Effect of tillage treatments on soil thermal conductivity for some Jordanian clay loam and loam soils

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Abstract

Soil thermal conductivity determines how a soil warms or cools with exchange of energy by conduction, convection, and radiation. The ability to monitor soil thermal conductivity is an important tool in managing the soil temperature regime to affect seed germination and crop growth. In this study, the temperature-by-time data was obtained using a single probe device to determine the soil thermal conductivity. The device was used in the field in some Jordanian clay loam and loam soils to estimate their thermal conductivities under three different tillage treatments to a depth of 20 cm. Tillage treatments were: no-tillage, rotary tillage, and chisel tillage. For the same soil type, the results showed that rotary tillage decreased soil thermal conductivity more than chisel tillage, compared to no-tillage plots. For the clay loam, thermal conductivity ranged from 0.33 to 0.72 W m^{-1} K^{-1} in chisel plowed treatments, from 0.30 to 0.48 W m^{-1} K^{-1} in rotary plowed treatments, and from 0.45 to 0.78 W m^{-1} K^{-1} in no-till treatments. For the loam, thermal conductivity ranged from 0.40 to 0.75 W m^{-1} K^{-1} in chisel plowed treatments, from 0.34 to 0.57 W m^{-1} K^{-1} in rotary plowed treatments, and from 0.50 to 0.79 W m^{-1} K^{-1} in no-till treatments. The clay loam generally had lower thermal conductivity than loam in all similar tillage treatments. The thermal conductivity measured in this study for each tillage system, in each soil type, was compared with independent estimates based on standard procedures where soil properties are used to model thermal conductivity. The results of this study showed that thermal conductivity varied with soil texture and tillage treatment used and that differences between the modeled and measured thermal conductivities were very small. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Soil thermal conductivity; Single probe; Rotary tillage; No-tillage; Chisel tillage

1. Introduction

Soil thermal properties are required in many areas of engineering, agronomy, and soil science. In recent years, considerable effort has gone into developing techniques to determine these properties. Knowledge of the transport of water and heat in soil would help soil and water management in irrigated agriculture.

The propagation of heat in a soil is governed by its thermal characteristics (De Vries, 1963). Seed germination, seedling emergence, and subsequent stand establishment are influenced by the microclimate. Soil thermal properties play an important role in influencing microclimate (Ghauman and Lal, 1985).

The thermal conductivity of a soil depends on several factors. These factors can be arranged into two broad groups, those which are inherent to the soil itself, and those which can be managed or controlled to a certain extent. Those factors or properties that are inherent to the soil itself include the mineralogical

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composition of the soil and the organic component of the soil (Wierenga et al., 1969). The way a soil is managed will play an important part in determining its thermal conductivity (Yadav and Saxena, 1973). Any practice or process which tends to cause soil compaction, such as tillage, will increase bulk density and decrease porosity. This in turn will have a significant effect on thermal conductivity. Erbach et al. (1992) evaluated the effect of no-till, chisel plow, moldboard plow, and para plow systems on three soils (poorly drained, medium, and fine textured) in Iowa and showed that all tillage tools influenced bulk density and penetration resistance to the depth of tillage. In addition to compaction, tillage can influence soil water content and other physical characteristics that can impact on soil thermal conductivity (Kunii and Smith, 1960; Al Nakshabandi and Kohnke, 1965; Cochran et al., 1967; Skaggs and Smith, 1967; Fritton et al., 1974; Parikh et al., 1979; Riha et al., 1980).

Thermal properties are determined indirectly by measuring the rise or fall of temperature in response to heat input to a line source at the point of interest (Jackson and Taylor, 1965). De Vries (1952, 1963) developed models that allowed estimation of thermal conductivity and volumetric heat capacity of soils from the volume fractions of their constituents and the shape of the soil particles. The dual-probe heat-pulse technique (Campbell et al., 1991; Bristow et al., 1993, 1994a,b; Kluitenberg et al., 1993) has been used to measure soil thermal properties. It consists of two parallel needle probes separated by a distance r. One probe contains a heater and the other a temperature sensor. With the dual-probe device inserted in the soil, a heat pulse is applied to the heater and the temperature at the sensor probe is recorded as a function of time. The soil thermal conductivity can then be determined from the measured temperature-by-time data at the sensor probe using the line source theory.

