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Residue Management Effects on Soil Temperature

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ABSTRACT

Soil temperatures are influenced by many factors, including surface residues. In turn, soil temperatures influence such factors as seed germination, plant growth, nutrient availability, insect populations, and pesticide degradation. Because of the increased use of conservation tillage involving surface residues, a better understanding of residue management effects on soil temperatures is needed. The objective of this study was to determine the effects of residue management practices on soil surface temperatures and on soil surface-air temperature relationships for the southern Great Plains. Soil surface and air (at 2-m height) temperatures were measured during the fallow period after winter wheat (*Triticum aestivum* L.) harvests in 1982 and 1983. Residue management treatments were disk, sweep, and no-tillage (with standing or shredded residues). Minimum surface temperatures differed only slightly among treatments at different seasons of the fallow period (summer, fall, winter, spring). Maximum temperatures were highest with no-tillage (standing residues) after dryland wheat in all periods, except in winter when they were highest with no-tillage with shredded residues. Relationships between soil surface and air temperatures were highly significant (R^2 = 0.931, $P \geq 0.001$). The relationships developed from the 1983 to 1984 data were used to predict surface temperature from weather station air temperatures for the 1982 to 1983 period. Differences between observed and predicted mean temperatures were significant only for no-tillage with standing residues in summer and fall and with shredded residues in spring. Normalized soil surface temperatures were affected more by season of the year than by residue management treatment.

Soil temperatures are influenced by many factors, including surface residues. Soil temperatures, in turn, influence such processes as seed germination, plant root and top growth, nutrient availability, insect populations, and pesticide degradation (Gupta et al., 1984). Consequently, with the increased use of conservation tillage in many regions, which involves the maintenance of surface residues, a better understanding of the effect of residue management practices on soil temperatures is needed.

Soil temperatures during various seasons of the year in the southern Great Plains were greatly affected by the amount of wheat (*Triticum aestivum* L.) residue (straw) placed on the soil surface (Unger, 1978). Different tillage or residue management practices were not involved in that study; but such practices in other regions affected soil temperatures which, in turn, affected crop responses (Griffith et al., 1973; Schneider and Gupta, 1985; van Wijk et al., 1959; Willis and Amemiya, 1973). For most locations, however, soil temperature data are lacking. The only temperature information available from most weather stations is the daily maximum and minimum air temperature measured at a known height above the soil surface.

Because of the unavailability of adequate soil temperature databases, scientists and practitioners use models to estimate soil temperatures. Cruse et al. (1982) and Gupta et al. (1984) reviewed some models that are available for predicting soil temperatures under various surface conditions. Most mechanistic models need hourly soil surface temperatures to predict soil temperatures at various depths. Gupta et al. (1983) presented a procedure to estimate hourly soil surface temperatures from daily maximum and minimum air temperatures. Coefficients for the relationships presented by Gupta et al. (1983) apply to climatic conditions in Minnesota and, at best, to the U.S. north central region. The broad objective of this study was to develop a database (similar to that of Gupta et al., 1983) that can be used to predict soil temperatures for the southern Great Plains. Specific objectives were to (i) determine the influence of residue management practices on soil temperatures, (ii) establish relationships between maximum and minimum soil surface and air temperatures for various surface residue conditions, and (iii) determine the average shape of the daily soil surface temperature wave for the southern Great Plains.

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MATERIALS AND METHODS

Soil and air temperatures were measured at the USDA Conservation and Production Research Lab., Bushland, TX, in conjunction with a tillage-residue management study involving a winter wheat-fallow-corn (*Zea mays* L.) cropping system from 1982 to 1984. The measurements were started after wheat harvest and continued until the corn shaded the soil. The soil was Pullman silty clay loam (fine, mixed, thermic Torrertic Paleustoll), which contained 17% sand, 53% silt, 30% clay, and 2% organic matter in the surface horizon (0- to 15-cm depth). The surface soil color is brown (7.5YR 4/2) when dry and dark brown (7.5YR 3/2) when moist.

