of soil, it increased the correlation between soil temperature and air temperature at the surface soil and reduced the correlation in the deep soil layer in high moisture treatment. At the low and middle soil moisture level, r was $F_m > F_l$; at high soil moisture level, r was $F_m > F_l$ in 5 and 10 cm of soil depth and $F_m < F_l$ in 20 and 35 cm of soil depth. This influence trend of water on the soil temperature was similar to the fertilizer on the soil temperature.

The effects of soil moisture and fertilizer on the correlation between the diurnal variations air temperature and soil temperature

In contrast, the correlation (R) between the diurnal variations of air temperature and soil temperature were different from the correlation (r) between the average daily air temperature and soil temperature. There was a significantly negative correlation between soil temperature and air temperature in 35 cm of soil depth, no significant correlation in 20 cm, positive correlation in 10 cm, and significantly positive correlation in 5 cm in the diurnal variations, and Table 2 shows the significant difference among the soil depth. The diurnal variations of soil temperature can describe the hysteresis of soil temperature. The correlation (R) decreased with the increase of soil depth. It implies that the hysteresis was more obvious with the increase of soil depth. The effect of air temperature on soil temperature was decreased with the increase of soil depth. At high fertility level, R was $W_m < W_h < W_l$ in 5 and 10 cm depth, $W_h < W_m < W_l$ in 20 and 35 cm of soil depth. At low fertility level, the three water treatments performance was inconsistent with the high fertility treatment (Table 2), R was $W_m < W_l < W_h$ in 5 and 10 cm of soil depth, $W_h < W_l < W_m$ in 20 and 35 cm depth; at the high soil moisture level, R was $F_m<F_l$; at the low soil moisture level, R was $F_m < F_l$ in 20 cm of soil depth, and $F_m > F_l$ in 5 and 10 cm of soil depth.

Effect of soil moisture and fertilizer on the diurnal change of soil Temperature

Data given in Figure 2 shows that the diurnal variation of soil temperatures changed at 5, 10, 20 and 35 cm depths of the soil. It was obvious that soil temperatures changed diurnally, and the pattern of soil temperature which changed with respect to time was similar to a sinusoidal curve; the same shape as air temperature change.

In our analysis, we applied the sine function $T_i = \overline{Ti} + A_i \sin(\omega t - \varphi_i)$ to best approximate the curves of soil temperatures collected at the depths of 5, 10, 20 and 35 cm, respectively. Table 3 shows that there was no significant difference among soil temperature (including

Table 2. The correlation coefficient (r) between the diurnal variations air temperature and soil temperature.

Soil depth (cm)	Treatment					
	W_hF_m	W_mF_m	W_lF_m	W_hF_l	W_mF_l	W_lF_l
35	-0.77**	-0.76**	-0.69**	-0.63**	-0.75**	-0.69**
20	-0.44*	-0.27	-0.21	-0.08	-0.07	-0.10
10	0.38	0.25	0.56**	0.70**	0.43*	0.54**
5	0.73**	0.72**	0.83**	0.80**	0.70**	0.76**

** Shows that the correlation coefficient (r) reached the statistical significant levels at 0.01, * shows that the correlation coefficient (r) reached the statistical significant levels at 0.05. W_l, deficit irrigation; W_m, moderate irrigation; W_h, high irrigation; F_l, deficit fertilizer; F_m, moderate fertilizer.