For Jordanian soils information on thermal properties is lacking. These data are needed for constructing models to predict soil thermal regimes. Such information assumes greater importance with increasing attention being paid to developing the agricultural industry in Jordan. Thermal conductivity of soil plays an important role in influencing seed germination, seedling emergence, and subsequent stand establishment. For this reason, the practical significant of knowing the soil thermal conductivity under given set of con-

ditions is most important as it relates to a soil's microclimate. Because of the general lack of information about the effects of tillage treatments on thermal conductivity of soils, the objective of this study was to determine the effects of tillage treatments on the apparent thermal conductivity of two soils.

2. Materials and methods

2.1. Experimental site and tillage

Three tillage treatments were investigated to determine the role of soil tillage on soil thermal conductivity. The tillage treatments were: rotary tillage, chisel plowing, and no-tillage. Two sites, 45 m×90 m each, located at Jordan University of Science and Technology (JUST), Irbid, Jordan, were selected for this study. The plots had been left fallow for 3 years prior to the study. The experiment in each site was arranged in six blocks representing six replicates of the treatments. Each block consisted of three plots representing the three tillage treatments. Plot size was 10 m×20 m. The soil type at the first site was clay loam (230 g kg^{-1} sand, 380 g kg^{-1} silt, 390 g kg^{-1} clay) and loam (400 g kg^{-1} sand, 360 g kg^{-1} silt, and 240 g kg^{-1} clay) at the second site. Soil particle size distribution was determined using the hydrometer method.

Chisel plowing at both sites was performed with one pass of a chisel plow using a 63.4 kW (front wheel assist) KUBOTA 8950DT tractor and was completed on 7 November 1999. The chisel plow was 3.35 m wide with nine shanks spaced at 38 cm apart. Tillage depth was approximately 20 cm. The mean soil volumetric moisture content at time of tillage was 0.17 m^3 m^{-3}, ranging from 0.13 to 0.18 m^3 m^{-3} at the first site; and with a mean soil moisture content of 0.16 m^3 m^{-3} ranging from 0.12 to 0.19 m^3 m^{-3} at the second site. Moisture content was determined using an oven-dry technique. Rotary tillage to a depth of 20 cm was conducted on 25 October 1999 in both sites with a 3-m-wide BEFCO Series-5 power harrow fitted with an open cage roller. All tillage occurred in the same relative direction.

Soil bulk density was measured directly after tillage using soil core samples obtained by a manually operated tool. These cores were 5 cm in diameter and

approximately 10 cm long. The soil sampling was made at four locations in each test plot and at two depths (10 and 20 cm) in each location. The data from the six replicates for each treatment were compiled and individual values were averaged to obtain the density at the plowing depth (20 cm) for each treatment. Some soil samples were taken to measure soil moisture content at specified depths.

2.2. Single probe methodology

The single probe methodology is based on a solution of the heat conduction equation for a line heat source in a homogenous and isotropic medium at a uniform initial temperature. Given the linear heat source and cylindrical geometry of these heat dissipation sensors, sensor temperature (T) during heating should be related to time (t) according to the theoretical solution for a line heat source (De Vries and Peck, 1958; Campbell et al., 1991; Bristow et al., 1994a,b; Reece, 1996). Thermal conductivity, k, can be simply estimated from the change in sensor temperature between two times by

$$k = 0.0795 \frac{I^2 R}{S} \tag{1}$$

where k is the thermal conductivity (W m^{-1} K^{-1}), I the current in the line source (A), R the specific resistance of the wire (Ω m^{-1}), and S is the slope of the linear portion of the relationship between temperature change and the logarithm of time (°C). It is assumed that energy transported in soil by radiation and convection of heat was negligible (De Vries, 1952; Jury et al., 1991). The experiments were carried out at ambient temperature.

Soil thermal conductivity was measured at four locations in each plot using the single probe method for a total of 24 measurements for each tillage system in each soil type. For each tillage system in each soil type, the average of four soil thermal conductivity values in each plot was reported. The probe configuration consisted of a heater and a temperature sensor mounted together in a thin needle-like probe. The needle was made from thin stainless steel tubing 170 mm long and 2 mm in diameter. The needle was fixed on an acrylic plate by epoxy glue. The line heater was made from enameled Evanohm wire (Wilbur B. Driver, Newark, NJ), which was pulled into the needle. The heater resistance (R) was 300 Ω m^{-1}. The temperature sensor consisted of copper–constantan thermocouple junction, which was pulled into and centered in the needle. With the heater and thermocouple in place, the needle was filled with high thermal conductivity epoxy glue to minimize radial temperature gradients through the probe and to provide a water resistance, electrically insulated probe. Heat was generated by applying voltage from a 9-V DC power supply to the heater for a fixed period of time. Lower power inputs were used to minimize the effects of heating on soil water movement, and hence, thermal conductivity. During application of power to the heater, temperature of the thermocouple and the applied voltage were recorded with a datalogger (Model CR7X, Campbell Scientific, Logan, UT). Thermal conductivity of the soil was calculated from the temperature–time record and power input according to Eq. (1).

