#1436

Reprinted from the Soil Science Society *of America Journal*
Volume 59, no. 3, May-June 1995
677 South Segoe Rd., Madison, WI 53711 USA

Spatio-Temporal Variability of Soil Temperature within Three Land Areas Exposed to Different Tillage Systems

B. P. Mohanty,* W. M. Klittich, R. Horton, and M. Th. van Genuchten

ABSTRACT

The rational (lateral) spacing between soil temperature sensors to obtain spatial independence of measurements in the field under various tillage systems is not well studied. In particular, properly positioning sensors in a tillage plot requires knowledge of the spatial dependence of the measurements. This study was conducted to measure the horizontal spatial variability of soil temperature and its diurnal fluctuation in three different tillage systems. Soil temperature was measured with copper-constantan thermocouples at 49 positions in each system at the I- and 10-cm depths. The thermocouples formed a 7 by 7 grid with a spacing of 3.0 (east-west) by I.5 m (north-south). The three management systems were fall moldboard plowing followed by spring disking and planter operation (MP), fall chisel plowing followed by spring disking and planter operation (CP), and ridge tillage slot planting (RN). Each management system had been under continuous field corn (*Zea mays* L.) for 8 yr. A novel finding of the study is that a hysteresis within the diurnal cycle existed between the mean and the sample variance. This hysteresis was presumably due to differences in soil surface heating and cooling rates during the diurnal cycle. Although no definitive relationships could be determined, semivariograms appeared to show a time dependence and anisotropy during the 24-h observation period. Correlation distances were ≈ 9 m in the E-W direction along crop rows and tillage operations but <1.5 m in the N-S direction across crop rows and tillage operations. These spatial correlation distances will be useful in deciding the minimum (lateral) spacing between adjacent soil temperature **sensors in the field.**

AFTER SOIL WATER, soil temperature is perhaps the most important transient physical property of soil to affect crop growth. Research shows that soil temperature affects both the rate and thoroughness with which a plant root system permeates soil (Kaspar and Bland, 1992, and references therein). Several factors influence the variability of soil temperature in the field (Shumway et al., 1989; Davidoff and Selim, 1988). Tillage affects both the surface microtopography and the subsurface soil thermal properties. Changes in surface microrelief can greatly influence the local radiation characteristics, and hence the heat balance, because of changes in surface orientation and surface slope (Benjamin et al., 1990). Local soil orientation may or may not be toward the sun. Possible nonuniform radiation loads at the surface may affect not only diurnal, vertical soil temperature fluctuations (de Vries, 1963; Papendick et al., 1973; Persaud and Chang, 1983; Horton and Wierenga, 1983; Horton et al., 1984; Gupta et al., 1984; Pikul, 1991; Kemp et al., 1992; Katul and Parlange, 1993) but also the horizontal variability in soil temperature (Vauclin et al., 1982). Moreover, tillage-based distributions of crop residues left on the soil surface or incorporated in the surface-soil horizon may also result in a nonuniform radiation load (Potter et al., 1987; Chung and Horton, 1987; Kluitenberg and Horton, 1990; Horton et al., 1994). Crop residues usually have reflective and conductive properties that differ from mineral soil, with concurrent changes in the surface net-radiation and soil heat-flux density. Several researchers have shown that crop residue and other surface mulches modify mineral-soil temperature (Burrows and Larson, 1962; Cruse et al., 1982; Radke, 1982; Gupta et al., 1982; Gupta et al., 1984; Bristow and Abrecht, 1989), but few studies have addressed the variability of soil temperature with and without nonuniformly distributed surface residues. Other factors that affect the measured field variability of soil temperature are the placement of sensors, both horizontally and vertically, the method of installation (Wierenga et al., 1982), and sensor sample size (ten Berge et al., 1983).

While most researchers are aware of possible lateral variabilities in soil temperature measurements (e.g., Kluitenberg and Horton, 1990), few have tried to quantify this variability (Wierenga et al., 1982; Vauclin et al., 1982). Hatfield et al. (1982, 1984) and Yates et al. (1988) studied the spatial correlation of remotely sensed surface soil temperature data obtained with infrared thermometers. Scharringa (1976) published perhaps the most comprehensive study to date on subsurface soil temperature variability. After using copper constantan thermocouples in a 5 by 5 grid with a spacing of 4 m, Scharringa reported standard deviations of the mean for soil temperature measurements in a carefully leveled and prepared soil. He showed that the standard deviation varied with time of year, time of day, and depth. While the variability of soil temperature should change with time because of solar-radiation changes on both a diurnal and yearly scale and because of continuously changing water contents, Scharringa (1976) showed that this variability decreased with depth. For example, the standard deviation (σ) of the mean for the month of June was reported to be 1.209, 0.752, 0.628, 0.516, and 0.465°C at the 0.05-, 0.10-, 0.20-, 0.50-, and l-m depths, respectively, at 13 h. This same progression in σ was evident during the spring and summer months and for most of the fall and winter months. Scharringa concluded that a single measurement of soil temperature could not satisfactorily estimate the average soil temperature in his plots at any depth. A logical extension of this important work is to examine the spatial and temporal variability of soil temperature

---

B.P. Mohanty and M Th. van Genuchten, U.S. Salinity Lab., USDA-ARS, 450 Big Springs Rd., Riverside, CA 92507; and W.M. Klittich and R. Horton, Agronomy Dep., Iowa State Univ., Ames, IA 50011. Contribution as journal paper no. J-15842 of the Iowa Agric. and Home Economics Exp. Stn., Ames, IA. Projects no. 2556 and 2715. Received 23 May 1994. *Corresponding author (bmohanty@ucracl.ucr.edu).

Published in Soil Sci. Soc. Am. J. 59:752-759 (1995).

