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Basic prediction approach for determination of soil temperature using air temperature in some selected soil orders of Eastern Turkey

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Abstract

Soil temperature evaluation is a crucial component in estimating field nutrient budgets. Air data, from a test chamber used to stimulate field air temperatures for a long periods, was collected under laboratory conditions to estimate daily mean soil temperature at a depth of 5 cm using an exponential model. This model was later tested using field data from regions located in 5 different big soil groups across the eastern part of the Turkey. The relationship between air and soil temperature derived from observed and estimated soil temperature was adequately described by an exponential equation with high coefficient determinants. The values of R^2 between observed and final predicted soil temperatures ranged from 0.98 to 0.99 with standard errors from 1.5 to 3.0°C for big soil groups. This model suggests that the exponential equation well describes the soil temperature as a function of the air temperature and some other soil properties such as soil water content, soil porosity, soil texture and soil structure, and changes with soil properties. The results show that the soils differed markedly in their heat conductivity and heat capacity for the soil big groups, and suggest that soils can have different heat-buffering capacities. When compared, the soil heat conductivities were in the order of Flavuquent > Calciorthid > Haplustept > Pellustert > Argiustoll and these sequences follow approximately the order of low clay content, porosity and air permeability, respectively. Daily soil temperatures may be predicted from daily air temperature once regional equations have been established, and since weather stations in Turkey can be generalized into a few regions, sites within each region may use the same equation.

Key words: Air temperature, soil temperature, soil order.

Introduction

Knowledge of the ground temperature distribution is important for seed germination and root growth during the growth period. There are a lot of direct or indirect earth-coupling techniques. Various researchers have shown that soil temperatures at shallow depths present significant fluctuation on both a daily and annual basis [13]. According to their studies, heat flow inside the earth is influenced by several parameters, such as solar radiation, air temperature, wind speed, time of the year, shading, soil properties, etc.; all of which present a monthly variation. For this reason, prediction and estimation of soil temperature is rather difficult, especially near the ground surface where the soil temperature variations are highest. Soil temperature is a critical variable controlling below-ground processes for global and continental nutrient budgets [22]. Although many climate stations across Turkey have long-term records of daily air temperature and precipitation, only a few of them monitor soil temperature. Data on soil temperatures are thus not easily available. Measurements of soil temperature in a field should be carried out with various types of sensors using an automated data acquisition system. This approach needs several sensors, and some manpower and expertise for installation in order to describe the spatial variation in soil temperature [7, 21]. Several comprehensive, physically-based models are available for calculation of soil temperature. However, these models need input parameters that are not easily available, just as it takes specific technical skills to set up and run such models. An alternative approach is to develop simple models, which on one hand are easy to operate, and on the other perform at a satisfactory level of accuracy for the purpose.

In various fields, air temperature has been estimated using several empirical and numerical models including meteorological parameters which are well correlated with soil temperature such as relative humidity, solar radiation, rainfall, and wind speed [6, 8, 9, 29, 33]. However, air temperature, especially air temperature at 2-3 m height, has been reported to be highly related to soil temperature and more impactful on the estimation of soil temperature, which was attributed to the energy balance at the ground surface which controls both [3, 17, 20, 27, 29, 31].

The present work, which was conducted under both laboratory and field conditions, includes 5 soil orders and presents a simple and operational model for obtaining daily mean soil temperature at 5 cm depth for a grass surface in various soils. Field experiments were conducted during late autumn and early spring season (November-April) because continuous freeze-thaw occurs in Eastern Anatolia region in Turkey in this period. The objectives of this study were to develop a general methodology for estimation of daily soil temperature at various soil order continental scales using daily air temperature data.