The tillage and residue management treatments were imposed after harvest of dryland (nonirrigated) and irrigated wheat in 1982 and 1983. Use of dryland and irrigated wheat provided two distinct residue levels (low and high, respectively) at the time the treatments were imposed each year. Further differences in residue levels resulted from the treatments imposed, which are given in Table 1. Disk and sweep tillage operations were performed four times during each fallow period. On no-tillage plots, weeds were controlled with herbicides. The treatments were replicated four times. Row orientation was northeast-southwest. Complete details regarding the study relative to treatment effects on soil water storage and corn production are in Unger (1986).

Surface residue amounts were determined before wheat harvest and at irregular intervals until corn planting the following year. Amounts present before harvest were determined by clipping and weighing the entire plants from two 1-m^2 areas per plot, then threshing and weighing the grain. The difference between entire plant and grain weights represented the residue weight. At subsequent determinations, all surface residues from two 1-m^2 areas per plot were removed, immersed in water to remove adhering soil, dried, and weighed. The residue amounts by weight were used to estimate the surface coverage provided by the residues, using the relationship established by Van Doren and Allmaras (1978).

After imposing the tillage-residue management treatments, four copper-constantan thermocouples, connected in

Table 1. Tillage and residue management treatments, Bushland, TX, 1982 to 1984.

Treatment	Description of treatment
DT-D	Disk tillage, after dryland wheat
DT-I	Disk tillage, after irrigated wheat
ST-D	Sweep tillage, after dryland wheat
ST-I	Sweep tillage, after irrigated wheat
NT-Sh-D	No-tillage, shredded residues, after dryland wheat
NT-Sh-I	No-tillage, shredded residues, after irrigation wheat
NT-St-D	No-tillage, standing residues, after dryland wheat
NT-St-I	No-tillage, standing residues, after irrigated wheat

parallel to give an average reading, were randomly installed at 0.00- (<2-mm) and 0.05-m depths in DT and St treatment plots and on ridges between rows of stubble in NT-Sh and NT-ST treatment plots. Hereafter, temperatures at the 0.00-m depth are referred to as soil surface temperatures. Air temperatures were measured at the field site at a 2-m height above the soil surface with unshielded thermocouples. Data were logged hourly with a Model CR-5 data logger (Campbell Scientific, Inc., Logan, UT).[1]

Data from the four replications were averaged for each tillage depth-residue level combination. The procedures of Gupta et al. (1983) were followed to normalize and average soil surface temperatures for a given period using

$$\Gamma_{o,t} = \frac{(T_{o,t} - T_{o,sn})}{(T_{o,sx} - T_{o,sn})} \quad [1]$$

and

$$\Gamma^*_{o,t} = \frac{1}{N}\Sigma \Gamma_{o,t} \quad [2]$$

where

$\Gamma_{o,t}$ = normalized hourly soil surface temperature at time t,

$T_{o,t}$ = hourly soil surface temperature (°C) at time t corresponding to a given tillage and residue treatment,

$T_{o,sn}$ = daily minimum soil surface temperature (°C) for the treatment under consideration,

$T_{o,sx}$ = daily maximum soil surface temperature (°C) for the treatment under consideration, and

$\Gamma^*_{o,t}$ = normalized soil surface temperature at time t averaged over N number of days.

Data were logged from August 1982 to June 1983 and from July 1983 to June 1984 on separate areas, but only data for the latter period will be discussed in the initial parts of this paper. In addition, the discussion will be limited to $T_{o,t}$ for individual days or 30-d periods during the summer, fall, winter, and spring. The periods covered were near the middle of the different seasons and were from 28 July through 26 Aug. 1983 [DY (day of year) 209 to 238], 1 through 30 Oct. 1983 (DY 274 to 303), 31 Jan. through 29 Feb. 1984 (DY 31 to 60), and 10 Apr. through 9 May 1984 (DY 101 to 130). In the last part of this paper, relationships established from the 1983 to 1984 data were tested by predicting $T_{o,t}$ for the 1982 to 1983 period.

RESULTS AND DISCUSSION

Surface Residues

Residue production by wheat and approximate amounts remaining on the surface during different periods are given in Table 2. Production by dryland and irrigated wheat was about normal in 1982 and well above normal in 1983. High residue yields in 1983 resulted primarily from very favorable precipitation during late winter and spring.