Abbreviations: MP, moldboard plowing followed by spring disking and planter operation; CP, fall chisel plowing followed by spring disking and planter operation; RN, ridge tillage slot planting; N, north; S, south; E, east; W, west; LSD, least significant difference.

for soils with nonuniform surface configurations and different surface-residue covers.

Soil surface condition is one feature that farmers can readily change through the implementation of different management systems. For example, Gupta et al. (1983) showed that the amount of surface residue can have a significant effect on soil temperature. Potter et al. (1985) similarly showed that soil thermal conductivity, and hence, soil temperature, can be altered by tillage. Accurate measurement of soil temperature under various tillage systems is not easy. In a review of the effect of tillage on soil temperature, Wierenga et al. (1982) stated that the horizontal or vertical placement of sensors, the number of sensors, and their method of installation, can significantly affect the measurements, particularly in the upper 5 cm of soil.

Variography and autocorrelation have been used extensively for studying the spatial variability of soil temperature (Folorunso and Rolston, 1984; Vauclin et al., 1982; Webster and Burgess, 1983; Davidoff et al., 1986; Yates et al., 1988). Of special interest to us is a study by Vauclin et al. (1982), who determined the spatial correlation of soil surface temperature along two transects in bare field soil immediately following irrigation. Measurements of soil surface temperature by infrared thermometry were obtained along a 60-m transect in the N-S direction and a 100-m transect in the E-W direction at solar noon for three consecutive days after a 0.1-m sprinkler irrigation. Using variography, they found that soil surface temperature was correlated with an average distance of 13 m in the E-W transect and 12 m in the N-S transect. Because the data represented only one realization of soil surface temperature in the diurnal cycle, Vauclin et al. (1982) could not determine if the correlation distances changed with time.

The objective of this study was to determine the horizontal spatial correlation of field soil temperatures during a diurnal cycle. Soil temperature data were collected at 1- and 10-cm depths in three tillage plots and analyzed for normality and uniformity of sample variance throughout a 24-h period. Semivariograms were used to obtain, during the diurnal cycle, the range of horizontal-spatial correlation in observed soil temperature measurements in the field plots. The information should lead to optimal spacing between adjoining soil temperature sensors in field soils and further understanding of spatial variation in soil temperature under different tillage-management practices.

METHODS

Three field plots with different tillage histories were used. The plots were located at the Agronomy and Agric. Engineering Res. Center of Iowa State Univ., 13 km west of Ames, IA. The soil is classified as a Nicollet (fine silty, mixed, mesic, Aquic Hapludoll). The three tillage treatments included MP, CP, and RN. Each plot had been maintained under continuous field corn for 8 yr. The planter operation was the same as during previous years, except that no seeds were dropped into the soil when the planter was pulled through the field. The planter rows were spaced 0.75 m apart and ran in the E-W direction.

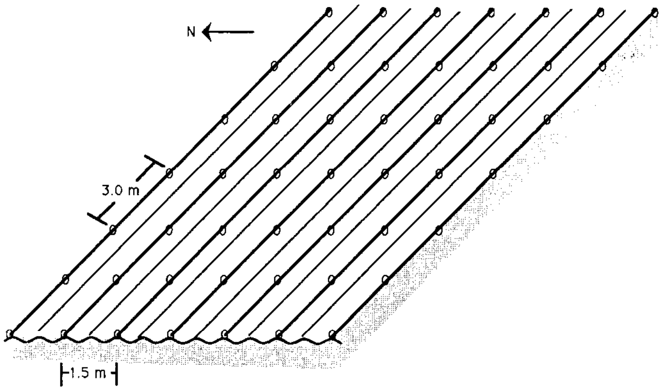

Fig. 1. Field-plot diagram showing thermocouple locations. The planter and tillage operation was in the East-West direction.

Copper-constantan thermocouples placed at 1- and 10-cm depths were located at 49 positions within each tillage field plot. The thermocouple locations formed a 7 by 7 grid, with spacings of 3.0 by 1.5 m in the E-W and N-S directions, respectively (Fig. 1). The fields were maintained free of vegetation during the measurements. The thermocouples were located within the planter rows and were allowed to equilibrate with the soil environment for 2 wk. Hourly soil temperature observations were recorded following soil moisture redistribution after a rain event. Because the data were not taken concurrently across tillage plots, no direct comparisons could be made between the three tillage systems. Hence, all data will be analyzed and interpreted mainly for variability within the individual tillage systems. We selected data representing one cloudless day from each tillage plot: 26 May for MP, 8 June for CP, and 21 June for RN. The three days had similar global solar radiation and rainfall histories.

Thermocouples were connected to a data-logger[1] (Model CR5, Campbell Scientific, Logan, UT), which recorded hourly temperature values. The thermocouples were constructed of 24-gauge copper-constantan wires joined with 60/40 rosin-core solder and sealed with epoxy. The junctions were tested to ensure environmental isolation and proper functioning. After excavating a short, narrow, and ≈ 11-cm-deep trench, the thermocouples were installed beginning near the planter row and extending away from the row, leaving an undisturbed soil face near the planter row. The thermocouples were pushed ≈ 2 cm horizontally into the undisturbed soil face of the trench until the sensor was in the planter row. A template was used to ensure that the depth from the surface and the distance between thermocouples remained the same. Lead wires were fastened to the bottom of the trench, leaving 20 cm of coiled lead in the bottom of the trench to minimize thermal conduction from the surface. Finally, the trench was carefully backtilled to its approximate original bulk density, and displaced plant residue was placed back on the soil surface. After obtaining the soil temperature data, soil bulk densities at the thermocouple sensor sites were measured at depths of 1.0 and 8.5 cm using an Uhland core sampler (Blake, 1965).

The observed soil temperature data were analyzed by means of Kolomogorov-Smirnov test statistics (Steel and Torrie, 1980) to give the relationship between the sample-order and normal-order statistics. This method was used to investigate

---

[1] Mention of trade names does not constitute an endorsement.

the data distribution and hence the need for possible data transformations.