Materials and Methods

Description of the site and material: Due to its geographical position, Turkey shows different climatic zones in almost every period of the year. Consequently, every region should be considered as unique for agricultural production. The main limiting factors for agricultural design are long-term mean annual climatic parameters such as air temperature, rainfall, soil temperature, and humidity. Because of its geographical location, climatic parameters of northeastern Anatolia show even more variation. Variations in precipitation, freeze-thaw and temperature can affect some physical, chemical and microbiological properties of soils and thus affect productivity of these soils. These effects, which may vary with different soil types (ordo), are especially important for nutrient uptake during the growth period. Five big soil groups were used in field studies in the Erzurum plain (Turkey). The study areas were situated at altitudes between 1880 and 2030 m above sea level in the eastern part of Turkey (Fig. 1). The parent materials mostly consisted of volcanic, marn and lacustrin residual and transported material. The study areas have a semi-arid climate with mean annual temperature, precipitation, evapotranspiration and relative humidity of 6.38°C, 398 mm, 1060 mm and 64%, respectively. Average summer temperatures rarely exceed 35°C, while in the winter, the temperatures of -35°C are not uncommon. Mean annual soil temperatures at 5, 10, 20, 50 and 100 cm depth are 11.4, 11.1, 10.3, 10.9 and 11.28°C, respectively [1]. Snow remains on average for 94 days and the region has 124 rainy days. Soil humidity and temperature regime are defined as Ustic and Mesic. According to soil taxonomy [26], the soils were classified as Argiustoll, Fluvaquent, Haplustept, Calciorthid, and Pellustert [19]. Five soil samples used in the laboratory were obtained from the same soil groups as the field study. Soil samples which had been passed through a 4-mm sieve were put into small pots, and saturated (all soil sampled saturated with pure water to the field capacity) and unsaturated soil samples (without any water application) were settled in an Environmental Test Chamber (Tenney Junior Test Chamber Models TUSR-CENY), and they were then subjected to the freeze and thaw process from +20°C to -30°C to simulate actual field conditions. To measure soil temperature, device probes were placed to a 5 cm soil depth and in every 5 second both air (9000 data) and soil temperature (9000 data) values were recorded.

Soil analysis: Soil samples were taken over 0-10 cm depths to determine some chemical and physical properties. Soil samples were air-dried, crushed, and passed through a 2-mm sieve prior to chemical analysis. Cation exchange capacity (CEC) was determined using the sodium acetate method according to Sumner and Miller [28]. The Kjeldahl method [2] was used to determine organic N and plant-available P was determined by using the sodium bicarbonate method of Olsen *et al.* [18]. Electrical conductivity (EC) was measured in saturation extracts according to Rhoades [23]. Soil pH was determined in 1:2 extracts, and calcium carbonate concentration was determined according to McLean [12]. Soil organic matter was determined using the Smith-Weldon method according to Nelson and Sommers [16]. Ammonium acetate buffered at pH 7 [30] was used to determine exchangeable cations. Microelements in the soils were determined by the diethylene triamine pentaacetic acid (DTPA) extraction methods [11]. Clay mineralogy of soils was performed using an X-ray diffractometer (Rigaku D/Max-2200/PC). The analysis results of the soils are given in Table 1.