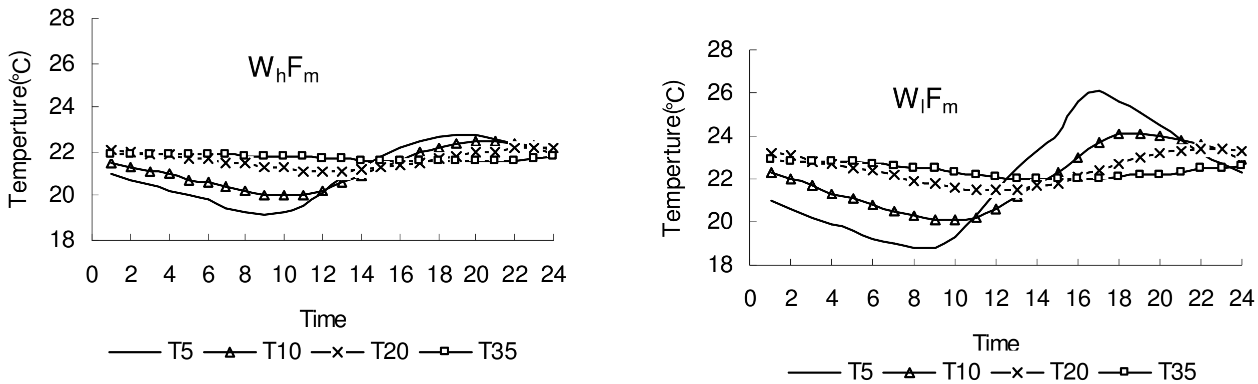

Figure 2. Diurnal variations of soil temperature in W_hF_m and W_lF_m treatments (15 August, 2008). Tair, air temperature; T35, the soil temperature in 35 cm of soil depth; W_l, deficit irrigation; W_h, high irrigation; F_m, moderate fertilizer.

minimum soil temperature, maximum soil temperature and mean soil temperature) in the different soil moisture level. The minimum soil temperature increased and the maximum soil temperature decreased with the increase of soil depth. The minimum soil temperature trend was $W_l > W_h > W_m$ in deep soil and $W_h > W_m > W_l$ in surface soil in high fertilizer level and $W_l > W_h >$ Wm in low fertilizer level. The maximum soil temperature trend was $W_l > W_m > W_h$ in high fertilizer level, $W_l > W_m > W_h$ in deep soil and $W_m > W_h > W_l$ in surface soil in low fertilizer level.

Amplitude is a very important variable to describe the diurnal variations of soil temperature. Table 3 shows that the soil temperature amplitudes decreased with the increase of soil depth. The soil temperature amplitude was $W_l > W_m > W_h$ in high fertilizer level, $W_l > W_m > W_h$ in deep soil and $W_m > W_h > W_l$ in surface soil in low fertilizer level. It is the same trend with the maximum soil temperature.

Here, we used initial phase which is a very important parameter to best describe the hysteresis effect of soil temperature. Table 3 shows that the soil initial phase increased with the increase in soil depth. The trend was in opposition to the amplitudes change. Table 3 shows that the initial phase of the soil temperature increased with the increase in soil moisture level; this indicate that the hysteresis effect of soil temperature aggrandized with the soil moisture increase. At high soil moisture level, the initial phase value was $F_l < F_m$ and at low soil moisture level, the initial phase value was $F_l > F_m$. It explained that in high soil moisture level, the hysteresis effect of soil temperature increased with the increased amount of fertilizer and in low soil moisture level, the hysteresis effect of soil temperature decreased with the increased amount of fertilizer.

DISCUSSION

As reported previously, it is still believed that soil temperature distribution at any depth below earth's surface remains unchanged throughout the year. There was no significant difference in mean soil temperature. However, various researchers showed that soil temperatures at shallow depths present significant fluctuation on both daily and annual basis (Penrod et al., 1960; Carson, 1963; Kusuda, 1975). The top slab is considered to be a depth with the vertical scale of the diurnal temperature wave, and the substrate is considered to remain at a diurnal mean fixed temperature (Dudhia, 1996). It is obvious that soil temperatures changed

Table 3. Parameters values in the sinusoidal curve $T_i = \overline{T_i} + A_i \sin(\omega t - \varphi_i)$.