We used a two-step approach to investigate the compliance of the data to the intrinsic hypothesis. First, we examined the mean for the presence of drift and looked at the homogeneity of the variance from the individual E-W rows and N-S columns in a manner similar to that outlined by Hamlett et al. (1986) and Mohanty and Kanwar (1994). Secondly, we compared the semivariograms constructed with and without a data detrending to remove any suspected drift that might be present.

The first part of the intrinsic hypothesis states that the expected difference between any two locations should be zero. To examine if our data set complied with this restriction, we compared local means to see if they were significantly different from each other. A least significant difference (LSD) test (Steel and Torrie, 1980) was used to statistically compare the minimum and maximum means from the 7 rows at each hour. The same procedure was used for the column direction. The last part of the intrinsic hypothesis states that the variance of the differences must be constant across space. Data that do not follow this assumption may be detected by comparing local variances. An *F*-test was used to check whether the row or column variances were significantly different. The ratio of maximum to minimum variance produced the *F*-statistics.

Semivariograms constructed for the raw and detrended data were also compared with check data nonstationarity. The data detrending was such that semivariograms computed in the E-W direction had the N-S column means removed, while those for the N-S direction had the E-W row means removed. This approach should identify semivariograms that have significant drift in the mean but are not significantly different in terms of the LSD comparison due to large overall variability. In instances where differences between the semivariograms were found, we selected the detrended semivariogram so as to use the best semivariogram estimate possible.

Each semivariogram (γ^*)was constructed by using the estimator (Matheron, 1963):

$$\gamma^*(h,\alpha) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i + h) - Z(x_i)]^2 \qquad [1]$$

where $Z(x_i)$ is the measured value of the regionalized variable at sampling location (x_i), h is the separation vector in direction α, and $N(h)$ is the number of sample pairs separated by vector h. We considered the resolution to be 4 lags, or just more than half of the maximum distance in any direction (David, 1977). Semivariograms were subsequently examined for general shape and the range of spatial correlation. The general shapes of semivariogram observed in this study were pure nugget (Type I), linear (Type II), or spherical (Type III). Typical characteristics and physical significance of different types of semivariogram model are described in detail in David (1977). Jack-knifing approach and different cross-validation criteria as proposed by Springer and Cundy (1987) were used to best fit theoretical model to sample semivariograms. Geostatistical software, STATPAC (Grundy and Miesch, 1987) was used for this purpose. In a few occasions, we had to make a qualitative decision when two or more different types of model fit the data equally well.

RESULTS AND DISCUSSION

Data presented in this paper are for single diurnal periods involving the MP, CP, and RN systems. The periods are as similar as the data allow with respect to rainfall and global radiation. Also, the most recent rainfall event for each diurnal period was at least 48 h before data collection had started. Global radiation on the days of measurement was 25.6, 24.3, and 27.4 MJ m^{-2} d^{-1} for the MP, CP, and RN fields, respectively. Average soil bulk densities of the 49 thermocouple sites were 1.18, 1.11, and 1.22 Mg m^{-2} for MP, CP, and RN tillage systems, respectively.

Figure 2 shows for each tillage plot, the hourly average and extreme temperatures of the 49 measurement sites at the 1-cm depth. The range (the difference between the hourly extremes) in the data was clearly time dependent; data taken close to a diurnal maximum had a greater range than measurements taken at or near a diurnal

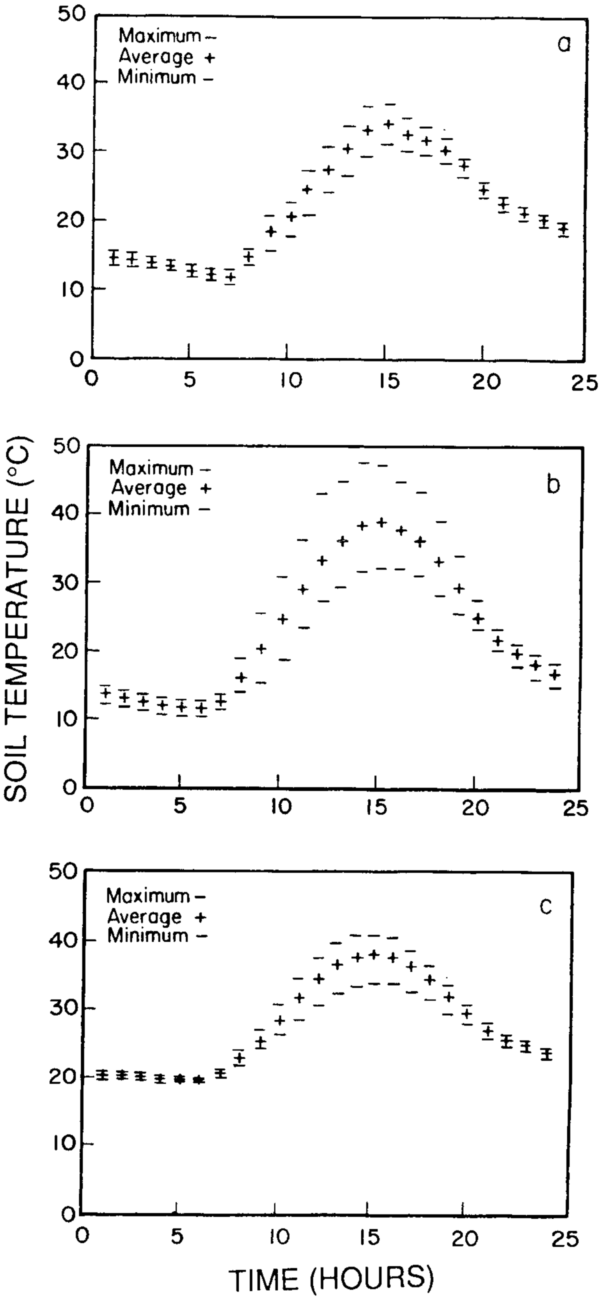

Fig. 2. Relationship between the mean and extreme values vs. time of soil temperature at the 1-cm depth for (a) moldboard, (b) chisel plow, and (c) ridge till.

minimum. Data for the 10-cm depth (not shown here) showed similar trends, except that the ranges across the complete diurnal periods were much smaller at the deeper depth. These findings are consistent with those of Scharringa (1976).