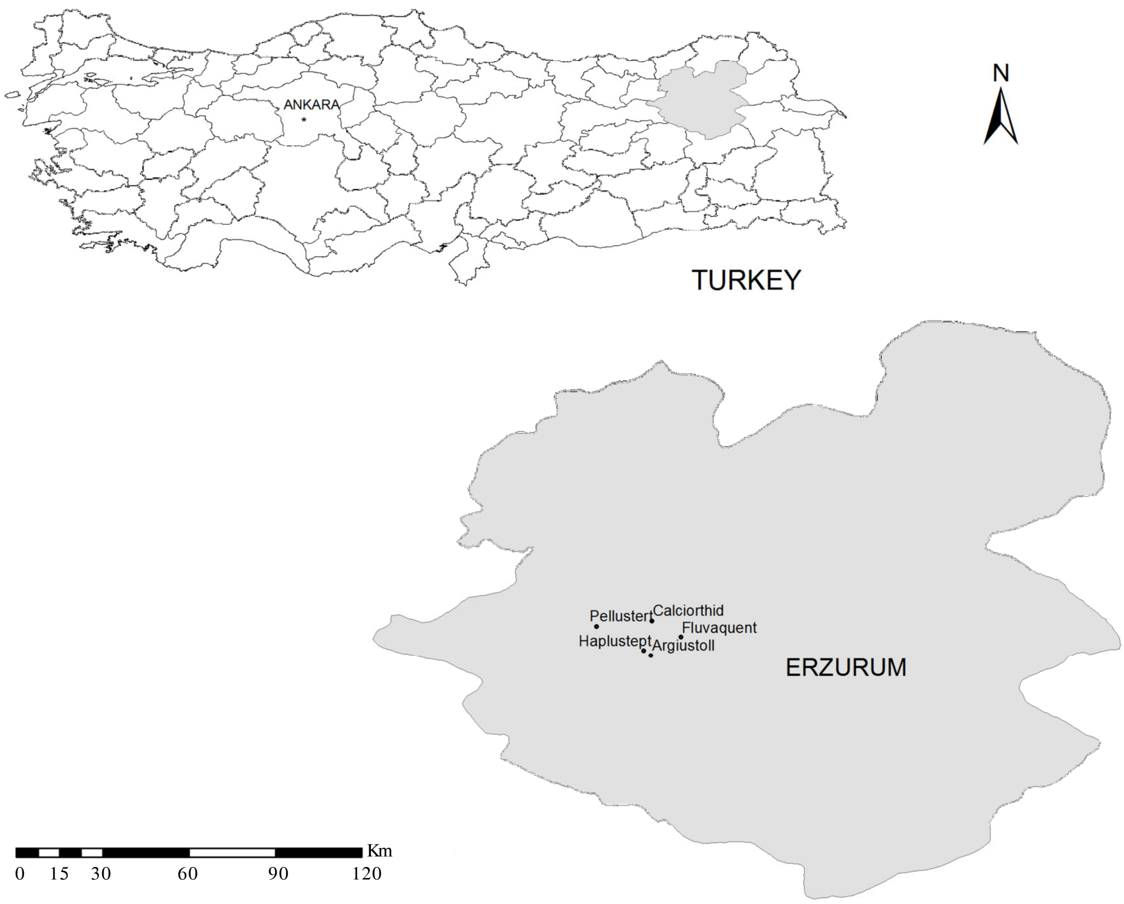

Figure 1. Study area and locations of big soil groups.

Table 1. Chemical and physical properties of studied soil groups.

		Pellustert	Argiustoll	Haplustept	Fluvaquent	Calciorthid
pH (1:2.5 s/w)		7.22	7.01	7.8	7.3	7.74
$CaCO_3$, %		0.37	0.44	1.15	0.98	26.35
Organic matter, %		1.21	1.33	2.43	1.84	2.28
Total nitrogen, %		0.0060	0.0052	0.0122	0.0092	0.0114
NH_4-N, %		0.005	0.0067	0.0092	0.005	0.0097
NO_3-N, %		0.0067	0.0084	0.0101	0.0059	0.0108
CEC, $cmol_c$/kg		25.73	35.64	20.75	22.39	28.33
K, $cmol_c$/kg		2.36	2.12	3.15	2.82	3.25
Ca $cmol_c$/kg		15.24	14.22	14.1	12.14	12.25
Mg $cmol_c$/kg		2.63	2.88	2.5	3.25	2.75
Na $cmol_c$/kg		0.52	0.7	1.22	0.61	1.04
P, mg/kg		8.25	10.67	21.25	24.27	12.11
Fe, mg/kg		3.68	3.2	2.88	2.4	3.36
Cu, mg/kg		20.64	24	24.96	33.6	34.56
Mn, mg/kg		16.25	17.35	14.12	18.12	13.6
Zn, mg/kg		4.25	4.36	4.56	5.25	4.28
B, mg/kg		0.28	0.2	0.36	0.32	0.34
mg C m^2/h		6.30	8.56	9.35	9.16	9.60
mg CO_2 m^2/h		23.10	31.39	34.28	33.59	35.20
Total bacteria x10^5		70	155.00	80.00	80.00	154.00
Total fungi x10^5		120	190.00	130.00	135.00	170.00
Clay, %		57.82	53.11	28.81	13.86	24.29
Silt, %		23.83	23.59	50.39	32.99	28.90
Sand, %		18.35	23.30	20.80	53.15	46.81
Aggregate stability, %		17.20	12.48	45.26	44.09	50.49
EC, µmhos/cm		285	260	470	425	435
Qualitative clay mineralogy [a]		H>I>K>M>V	M>I>K>H>V	I>M>K>V>H	H>I>K>M>V	I>M>K>V>H
Bulk density g/cc^3		1.09	1.15	1.22	1.34	1.19
Air	<4.0 m	97.06	125.13	27.52	21.22	26.73
permeability μ^2/h	1-2 mm	248.27	257.68	252.89	235.83	235.38
Water	<4.0 m	0.77	0.49	0.33	0.88	1.26
permeability μ^2/h	1-2 mm	1.34	0.68	2.28	6.54	3.62
Hydraulic	<4.0 m	2.84	1.86	1.21	3.27	4.71
conductivity, cm/h	1-2 mm	4.42	2.25	7.52	21.53	11.93