Treatment	F_m				F_l			
	35 cm	**20 cm**	**10 cm**	**5 cm**	**35 cm**	**20 cm**	**10 cm**	**5 cm**
T_{min} (Minimum soil temperature)								
W_h	21.60	21.10	20.00	19.20	21.70	21.10	20.00	19.30
W_m	21.50	20.80	19.70	18.90	22.00	20.90	19.90	18.80
W_l	22.00	21.50	20.10	18.80	22.00	21.40	20.10	19.40
T_{max} (Maximum soil temperature)								
W_h	21.90	22.20	22.50	22.80	22.00	22.20	22.40	23.10
W_m	22.00	22.20	22.50	22.90	22.50	22.60	23.20	24.20
W_l	22.90	23.40	24.10	26.10	22.60	22.50	23.10	23.90
A_i (Amplitude)								
W_h	0.15	0.55	1.25	1.80	0.15	0.55	1.55	1.55
W_m	0.25	0.70	1.40	2.00	0.25	0.85	1.65	2.70
W_l	0.45	0.95	2.65	3.00	0.30	0.55	1.50	2.25
$\overline{Ti}$ (Mean soil temperature)								
W_h	21.74	21.65	21.24	21.05	21.87	21.63	21.19	21.25
W_m	21.77	21.46	21.13	20.90	22.24	21.74	21.63	21.60
W_l	22.39	22.46	22.03	21.95	22.26	21.96	21.60	21.66
φ_i (Initial phase)								
W_h	6.28	4.22	3.28	2.94	6.02	4.19	3.41	2.88
W_m	5.63	4.19	3.18	2.84	5.63	3.80	3.01	2.46
W_l	4.98	3.54	2.88	2.36	5.37	4.06	2.93	2.44

W_l, Deficit irrigation; W_m, moderate irrigation; W_h, high irrigation; F_l, deficit fertilizer; F_m, moderate fertilizer.

diurnally, and the pattern of the temperature that changed with respect to time was similar to a sinusoidal curve; the same shape as air temperature change. But the effects of air temperature on soil temperature decreased and hysteresis effect of soil temperature was more and more obvious with the increase of soil depth; this result is consistent with the related results obtained by other researchers (Li et al., 2001; Fan et al., 2003).

Soil temperature and soil moisture are two interacting physical quantities which together have a strong influence on the growth of crops. With the increased of soil moisture, the soil temperature amplitude decreased. This implies that there was a significantly negative correlation between soil temperature and soil moisture (Chen et al., 2008) but soil moisture had no significant effects on the soil mean temperature due to the soil hysteresis existence. This is because soil itself is a poor conductor of heat (Lv et al., 2006). Water has good thermal conductivity. After adding water, soil thermal conductivity increased by replacing the air in the soil pores and water also has high heat capacity; it keep the heat in the soil and transfer heat slowly. So, the soil moisture had no significant effects on the soil mean temperature but had significant effects on the soil hysteresis. The optimal combination of fertilizer and water can promote the crops growth. With high content of soil moisture level, the hysteresis effect of soil temperature increased with increase in the amount of fertilizer while in low content of soil moisture level, the hydsteresis effect of soil temperature decreased with the increased amount of fertilizer. The earlier analysis showed that it was more accurate to use instantaneous temperature to analyze the effect of water and fertilizer on soil temperature than to use daily average temperature. When forecasting the soil hysteresis, we need to take into account, the change of the diurnal variations, soil temperature, the amplitude of soil temperature and initial phase.

ACKNOWLEDGEMENTS

This work was supported by grant from the Knowledge

Innovation Program of the Chinese Academy of Sciences, No. KZCX2-YW-443-3 (2009-2011) and West-action Program of the Chinese Academy of Sciences (KZCX2-XB2-05).

REFERENCES

Al-Kayssi AW (2002). Spatial variability of soil temperature under greenhouse conditions. Renew. Energ. 27: 453-462

Al-Kayssi AW, Al-Karaghouli AA, Hasson AM, Beker SA (1990). Influence of soil moisture content on soil temperature and heat storage under greenhouse conditions. J. Agric. Eng. Res. 45: 241-52.

Carson JE (1963). Analysis of soil and air temperature by Fourier techniques, J. Geophys. Res. 68:2217-2232.