Table 2. Amounts of residues on the surface at various times during fallow periods at Bushland, TX, 1982 to 1984.

Fallow period	Treatment	Time of measurement: Initial†	Summer	Fall	Winter	Spring
		Mg ha^{-1}				
1982–83	DT-D	4.6	2.3	1.2	1.0	0.7
	ST-D	4.8	4.3	3.8	3.2	2.9
	NT-Sh-D	4.6	4.5	4.5	4.3	4.1
	NT-St-D	4.9	4.8	4.8	4.2	3.5
	DT-I	9.2	5.5	2.8	2.2	1.5
	ST-I	9.4	8.5	7.6	7.0	6.0
	NT-Sh-I	9.4	9.0	9.0	7.5	7.0
	NT-St-I	9.7	9.3	9.3	8.0	7.5
1983–84	DT-D	10.1	6.0	4.0	1.7	0.9
	ST-D	9.2	8.2	7.4	5.0	2.3
	NT-Sh-D	9.3	9.0	8.8	6.5	6.0
	NT-St-D	10.1	9.8	9.5	7.5	6.4
	DT-I	15.3	9.2	7.7	3.7	1.7
	ST-I	15.6	14.0	11.9	8.0	2.3
	NT-Sh-I	16.4	16.0	15.5	11.0	10.6
	NT-St-I	15.3	15.0	14.5	10.8	10.5

† Residues present at wheat harvest.

Residue amounts present at subsequent times during the fallow period were influenced by tillage method and natural deterioration of the residues. Because of high amounts initially present, relatively high surface coverage remained throughout the 1983 to 1984 fallow period with the lowest estimated surface cover being 49% for the DT-D treatment in spring (Table 3). The DT-D treatment also resulted in the lowest estimated surface cover (41%) for the 1982 to 1983 fallow period. The surface cover estimates for the NT-St and NT-Sh treatments may be high. For the NT-St treatments, most residues were standing in drill rows (0.25-m spacing) and, hence, did not uniformly cover the surface. Some uncovered soil was present between the drill rows, except where chaff from the harvester fell on the surface. For the NT-Sh treatments, shredding moved much of the residues from the ridges to the furrows, again resulting in some bare spots on the surface.

Hourly Surface Temperatures

Soil $T_{o,t}$ due to tillage treatments and air temperatures (T_a) at a 2-m height for DY 221 are shown in Fig. 1. On DY 221 on dryland plots, $T_{o,sx}$ was highest with the NT-St-D treatment. For the remaining treatments, $T_{o,sx}$ differed only about 3 °C (Fig. 1A). In summer, sufficient residues for nearly 100% surface coverage were present, which resulted in the relatively low $T_{o,sx}$ for the DT-D, ST-D, and NT-Sh-D treatments because of relatively uniform distribution of the residues. In contrast, $T_{o,sx}$ was higher for the NT-St-D treatment because the soil was relatively free of residues on the ridges (between rows of standing stubble). The $T_{o,sn}$ were similar for all treatments on dryland plots.

On irrigated plots, $T_{o,sn}$ also were similar for all treatments (Fig. 1B); but the trends in $T_{o,sx}$ were different from those on dryland plots. Highest $T_{o,sx}$ occurred with the DT-I treatment. This maximum was about 4 °C lower than it was for the NT-St-D treat-

[1] Mention of a trade name or product does not constitute a recommendation or endorsement for use by the USDA, nor does it imply registration under FIFRA as amended.

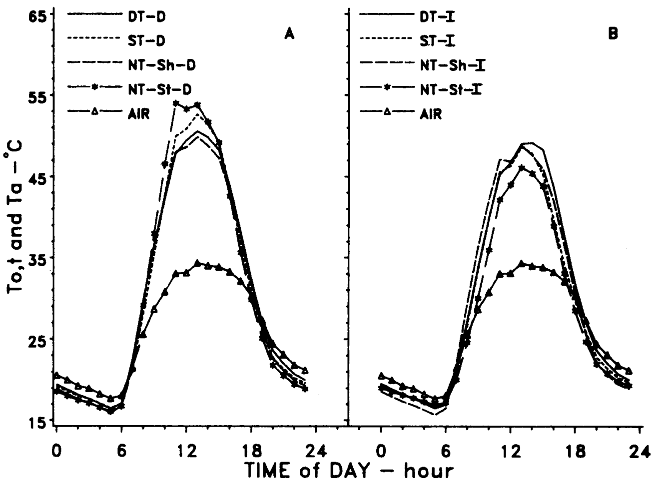

Fig. 1. Air (T_a) (2-m height) and soil surface ($T_{o,t}$) temperatures for DY 221, summer 1983.