Consideration of the range of soil temperature allows a quick assessment of the diurnal changes in temperature variance for the three plots. Figure 2 implies that the variance will be time dependent and that the CP field will have a much larger variance than the MP and RN fields. The CP field had lower bulk densities (indicating lower thermal conductivities) and higher but statistically not (significantly) different percentages of residue cover than RN. The CP field tended to have a more random distribution of surface residue compared with RN; this result means that relatively more thermocouples in the CP field may have been influenced by the residue cover. Earlier, Gupta et al. (1983) discovered that residue cover delays cooling more than heating of the soil surface causing larger difference in soil temperature between residue and no-residue cover treatments for cooling than for heating periods. In this study, more random distribution of surface residue was perhaps also responsible for the greater variability in the CP temperature measurements.

Figure 3 shows a relationship between the mean and the variance of soil temperature data collected during the 24-h measurement cycle for the CP field at 1-cm depth. Interestingly, the data show increased variance as the mean increases. However, no unique function describes the relationship between variance and mean temperature. A lower temperature variability is evidently present during cooling than during heating. This hysteretic relationship was observed at both depths for all three tillage systems. The hysteresis is likely a result of the time available for horizontal heat transport to occur in the soil. There is evidently a quicker change in soil temperature during heating of the soil than during soil cooling. This process, in turn, allows less time for horizontal equilibrium of soil heat flow when the soil is warming. Coupled heat and mass transport may be another factor associated with the observed hysteresis in temperature means and variances. During the heating period, fluid (water and air) moves out of the intraparticular pore space (i.e., evaporation), while during the cooling period, fluid (water and air) moves into the intraparticular pore space (i.e., condensation). Spatial and temporal inequalities in evaporation and condensation can impact soil temperature variability. Different mechanisms of soil heat transport processes involved during the heating and the cooling periods can produce a hysteresis phenomenon in the mean and the variance of temperatures during a diurnal cycle. The magnitude of hysteresis (difference in the temperature variance between heating and cooling periods for the same mean temperature) is found to be maximum (6.7°C^2) between Hours 12 and 18, in this particular case, when the mean soil temperature is ≈33°C. As the variances and the means of hourly temperature for the heating and the cooling cycles were based on same sensors at same spatial locations, we presume that the magnitude of hysteresis may not be affected significantly by the number of data points. Future studies may be designed with more number of sampling points to verify this presumption. This hysteresis phenomenon, however, will be a critical factor in field-scale or plot-scale (simultaneous) transport of heat and fluid in soil across diurnal cycle(s).

Figure 4 shows surface plots of the soil temperature

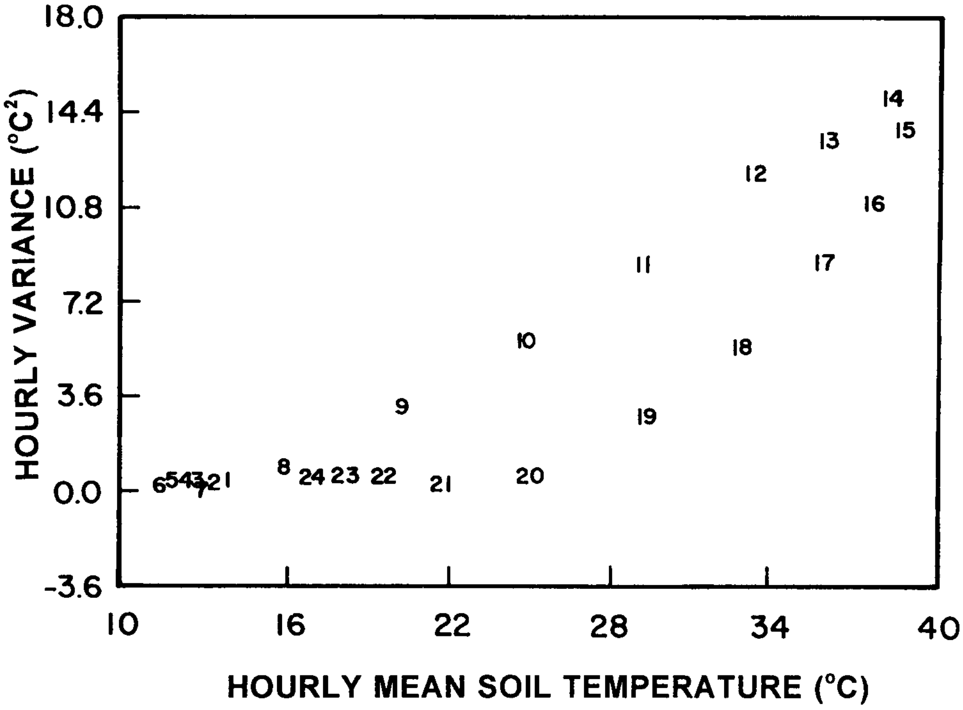

Fig. 3. Relationship between the mean hourly soil temperature at the 1-cm depth and the measured hourly variance of the chisel plowed field.