[a] Chlorite, C; Halloysite, H; Kaolinite, Ka; Illite, I; Montmorillonite, M; Vermiculite, V.

Model description: Air temperature correlates well with soil temperature because the energy balance at the ground surface determines both. All of the chemical and some physical changes occur within a depth of 5 cm, so soil temperature measurements were done in the top soil [33]. This model is suitable for bare ground area soil temperature estimation [4]. For prediction of soil temperature under bare ground the input data required are daily maximum air temperature (°C), and minimum air temperature (°C). Daily mean soil and air temperatures in the field conditions were calculated as the simple average of the daily maximum and minimum values during 2008-2009 years and 60 years average soil and air temperature values, used as reference in laboratory studies, were obtained from the National Meteorology Station, Erzurum, Turkey [1].

The initial values for depth of snowpack in the model simulations varies from 0 to 30 mm. Estimated daily soil temperatures from the regional equations were modified according to determination of snowpack on the ground, because the rate of change in soil temperature under snow cover will be less. When snowpack is not present, Eq. (1) is used:

$$F(T) = [A(T) - A(T - 1)] * M_2 + E (T) \quad (1)$$

where E(T) is the soil temperature estimated from the regression equation on the current day; and M_2 is a rate scalar of 0.25. E(T) was used for Eq. (1).

The annual means of the predicted soil temperatures using constant scalars were less than 0.6°C different from those predicted from the regressions.

Results and Discussion

Soil characteristics: Selected chemical and physical properties of the soil studied are given in Table 1. The soils were neutral to slightly alkaline and low and moderate in organic matter and lime contents. Clay contents in soils ranged from 14% to 58%, with a mean of 36%. The CEC ranged from 21 to 36 cmol/kg. The particle-size distribution of soils exhibited a substantial variation in sand, silt, and clay contents ranging from 18 to 53% for sand, 24 to 50% for silt, and 14 to 58% for clay. The clay mineralogy shows that significant differences exist in the types of clay minerals in the soils. The clay minerals of Fluvaquent, and Calciorthid soils are dominated by illite with a moderate montmorillonite, Argiustoll is dominated by montmorillonite with moderate illite, and Haplustept and Pellustert consist mainly of halloysite and have small amounts of illite.

Soil temperature prediction model: This study was conducted under both laboratory and field conditions to predict soil temperatures at various soil orders using a regression model derived from air temperature in saturated and unsaturated soil conditions. There were strong relationships between the average daily air temperatures and observed daily soil temperatures at 5 cm depth in both laboratory and field studied soil orders under saturated soil but not unsaturated soil water conditions, and in laboratory tests were adequately described by the exponential equation. Soil temperature prediction models for the 5 soil big groups in the region showed similar shape (Figs 2 and 3).