ment but similar to that for the ST-I and NT-Sh-I treatments. The lowest $T_{o,sx}$ occurred with the NT-St-I treatment.

Results are shown in Fig. 2 for treatments that caused the largest differences in $T_{o,sx}$ on selected days in summer (DY 221), fall (DY 296), winter (DY 33), and spring (DY 118). In all seasons except winter, $T_{o,sx}$ was highest with the NT-St-D treatment because of exposed bare soil between rows of standing residue. In winter, standing residue with the NT-St-D treatment possibly shaded the soil due to a lower sun angle and, therefore, resulted in lower $T_{o,sx}$ than with other treatments. In winter, the highest $T_{o,sx}$ occurred with the NT-Sh-D treatment.

The lowest $T_{o,sx}$ in summer occurred with the NT-St-I treatment, which resulted in major shading of the soil due to the presence of a large amount of relatively tall (~40 cm) standing residues. The NT-St-I treatment also resulted in the lowest $T_{o,sx}$ in the fall. In winter and spring, lowest $T_{o,sx}$ occurred with the ST-D and ST-I treatments, respectively. The reason for lower $T_{o,sx}$ in winter with the ST-D treatment is not known. In spring, lower $T_{o,sx}$ with the ST-I treatment

Table 3. Approximate percentage of surface covered by residues† at various times during fallow at Bushland, TX, 1982 to 1984.

Fallow period	Treatment	Initial‡	Summer	Fall	Winter	Spring
		%				
1982-83	DT-D	94	80	60	51	41
	ST-D	95	92	91	88	86
	NT-Sh-D	94	93	93	92	91
	NT-St-D	95	95	95	92	90
	DT-I	100	96	85	80	65
	ST-I	100	99	99	99	97
	NT-Sh-I	100	100	100	99	99
	NT-St-I	100	100	100	99	99
1983-84	DT-D	100	97	90	68	49
	ST-D	100	99	98	95	80
	NT-Sh-D	100	100	100	97	97
	NT-St-D	100	100	100	98	97
	DT-I	100	100	98	91	68
	ST-I	100	100	100	99	80
	NT-Sh-I	100	100	100	100	100
	NT-St-I	100	100	100	100	100

† Based on relationships established by Van Doren and Allmaras (1978).
‡ Residues present at wheat harvest.

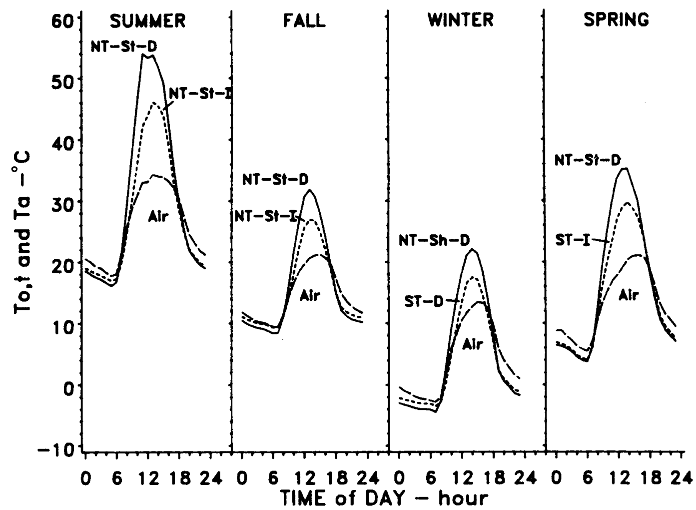

Fig. 2. Air (T_a) (2-m height) and soil surface ($T_{o,t}$) temperatures in different seasons of the 1983 to 1984 fallow period for treatments resulting in the greatest temperature differences.

possibly resulted from greater heat capacity and evaporative cooling of the soil. The DT and ST treatment plots were irrigated on DY 109, and evaporation from them undoubtedly was at a greater rate than from NT-Sh and NT-St treatment plots, which were not irrigated and which received a total of only 10 mm of rain in five storms during the 27-d period that preceded the day of measurement (DY 118).