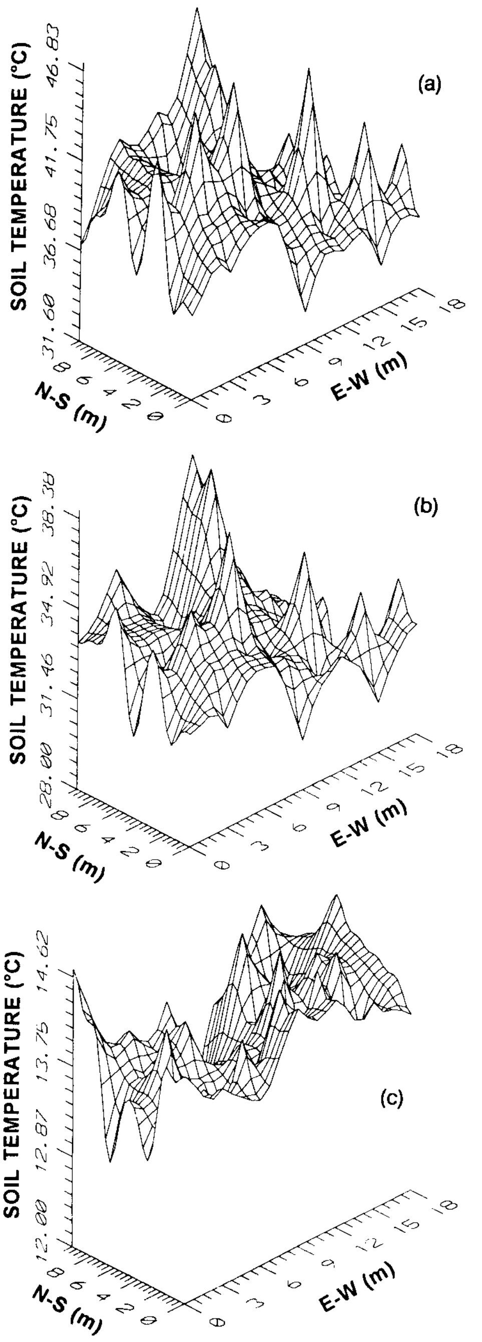

Fig. 4. Surface plots of soil temperature at 1-cm depth for chisel plow during (a) 14 h, (b) 18 h, and (c) 1 h.

for two extreme points in the hysteresis loop (at 1 and 14 h) and for one point in the middle of the hysteresis loop (at 18 h during the cooling cycle). The plots give a good visual comparison of the spatial distribution of the data. The general behavior of the data in Fig. 3 is readily apparent from the surface plots in Fig. 4, e.g., more variability at 14 h and little variability at 1 h.

Field variability was further examined by using the commonly reported diurnal maximum, average, and minimum soil temperature values. The maximum and minimum values correspond to the closed ends of the hysteresis loop in Fig. 3. The means and standard deviations for the data sets are shown in Table 1. The largest standard deviation occurred for the maximum soil temperature in the CP field. The standard deviations were generally greater at the 1-cm depth than at the 10-cm depth. As expected, and consistent with the data in Fig. 3 and 4, standard deviations were highest for the maximum temperatures and smallest for the minimum temperature within a tillage system.

Table 1. Mean and standard deviations for the diurnal maximum (MAX), average (AVG), and minimum (MIN) temperature values (°C) at 1- and 10-cm depths on three tillage plots.

Diurnal temperature	1-cm depth Mean	1-cm depth Standard deviation	10-cm depth Mean	10-cm depth Standard deviation
		Moldboard plowing		
MAX	34.3	1.35	24.2	0.79
AVG	22.2	0.42	19.1	0.35
MIN	12.3	0.35	14.4	0.19
		Chisel plowing		
MAX	38.7	3.77	24.2	1.21
AVG	23.3	1.15	19.4	0.61
MIN	11.6	0.54	15.1	0.26
		Ridge no till		
MAX	38.0	1.49	28.1	0.78
AVG	27.8	0.58	23.7	0.39
MIN	19.9	0.10	20.0	0.11

Table 2 presents the Kolmogorov–Smirnov test statistics for the diurnal extremes and the diurnal average soil temperature at 1- and 10-cm depths, under three tillage systems. The diurnal maximum and diurnal average data were normally distributed. Some deviations from a normal distribution that occurred for the diurnal minimum data are attributed to a limited resolution of the datalogger (0.1°C) when the range in soil temperatures is relatively small, rather than to the absence of fluctuations in the actual soil temperature values.

Different methods have been proposed for evaluating the presence of a drift or trend, and hence for a need to detrend the spatial data before estimating semivariograms and autocorrelograms (David, 1977; Davidoff et al., 1986; Hamlett et al., 1986; Mohanty et al., 1991; Mohanty and Kanwar, 1994). We examined the mean for the presence of drift and also looked at the homogeneity of the variance for the data from the individual rows and columns to validate the intrinsic hypothesis assumption. Our analyses revealed no significant difference ($P = 0.95$) between the minimum and maximum local variances at each hour. The F-statistic in most cases was close to unity, indicating that the variances were almost equal. We found that, within the 7-row means and 7-column means, there was no significant difference ($P = 0.95$) on a hourly basis, although several means were close to being significantly different. For this reason, we decided to compare semivariograms with and without a data detrending to obtain semivariograms that indeed have a drift component. Semivariograms from the MP field and the 10-cm depth from the RN field were not found to have apparent drift. Thus, the appropriate semivariograms for these cases were estimated by using the measured values directly. On the other hand, data from the CP field and the 1-cm depth from the RN field did

Table 2. Kolmogorov-Smirnov test statistics (β) for the diurnal maximum (MAX), average (AVG), and minimum (MIN) temperature values (°C) at 1- and 10-cm depths on three tillage plots. In all cases, the number of samples is equal to 49.

Diurnal temperature	1-cm depth	10-cm depth
	Moldboard plowing	
MAX	0.073	0.114
AVG	0.082	0.104
MIN	0.100	0.203*
	Chisel plowing	
MAX	0.113	0.125
AVG	0.075	0.118
MIN	0.140*	0.115
	Ridge no till	
MAX	0.076	0.079
AVG	0.143	0.064
MIN	0.200*	0.194*

* Hypothesis of normal distribution is rejected at 0.05 probability level. Sample statistics were used to calculate the critical values of β.

show differences between the transformed and untransformed semivariograms. Appropriate semivariograms from the CP field and from the 1-cm depth of the RN field were estimated from the transformed data, i.e., after removing the row or column means.