This model suggested that the exponential equation well described the soil temperature as a function of air temperature for soils with different properties such as water content, porosity, texture and structure. These results are consistent with work by Givoni and Katz [10], and Mihalakakou *et al.* [14]. When the air temperature was -10°C for Pellustert and Argiustoll soils and was -8°C for Haplustept, Flavuquent and Calciorthid the soil temperature in 5 cm depth of the Pellustert, Haplustept, Flavuquent and Calciorthid was 0°C and freezing started. This variation can be attributed to soil porosity, clay content and water holding capacity [5]. Results show that the soils differed markedly in their heat conductivity and heat capacity for the big soil groups, and suggested that soils could have different buffering heat capacities. As compared, the soil orders for heat conductivity were Flavuquent > Calciorthid > Haplustept > Pellustert > Argiustoll and these sequences follow approximately the order of the low clay content, porosity, and air permeability (Fig. 2 and Table 1).

To test the validity of the laboratory equation, field soil temperatures were evaluated using predicted data from the laboratory equation and this data was correlated with observed field temperature data (Fig. 4). There were strong relationships between the observed daily air temperatures obtained from field conditions and the prediction model from calculated soil temperatures at the 5 cm depth for all soil orders. The relationship between the prediction of soil temperature according to the exponential model in the laboratory and observed soil temperatures obtained from field conditions were adequately described by a linear equation with high coefficient determinants. R^2 values for each amount ranged from 0.98 to 0.99. Soil temperature prediction models for the 5 soil big groups in the region show differences in the shape and model according to late autumn and early spring plant growth seasons. Soil temperature prediction with the exponential model obtained from saturated conditions had a higher linear relation than the unsaturated condition. The predictions of soil temperature from model testing are cheaper and more convenient than the field observed data. This model provided method to protect cold hardiness damage for annual and biannual plant production and to evaluate and judge how freeze-thaw will affect soil properties and make proper management.

For exponential model-development sites of all soil orders, the average annual soil temperature at 5 cm depth for both laboratory and field study is higher than the average annual air temperature (Figs 1-3). Higher average soil temperatures have been reported before by the other researchers and might be expected in light of the low specific heat of soil and the reduced air mixing that usually occurs in the air layer adjacent to the soil surface [25,32]. The models were of a similar quality to the model found for a bare soil by Müller and Döring [15] and a soil temperature model by Roodenburg [24].

Conclusions

Daily soil temperature at 5 cm depth for various sites and years may be predicted from daily air temperature, once equations have been established for different climatic regions.

This model could provide some indication about the best seed sowing time and depth in late autumn and early spring to protected cold hardeners, and give information about sustainable soil nutrient management methods for crop production in the region. We suggest that this methodology may be appropriate for predicting daily soil temperatures from daily air temperature at large scales.