The probe was vertically inserted from the soil surface to a 17-cm depth. The electrical wire was then connected to the power supply unit. Temperature was measured and recorded every 5 s for the first minute and then every 10 s till the end of the heating period (200 s). The power supply unit was then disconnected and cooling period was started immediately. The thermocouple continued to record the temperature after the battery was disconnected. The temperature was recorded every 5 s for the first 30 s and then every 10 s until the end of the cooling period. Temperature was plotted versus the logarithm of time. Slopes of the linear portions of these curves were determined, and these values were used to calculate thermal conductivity. Figs. 1 and 2 show an example of these plots. On an average, these curves became linear 20 s after heating was initiated.

A paired t-test was used to test the null hypothesis that k obtained from heating data was not different than k obtained from cooling data. The P value was 0.28, indicating that both the heating method and cooling method yield identical thermal conductivity values. The average of heating and cooling estimates of k was used in this study. A statistical analysis performed on the measured thermal conductivity data using the statistical software MINITAB (1994) shows that thermal conductivity for each tillage system is significantly different from those for other tillage systems in each soil type.
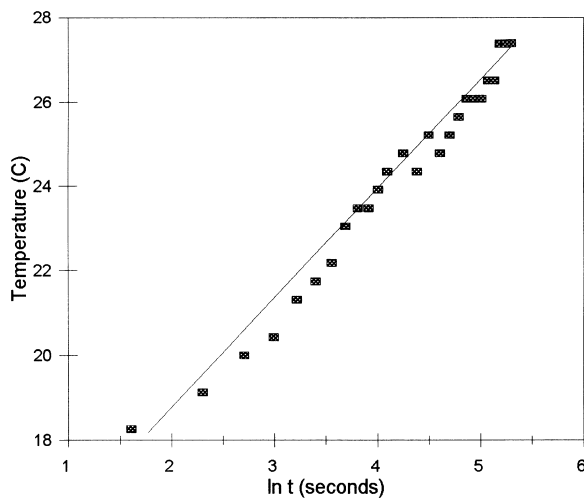
Fig. 1. Probe temperature as a function of ln(t) during heating for loam soil using single probe method.

2.3. Modeled thermal conductivity

Independent estimates of soil thermal conductivity under varying water content, soil density, and soil texture were also made using the procedure of De Vries (1963) and Campbell (1985). Estimated thermal conductivity, k, can be calculated by

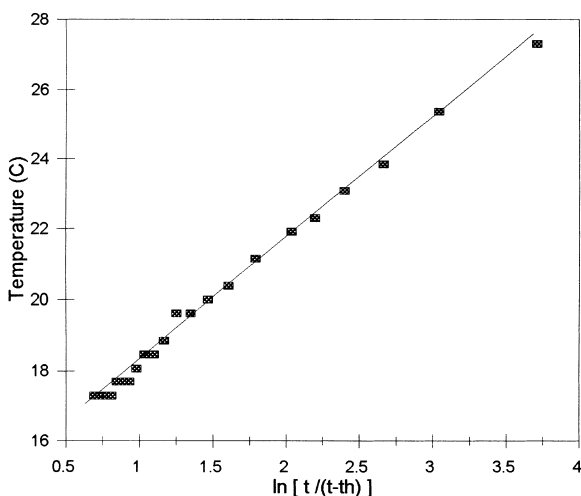$$k = A + B\theta_v - (A - D)\exp[-(C\theta_v)^E] \qquad (2)$$

Fig. 2. Probe temperature as a function of ln($t/(t-t_h)$) during cooling after t_h seconds of heating for loam soil using single probe method.

where A, B, C, D and E are soil dependent coefficients which have been related to soil properties by Campbell (1985). These relationships are:

$$A = 0.65 - 0.78\rho_b + 0.60\rho_b{}^2 \qquad (3)$$

$$B = 1.06\rho_b \qquad (4)$$

$$C = 1 + \frac{2.6}{m_c{}^{0.5}} \qquad (5)$$

$$D = 0.03 + 0.1\rho_b{}^2 \qquad (6)$$

$$E = 4 \qquad (7)$$

where m_c is the clay fraction.