Our initial investigation of the data showed a significant correlation between the mean and variance with respect to time. The relationship was shown to be hysteretic during each 24-h period. The presence of hysteresis made it impossible for us to combine the data with time to form one daily average semivariogram as was done previously by Hamlett et al. (1986) for his daily soil water tension data. However, when we examined observations at each hour individually, no significant correlation was found to exist between the means and variances along the E-W or N-S direction. Thus, the intrinsic-hypothesis assumption was satisfied, and use of the semivariogram was validated.

Rather than presenting individual semivariograms for each tillage treatment, hour, depth, and/or direction combination, we decided to categorize the semivariograms into three basic shapes: viz, pure nugget (Type I), linear (Type II), and spherical (Type III). Tables 3 and 4 present a summary of the semivariogram types and the corresponding correlation distances. The information in these tables indicates that the semivariograms are neither constant, nor seem to occur in a random manner. The MP semivariograms in the E-W direction show strong consistency with respect to type and correlation distance, whereas the CP and RN systems show more variability; however, similar types (shapes) of semivariograms appeared during certain parts of the day. For example, the E-W direction semivariograms from the MP 1-cm depth are all of Type III from Hours 1 through 7 and 14 through 24 and of Type II from Hours 8 through 13. We therefore found a time dependency in the type and correlation distance. This conclusion is supported by our earlier finding that the data set is time dependent, having a larger variance during heating than during cooling at the same mean temperature. Although there is an obvious time dependency, the manner in which the spatial correlation varies with time cannot be readily deduced from the data in Tables 3 and 4.

Data from the MP field at the 1-cm depth showed correlation distances of ≈9 m in the E-W direction,

Table 3. Summary of semivariogram shapes and spatial correlation distances for the E-W direction at the 1- and 10-cm depths. Shapes are given three general forms. Type I displays a pure nugget effect, Type II increases but shows no sill, and Type III increases to a sill. Correlation distances are given in lags.†

	Tillage system‡											
	MP				CP				RN			
	1 cm		10 cm		1 cm		10 cm		1 cm		10 cm	
Hour	Type	Lag	Type	Lag	Type	Lag	Type	Lag	Type	Lag	Type	Lag
1	III	3	III	3	III	3	III	3	I		I	
2	III	3	III	3	III	3	III	3	I		I	
3	III	3	III	3	III	3	I		I		I	
4	III	3	III	3	III	3	II	+	I		I	
5	III	3	III	3	III	3	I		I		III	4
6	III	3	III	3	III	3	II	+	I		III	4
7	III	3	III	3	I		III	4	I		I	
8	II	+	III	3	III	2	III	4	I		I	
9	II	+	III	3	III	3	II	+	I		III	3
10	II	+	III	3	III	3	II	+	I		III	3
11	II	+	III	3	III	3	II	+	I		III	3
12	II	+	III	3	III	3	II	+	I		III	3
13	II	+	III	3	III	3	I		I		I	
14	III	3	III	3	III	3	I		I		I	
15	III	3	III	3	III	3	I		I		I	
16	III	3	III	3	III	3	I		I		I	
17	III	3	III	3	I		I		I		I	
18	III	3	III	3	I		I		I		I	
19	III	3	III	3	I		I		I		I	
20	III	3	III	3	I		I		III	3	I	
21	III	2	III	3	III	3	I		III	3	I	
22	III	2	III	3	III	3	I		II	+	I	
23	III	3	II	+	III	3	I		I		I	
24	III	3	II	+	III	3	III	3	III	3	I	

† 1 lag = 3 m, 2 lags = 6 m, 3 lags = 9 m, and 4 lags = 12 m, + = 4 lags (12 m) or more, – = correlation is unknown and may be nonexistent.
‡ MP = moldboard plowing; CP = chisel plowing; RN = ridge no till.

Table 4. Summary of semivariogram shapes and spatial correlation distances for the N-S direction at the 1- and 10-cm depths. Shapes are given three general forms, Type I displays a pure nugget effect, Type II increases but shows no sill, and Type III increases to a sill. Correlation distances are given in lags.†

	Tillage system‡											
	MP				CP				RN			
	1 cm		10 cm		1 cm		10 cm		1 cm		10 cm	
Hour	Type	Lag	Type	Lag	Type	Lag	Type	Lag	Type	Lag	Type	Lag
1	I		I		III	2	III	2	I		I	
2	I		I		III	2	III	2	I		I	
3	I		I		III	3	III	2	I		I	
4	I		I		III	3	III	2	I		I	
5	I		I		III	3	I		I		I	
6	I		I		III	3	III	3	I		I	
7	I		I		I		I		II	+	I	
8	I		I		I		III	3	I		I	
9	I		III	2	I		I		I		I	
10	I		III	3	I		I		I		I	
11	I		I		I		I		I		I	
12	I		I		I		I		I		I	
13	I		I		I		I		I		I	
14	I		I		I		I		I		I	
1s	I		I		I		I		I		I	
16	I		I		I		I		I		I	
17	I		III	3	I		I		I		I	
18	I		III	3	II	+	I		I		I	
19	I		III	3	III	3	I	–	I		I	
20	I		III	3	III	3	I		I		I	
21	III	2	III	2	I		I		III	2	I	
22	III	3	III	3	I		I		III	3	I	
23	I		III	3	I		II	+	III	3	I	
24	I		III	3	I		III	3	I		I	

† 1 lag = 1.5 m, 2 lags = 3 m, 3 lags = 4.5 m, and 4 lags = 6 m, + = 4 lags (6 m) or more, – = correlation is unknown and may be nonexistent.
‡ MP = moldboard plowing; CP = chisel plowing; RN = ridge no till.

with slightly greater correlation distances during Hours 8 to 13. The correlation distance at the 10-cm depth was mostly 9 m, with 2 semivariograms (for Hour 23 and 24) showing a greater correlation distance. The semivariograms in the E-W direction for the CP data at 1-cm depth showed spatial correlation until a distance of 9 m for most of the diurnal cycle, whereas those for the 10-cm depth were highly variable. The RN data revealed several Type I semivariograms in the E-W direction. A group of semivariograms for the 10-cm-depth data in the RN field during Hours 5 through 12 (excluding 7 and 8) showed spatial correlation distances of 9 to 12 m.