Carlson TN, Dodd JK, Benjamin SG, Cooper JN (1981). Satellite Estimation of the Surface Energy Balance, Moisture A vailability and Thermal Inertia. J. Appl. Meteorol. 20(1): 67-87.

Chandra P, Albright LD, Scott NR (1981). A time dependent analysis of greenhouse thermal environment, Trans. ASAE, 24 (2): 442–449.

Chen LJ, Zhang XM, Wang XJ, Cheng ZY, Shan YY (2008). Effect of different soil moisture treatments on soil temperature of plastic film mulched spring wheat. Trans. Chin. Soc. Agric Eng. 24(4): 9-13.

Dudhia J (1996). A multi-layer soil temperature model for MM5. The 6th PSU/NCAR Mesoscale Model Users Workshop.

Fan AW, Liu W, Wang CQ (2003). Simulation on the daily changes of soil temperature various environment conditions. Acta Energ. Solar. Sinic. 24(2): 167-171.

Gao ZQ, Fan X, Bian L (2003). Analytical solution to one-dimen-sional thermal conduction convection in soil. Soil Sci. 168(2): 99-106.

Gehrig-Fasel J, Guisan A, Zimmermann NE (2008). Evaluating thermal treeline indicators based on air and soil temperature using an air-to-soil temperature transfer model. Ecol. Model. 213(3-4): 345-355.

Idso S, Schmugge T, Jackson R, Reginto R (1975). The Utility of Surface Temperature Measurements for the Remote Sensing of Surface Soil Water Status. J. Geophys. Res. 80(21): 3044-3049.

Kang S, Kim S, Oh S, Lee D (2000). Predicting spatial and temporal patterns of soil temperature based on topography, surface cover and air temperature. Forest Ecol. Manage. 136(1-3): 173-184.

Kindelam M (1980). Dynamic modeling of greenhouse environment, Trans. ASAE, 23(5): 1232–1236

Kusuda T (1975). The effect of ground cover on earth temperature, in: Proc. Conf. Alternatives in Energy Conservation:The Use of Earth-Covered Buildings, Fort Worth, TX pp. 9-12.

Lee R (1969). Chemical Temperature Integration. J. Appl. Meteorol. 8(3): 423-430.

Li Y, Wang WY, Men Q, Zhong XC, Xie XW (2001). Field characters of soil temperature under the wide plastic mulch. Trans. Chin. Soc. Agric Eng. 17(3): 32-36.

Lv XJ, LU WL, Song, ZW, Zhang Y (2006). Study on Spatial Variability of Soil Temperature and Water in Field. J. Irrig. Drain. 25(6): 79-81.

Penrod E, Elliot JM, Brown WK (1960). Soil temperature variation at Lexington, Kentocky. J. Soil Sci. 90: 275-283.

Plauborg F (2002). Simple model for 10 cm soil temperature in different soils with short grass. Eur. J. Agron. 17(3): 173-179.

Pratt DA, Ellyett CD (1979). The thermal inertia approach to mapping of soil moisture and geology. Remote Sens. Environ. 8(2): 151-168.

Price JC (1980). The potential of remotely sensed thermal infrared data to infer surface soil moisture and evaporation. Water Resour. Res. 16(4): 787-795.

Timlin DJ, Pachepsky Y, Acock BA, Simunek J, Flerchinger G, Whisler F (2002). Error analysis of soil temperature simulations using measured and estimated hourly weather data with 2DSOIL. Agr. Syst. 72(3): 215-239.

Trigui M, Barington S, Gauthier L (2001). A strategy for greenhouse climate control, part-II, model validation, J. Agric. Eng. Res. 79 (1):99–105.

Tyagi B, Satyanarayana ANV (2010). Modeling of soil surface temperature and heat flux during pre-monsoon season at two tropical stations. J. Atmos. Sol-Terr. Phy. 72(2-3): 224-233.

Yang X, Short TH, Fox RD, Bauerle WL (1990). Dynamic modeling of the microclimate of a greenhouse cucumber row-crop. Part II. Validation and simulation, Trans. ASAE. 33(5): 1710–1716.