3. Results and discussion

3.1. Soil bulk density

Average dry bulk densities of loam soil at tillage depth (0–20 cm) were 1.34, 1.31, and 1.16 Mg m^{-3} for no-tillage, chisel tillage, and rotary tillage, respectively. For clay loam soil, average dry bulk densities at tillage depth (0–20 cm) were 1.36, 1.32, and 1.15 Mg m^{-3} for no-tillage, chisel tillage, and rotary tillage, respectively. The plots that were tilled to 20 cm had, as expected, a lower average dry density in the tillage depth, compared to the untilled plots. Volumetric moisture contents of loam and clay loam at thermal conductivity measurements for the three tillage systems are shown in Table 1.

3.2. Thermal conductivity

Measured and modeled thermal conductivities of the two soils as a function of volumetric moisture

Table 1
Soil bulk densities, and moisture contents for two Jordanian soils used in the thermal conductivity study

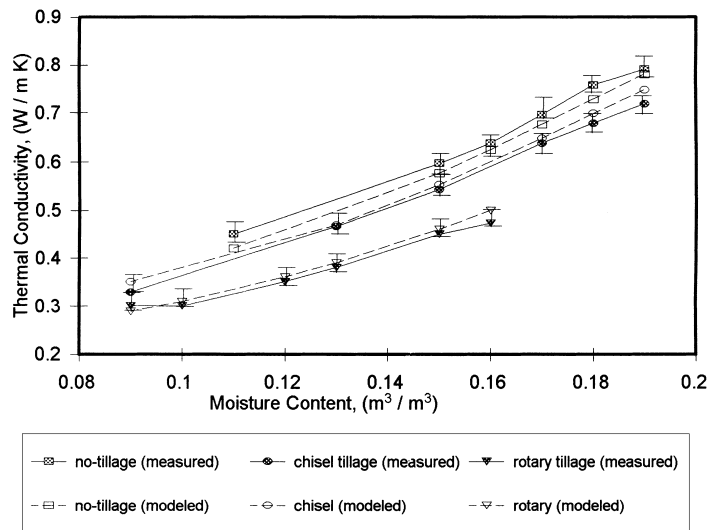| Type of soil	Tillage system	Bulk density (Mg m^{-3})	Water content (m^3 m^{-3})
Loam	No-tillage	1.34	0.11–0.17
Loam	Chisel tillage	1.31	0.10–0.17
Loam	Rotary tillage	1.16	0.09–0.15
Clay loam	No-tillage	1.36	0.11–0.19
Clay loam	Chisel tillage	1.32	0.09–0.19
Clay loam	Rotary tillage	1.15	0.09–0.16

Fig. 3. The effect of tillage treatments (no-tillage, chisel tillage, and rotary tillage) on measured and modeled thermal conductivity (W m^{-1} K^{-1}) for a clay loam at 0–20 cm depth.

content for the three tillage treatments are shown in Figs. 3 and 4. Soil tillage significantly reduced thermal conductivity ($p \leq 0.1$) for both soils. All plots tilled by chisel plow had higher thermal conductivity than those plots tilled by rotary tillage. Since all chisel plowed plots had higher bulk densities than rotary tilled plots, it appears that thermal conductivity increased with increasing bulk density for both soil types probably as a result of particle contact enhancement as porosity decreased. For the clay loam, measured thermal conductivity increased rapidly with increasing moisture content for all tillage systems (Fig. 3). At any given moisture content, there was a rapid increase in the thermal conductivity of the clay loam soil when moving from rotary tilled plots to chisel plowed plots. Such a phenomenon was absent in the loam (Fig. 4).
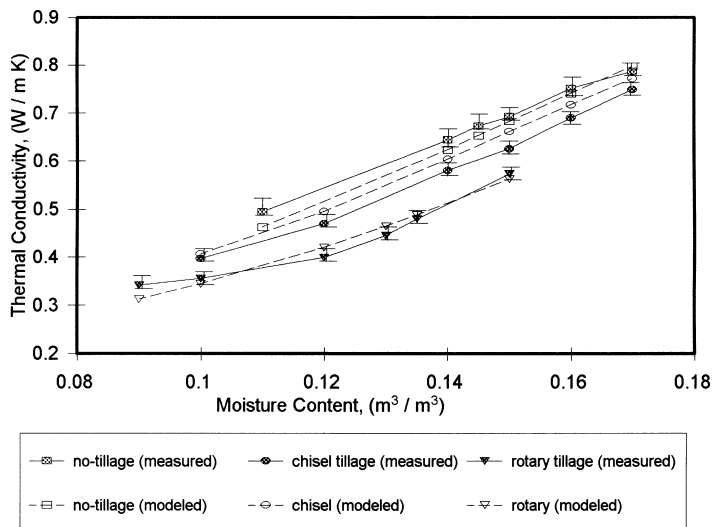

Fig. 4. The effect of tillage treatments (no-tillage, chisel tillage, and rotary tillage) on measured and modeled thermal conductivity (W m^{-1} K^{-1}) for a loam at 0–20 cm depth.