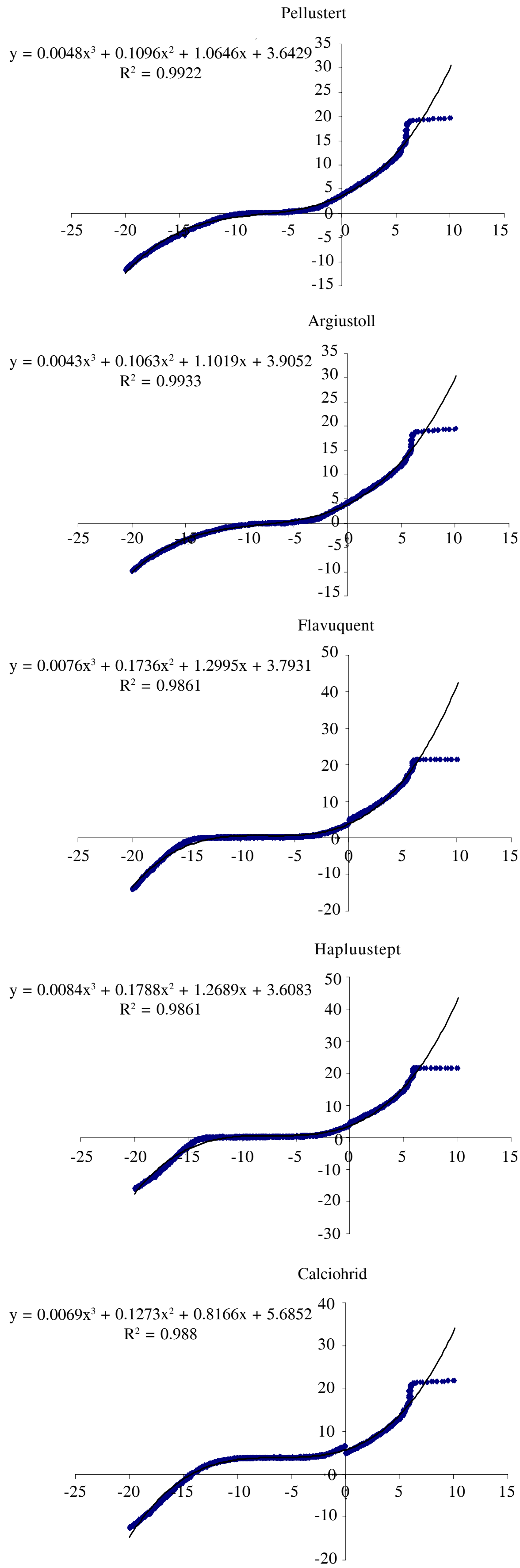

Figure 2. Relationships between air temperature and soil temperature at 5 cm depth under saturated soil condition in five soil big groups under laboratory experiments.

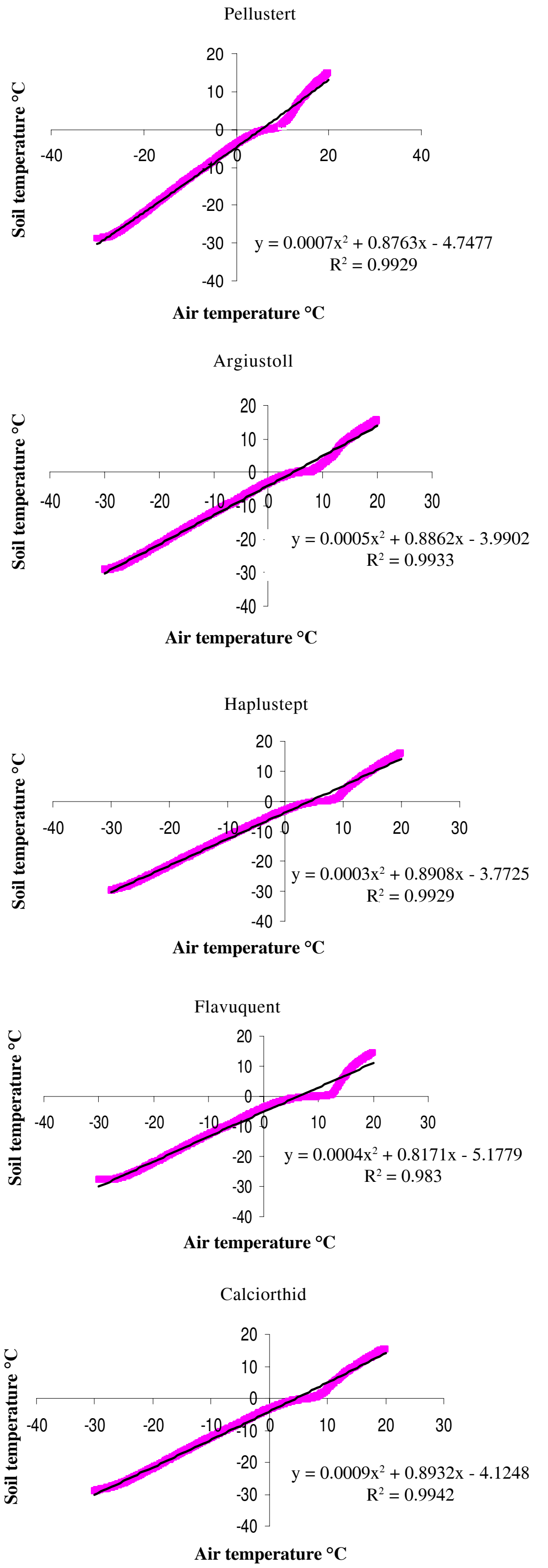

Figure 3. Relationships between air temperature and soil temperature at 5 cm depth under unsaturated soil condition in five soil groups under laboratory experiment.