Soil Surface-Air Temperature Relationships

The relationship between $T_{o,sx}$ and $T_{o,sn}$ and the corresponding maximum (T_{ax}) and minimum (T_{an}) air temperatures for the DT-D treatment during the fall period is illustrated in Fig. 3. Shown is the scatter of data points and the best-fit line obtained by use of the cubic regression technique (SAS, 1985) to estimate soil surface maximum or minimum temperature ($T_{o,smm}$) as a function of T_a. The high R^2 value obtained indicated that the cubic regression technique satisfactorily described the relationship between daily $T_{o,smm}$ and corresponding daily T_{ax} and T_{an}, but there was some significant deviation in the $T_{o,sx}$ values. The pro-

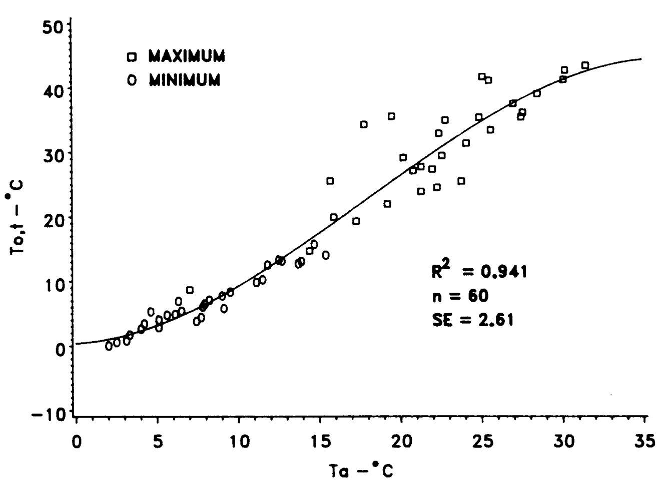

Fig. 3. Cubic regression relationship between air (T_a) and soil surface ($T_{o,t}$) temperatures for the DT-D treatment in fall 1983 (DY 274–303).

cedure also was used to determine the relationship for other treatments in the four seasons. The best-fit lines for $T_{o,smm}$ and T_a relationships for all tillage-residue level combination treatments during the 30-d summer period are illustrated in Fig. 4. Regression statistics for all periods are given in Table 4.

During summer (DY 209–238), differences in $T_{o,smm}$ due to treatments were less than about 3 °C at T_a at or below 23 °C (Fig. 4). At higher T_a, highest and lowest $T_{o,smm}$ occurred with the NT-St-D and NT-St-I treatments, respectively, with the greatest difference in $T_{o,smm}$ being about 10 °C at about 35 °C T_a. The higher $T_{o,smm}$ with the NT-St-D treatment are attributed to unshaded bare soil between the rows of standing stubble. For the NT-St-I treatment, taller, denser standing stubble, along with more chaff on the surface, partially shaded the surface and shielded it from incoming radiation.

For all other periods, differences in minimum $T_{o,smm}$ due to tillage treatments were less than for the summer period, except that the maximum difference was about 5 °C for the winter period (relationships not shown). The maximum differences in $T_{o,smm}$ of 10 °C or less

Table 4. Coefficients for cubic regression equations relating air temperatures and soil surface temperatures during the various periods for the different tillage treatments and residue levels, 1983 to 1984.