The semivariograms for the N-S direction were found to be very consistent. Type I semivariograms dominated all three tillage-plots in the N-S direction, indicating that the horizontal spatial-correlation distance was either <1.5 m (1 lag) or >6 m (4 lags). Some similarities between MP and CP fields were found in terms of their spatial structures. A group of Type III semivariograms between Hours 17 and 24 existed for the 10-cm-depth data in the MP field. The CP field showed correlation at both the 1- and 10-cm depths between Hours 1 and 6. Correlation distances in the N-S direction tended to be <1.5 m (1 lag), indicating that correlation may have existed at intervals shorter than those used in this study (1.5 m).

The study shows that the semivariograms in the E-W and N-S directions are largely anisotropic. Semivariograms in the E-W direction showed more spatial structure than those in the N-S direction. Because the MP and CP plots exhibited some spatial structure, while the RN plot was essentially structureless, the anisotropy may have been a result of the tillage operations. The results of Vauclin et al. (1982) support the existence of spatial correlation for the soil used in their study. Cressie and Horton (1987) and Mohanty and Kanwar (1994) concluded that plowing makes a soil more uniform and thus should contribute to increased horizontal spatial correlation of soil properties. Likewise, this study indicates that the spatial correlation of soil temperature is a function of time; the time-dependency is likely a function of the involved tillage operation.

Using the knowledge of spatial correlation, we now can optimize the lateral spacing of sensors for the measurement of soil temperature in a field plot. In plots that are anisotropic, it would be beneficial to either place the sensors more than 9 m apart in the direction of tillage or to place the sensors more than 1.5 m apart perpendicular to the tillage direction.

CONCLUDING REMARKS

One of the most important conclusions of this study was that a hysteresis existed between mean and variance of the hourly soil temperature under all three tillage practices (CP, RN, and MP) and both depths (1 and 10 cm). The hysteresis is possibly due to differences in soil-surface heating and cooling rates during the diurnal cycle. Spatial and temporal variability of surface energy and subsurface mechanisms of heat transfer affect soil heating and cooling rates. Hourly semivariograms of soil temperature for three management systems displayed a time dependency as manifested by the presence of similar semivariogram types during certain parts of the diurnal cycle. Semivariograms in the direction of tillage (E-W) indicated a spatial correlation of ≈ 9 m for the MP and CP fields and of unknown distance for the RN field. Range of semivariograms in the N-S direction was generally <1.5 m. This anisotropy is likely the result of the invoked tillage and planting operations.

ACKNOWLEDGMENT

Thanks to Dr. R.M. Cruse for providing the thermocouple wire used in this study.

REFERENCES

Benjamin, J.G., A.D. Blaylock, H.J. Brown, and R.M. Cruse. 1990. Ridge tillage effects on simulated water and heat transport. Soil Tillage Res. 18:167-180.

Blake, G.R. 1965. Bulk density. p. 374-390. In C.A. Black (ed.) Methods of soil analysis. Part 1. Agron. Monogr. 9. ASA, Madison, WI.

Bristow, K.L., and D.G. Abrecht. 1989. The physical environment of two semi-arid tropical soils with partial surface mulch cover. Aust. J. Soil Res. 27:577-588.

Burrows, W.L., and W.E. Larson. 1962. Effect of amount of mulch on soil temperature and early growth of corn. Agron. J. 54:19-22.

Chung, S.O., and R. Horton. 1987. Soil heat and water flow with a partial surface mulch. Water Resour. Res. 23:2175-2186.

Cressie, N.A.C., and R. Horton. 1987. A robust-resistant spatial analysis of soil-water infiltration. Water Resour. Res. 23:911-917.

Cruse. R.M.. K.N. Potter. and R.R. Allmaras. 1982. Modeling tillage effects on soil temperature. p. 133-150. In P.W. Unger and D.M. Van Doren, Jr. (ed.) Predicting tillage effects on soil physical properties and processes. ASA Spec. Publ. 44. ASA and SSSA, Madison, WI.

David, M. 1977. Geostatistical ore reserve estimation. Elsevier Scientific Publishing Company, New York.

Davidoff, B., J.W. Lewis, and H.M. Selim. 1986. A method to verify the presence of a trend in studying spatial variability of soil temperature. Soil Sci. Soc. Am. J. 50:1122-1127.

Davidoff, B., and H.M. Selim. 1988. Correlation between spatially variable soil moisture content and soil temperature. Soil Sci. 145: I-10.

de Vries, D.E. 1963. Thermal properties of soils. In W.R. Van Wijk (ed.) Physics of the plant environment. North-Holland Publishing Company, Amsterdam.

Folorunso, O.A., and D.E. Rolston. 1984. Spatial variability of field-measured denitrification gas fluxes. Soil Sci. Soc. Am. J. 48: 1214-1219.

Grundy, W.D., and A.T. Miesch. 1987. Brief description of STATPAC and related statistical programs for the IBM personal computers. U.S. Geological Survey Open File Rep. 87411-A.