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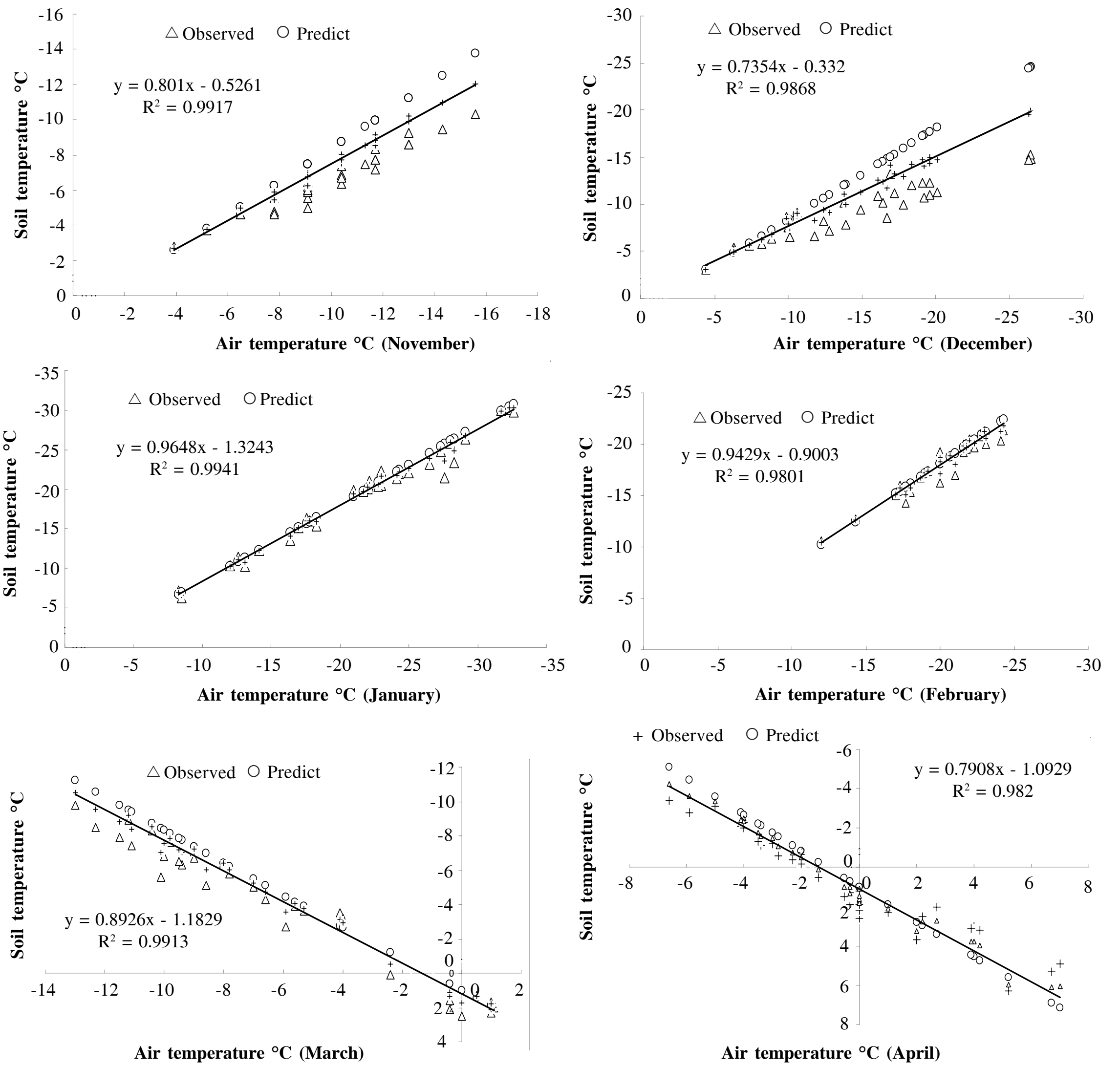

Figure 4. Validation of soil temperature prediction model derived from laboratory equation with field observed data at 5 cm depth late autumn and early spring period.