Table 2
Average measured and modeled thermal conductivities (W m^{-1} K^{-1}) for the three tillage systems on two Jordanian soils[a]

Soil type	No-tillage		Chisel tillage		Rotary tillage	
	Measured k	Modeled k[b]	Measured k	Modeled k[b]	Measured k	Modeled k[b]
Loam	0.67(a)	0.66(a)	0.59(b)	0.61(b)	0.43(c)	0.43(c)
Clay loam	0.66(a)	0.64(a)	0.56(b)	0.58(b)	0.38(c)	0.39(c)

[a] Means represent 24 measurements in each soil type. Means in rows, within a soil type, followed by the same letter were not significantly different at a 10% level using Tukey's Studentized range test.

[b] Modeled thermal conductivity determined using the De Vries and Campbell methods.

It appears that an increase in bulk density of the clay loam beyond 1.15 Mg m^{-3} did improve contact between the soil particles, and hence produced a relatively more homogenous soil mass. Clay loam had a lower thermal conductivity than loam in all tillage treatments studied. Average measured thermal conductivities for the three tillage systems are given in Table 2. Thermal conductivity values reported here lie well within the range 0.15–0.79 W m^{-1} K^{-1} for loam soil as given by Ghauman and Lal (1985). The highest thermal conductivity value obtained for clay loam soil (0.78 W m^{-1} K^{-1}) was higher than the 0.64 W m^{-1} K^{-1} obtained by Van Wijk (1963). Mineralogical and particle size distribution differences between the soil of Van Wijk (1963) and the present study may account for this variation.

Comparisons of the thermal conductivity determined using the De Vries and Campbell methods with the values measured with the single-probe device are shown in Figs. 3 and 4. The differences between the measured and modeled results were very small and confirmed the ability of the single probe to provide high quality thermal conductivity data. Another analysis was performed at a 10% level of significance on the measured and modeled data for each tillage system in each soil type. The null hypothesis was that the measured and modeled data for each tillage system in each soil type have the same mean. In general, there was no statistical difference among these sets of data for each tillage system in each soil type (Table 2).

As mentioned earlier, higher values of thermal conductivity were obtained for the loam than for the clay loam in all tillage treatments. The decrease of effective thermal conductivity with decrease in grain size may be explained by the fact that as the grain size decreases, more particles are necessary for the same porosity, which means more thermal resistance between particles. This suggests that clay loam soils with low thermal conductivities would exhibit larger surface temperature amplitudes, compared with loam soils under equal heat flux densities. For the same soil type, rotary tilled plots would exhibit larger surface temperature amplitudes, compared with no-till and chisel plowed plots under equal heat flux densities, however the use of rotary tiller would be restricted in weedy and stony lands.

One possible error in determination of thermal conductivity may arise from poor contact between the probe and surrounding soil. Poor probe/soil contact, possibly from wobbling during probe insertion, may results in an air gap around the probe. This air gap decreases the conductance of the soil adjacent to the probe which produces errors in temperature readings and leads to errors in the determination of k, so care is needed when inserting the probe into the soil.

4. Conclusions

The objective of this study was to determine the effects of tillage treatments on the apparent thermal conductivity of two soils. The results showed that thermal conductivity varied with soil texture and tillage treatment used. For the two soils studied, rotary and chisel tillage decreased thermal conductivity compared to no-tillage. The amount of decrease in soil thermal conductivity was higher in rotary tilled plots than in chisel tilled plots. The loam soil exhibited a rapid increase in thermal conductivity beyond a certain bulk density. Clay loam soil generally had lower thermal conductivity than loam soil at all similar tillage treatments. Because the thermal conductivities obtained were within the range of values obtained from other studies, and because the differences

between the modeled and measured thermal conductivities were very small, the measuring probe could be used for immediate in situ estimation of thermal conductivity of soils under Jordanian soil conditions. This could be achieved by designing a portable system utilizing data acquisition to allow for better accuracy, reduced operator effort, and improved speed.

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