Gupta, S.C., W .E. Larson, and R.R. Alhnaras. 1984. Predicting soil temperature and soil heat flux under different tillage-surface residue conditions. Soil Sci. Soc. Am. J. 48:223-232.

Gupta, S.C., W.E. Larson, and D.R. Linden. 1983. Tillage and surface residue effects on soil upper boundary temperatures. Soil Sci. Soc. Am. J. 47:1212-1218.

Gupta, S.C., J.K. Radke, W.E. Larson, and M.J. Shaffer. 1982. Predicting temperatures of bare- and residue-covered soil from daily maximum and minimum air temperatures. Soil Sci. Soc. Am. J. 46:372-376.

Hamlett, J.M., R. Horton, and N.A.C. Cressie. 1986. Resistant and exploratory techniques for use in semivariogram analyses. Soil Sci. Soc. Am. J. 50:868--875.

Hatfield, J.L., J.P. Millard, and R.G. Goettelman. 1982. Variability of surface temperature in agricultural fields of central California. Photogramm. Eng. Remote Sens. 48:1319-1325.

Hatfield, J.L., M. Vauclin, S.R. Vieira, and R. Bernard. 1984. Surface temperature variability patterns within irrigated fields. Agric. Water Manage. 8:429-437.

Horton, R., O. Aguirre Luna, and P.J. Wierenga. 1984. Observed and predicted two-dimensional soil temperature distributions under a row crop. Soil Sci. Soc. Am. J. 48:1147-1152.

Horton, R., G.J. Khrintenberg, and K.L. Bristow. 1994. Surface crop residue effects on the soil surface energy balance. In P. W. Unger (ed.) Managing agricultural residue. Lewis Publishers, Boca Raton, FL.

Horton, R., and P.J. Wierenga. 1983. Determination of the mean soil temperature for evaluation of heat flux in soil. Agric. Meteorol. 28:309-319.

Kaspar, T.C., and W.L. Bland. 1992. Soil temperature and root growth. Soil Sci. 154:290-299.

Katul, G.G., and M.B. Parlange. 1993. Determination of average field scale soil surface temperature from meteorological measurements. Soil Sci. 155:166-174.

Kemp, P.R., J.M. Cornelius, and J.F. Reynolds. 1992. A sample model for predicting soil temperatures in desert ecosystems. Soil Sci. 153:280-287.

Khritenberg, G.J., and R. Horton. 1990. Analytical solution for two-dimensional heat conduction beneath a partial surface mulch. Soil Sci. Soc. Am. J. 54:1197-1206.

Matheron, G. 1963. Principles of geostatistics. Econ. Geol. 58: 1246-1266.

Mohanty, B.P., and R.S. Kanwar. 1994. Spatial variability of residual nitrate-nitrogen under two tillage systems in central Iowa: A composite 3-D resistant and exploratory approach. Water Resour. Res. 30:237-251.

Mohanty, B.P., R.S. Kanwar, and R. Horton. 1991. A robust-resistant approach to interpret spatial behavior of saturated hydraulic conductivity of a glacial till soil under no-tillage system. Water Resour. Res. 27:2979-2992.

Papendick, RI., M.J. Lindstrom, and V.L. Cochran. 1973. Soil mulch effects on seedbed temperature and water during fallow in eastern Washington. Soil Sci. Soc. Am. Proc. 37:307-314.

Persaud, N., and A.C. Chang. 1983. Estimating soil temperature by linear filtering of measured air temperature. Soil Sci. Soc. Am. J. 47:831-847.

Pikul, J.L. 1991. Estimating soil surface temperature from meteorological data. Soil Sci. 151:187-195.

Potter, K.N., R.M. Cruse, and R. Horton. 1985. Tillage effects on soil thermal properties. Soil Sci. Soc. Am. J. 49:968-973.

Potter, K.N., R. Horton, and R.M. Cruse. 1987. Soil surface roughness effects on radiation reflectance and soil heat flux. Soil Sci. Soc. Am. J. 51:855-860.

Radke, J.K. 1982. Managing early season soil temperatures in the northern Corn Belt using configured soil surfaces and mulches. Soil Sci. Soc. Am. J. 46:1067-1071.

Scharringa, M. 1976. On the representativeness of soil temperature measurements. Agric. Meteorol. 16:263-276.

Shumway, R.H., J.W. Biggar, F. Morkoc, M. Bazza, and D.R. Nielsen. 1989. Time and frequency-domain analysis of field observations. Soil Sci. 147:286-298.

Springer, E.P., and T.W. Cundy. 1987. Field-scale evaluation of infiltration parameters from soil texture for hydrologic analysis. Water Resour. Res. 23:325-334.

Steel, R.G.D., and J.H. Torrie. 1980. Principles and procedures of statistics. McGraw-Hill Book Company, New York.

ten Berge, H.F.M., L. Stroosnijder, P.A. Burrough, A.K. Bregt, and M.J. de Heus. 1983. Spatial variability of physical soil properties influencing the temperature of the soil surface. Agric. Water Management 6:213-226.

Vauclin, M., S.R. Vieira, R. Bernard, and J.L. Hatfield. 1982. Spatial variability of surface temperature along two transects of a bare soil. Water Resour. Res. 18:1677-1686.

Webster, R., and T.M. Burgess. 1983. Spatial variation in soil and the role of kriging. Agric. Water Manag. 6:111-122.

Wierenga, P.S., D.R. Nielsen, R. Horton, and B. Kies. 1982. Tillage effects on soil temperature and thermal conductivity. p. 69-90. ***In*** P.W. Unger and D.M. Van Doren, Jr. (ed.) Predicting tillage effects on soil physical properties and processes. ASA Spec. Publ. 44. ASA and SSSA, Madison, WI.

Yates, S.R., A.W. Warrick, A.D. Matthias, and S. Musil. 1988. Spatial variability of remotely sensed surface temperatures at field scale. Soil Sci. Soc. Am. J. 52:40-45.