	Coefficients					
Treatment	*a*	*b*	*c* × 10	*d* × 10³	R^2†	SE‡
			Summer, DY§ 209–238, *n* = 60			
DT-D	51.68	−6.50	3.25	−3.95	0.985	2.36
ST-D	54.54	−6.71	3.25	−3.79	0.983	2.68
NT-Sh-D	53.87	−6.97	3.48	−4.30	0.988	2.16
NT-St-D	66.84	−8.57	4.08	−4.90	0.985	2.66
DT-I	42.53	−5.12	2.60	−3.05	0.981	2.60
ST-I	43.70	−5.06	2.50	−2.86	0.984	2.34
NT-Sh-I	46.03	−5.80	2.93	−3.52	0.989	2.04
NT-St-I	44.89	−4.82	2.27	−2.47	0.981	2.32
			Fall, DY 274–303, *n* = 60			
DT-D	0.42	0.13	0.93	−1.75	0.941	3.36
ST-D	1.73	0.12	0.91	−1.57	0.941	3.35
NT-Sh-D	1.43	−0.14	1.11	−2.07	0.936	3.50
NT-St-D	2.13	−0.46	1.41	−2.63	0.931	4.03
DT-I	0.20	0.27	0.74	−1.31	0.945	3.07
ST-I	−0.23	0.48	0.57	−0.93	0.952	2.84
NT-Sh-I	0.68	−0.05	1.05	−1.97	0.944	3.25
NT-St-I	2.42	0.22	0.64	−1.04	0.971	2.81
			Winter, DY 31–60, *n* = 60			
DT-D	−0.45	1.64	0.43	−2.63	0.971	2.61
ST-D	−0.65	1.23	0.40	−1.98	0.960	2.52
NT-Sh-D	−0.33	1.67	0.49	−2.95	0.970	2.71
NT-St-D	−1.45	1.59	0.62	−3.16	0.960	3.17
DT-I	−0.32	1.62	0.49	−2.87	0.967	2.76
ST-I	−0.93	1.39	0.60	−3.03	0.950	3.12
NT-Sh-I	−0.60	1.53	0.45	−2.62	0.972	2.45
NT-St-I	−1.26	1.24	0.58	−2.74	0.940	3.19
			Spring, DY 101–130, *n* = 60			
DT-D	−0.84	0.30	1.05	−2.22	0.950	3.65
ST-D	−1.05	0.36	0.96	−2.01	0.945	3.72
NT-Sh-D	−1.29	0.09	1.42	−3.20	0.969	2.96
NT-St-D	−1.54	−0.01	1.64	−3.65	0.955	4.01
DT-I	−1.08	0.32	0.99	−2.10	0.945	3.67
ST-I	−0.88	0.29	1.01	−2.15	0.934	4.00
NT-Sh-I	−1.20	0.17	1.24	−2.74	0.972	2.68
NT-St-I	−0.46	−0.08	1.57	−3.59	0.958	3.44

† Coefficient of determination. All were significant at the 0.0001 level.
‡ Standard error of the regression.
§ DY = Day of year.

during all periods, in general, are lower than those reported by Gupta et al. (1983) for conditions in Minnesota and those reported for the same soil at Bushland, TX (Unger, 1978). The study by Gupta et al. (1983) involved corn residues that provided surface coverage ranging from 0 to 75% with the different tillage methods evaluated. In this study, minimum surface coverage was estimated to be 49% with the DT-D treatment in the spring. For all other treatments, surface coverage was 80% or greater. Consequently, differences in the amount of radiation reaching the surface and differences in insulating effect due to residues undoubtedly were much lower in this study than in the study by Gupta et al. (1983).

In the study by Unger (1978), soil temperatures were measured only at a 100-mm depth. At that depth, temperature differences up to 10 °C were measured on some days. Undoubtedly, greater differences occurred at the surface; and those greater differences were attributed to the greater differences in amounts of surface residues, which ranged from 0 to 12 Mg ha⁻¹. Surface coverage was 100% with 4.0 Mg ha⁻¹ of surface residues. The current study suggests that even relatively small differences of surface residue amounts and conditions have a major effect in moderating $T_{o,t}$. In general, maximum temperatures are lower and minimum temperatures are higher with increased amounts of residues at the soil surface.

Normalized Soil Surface Temperatures

Hourly average normalized soil surface temperatures ($\Gamma^*_{o,t}$) for the summer period were similar for all tillage and residue management treatments (plots not shown). Hence, only results for treatments resulting in maximum differences in $\Gamma^*_{o,t}$ during all periods are

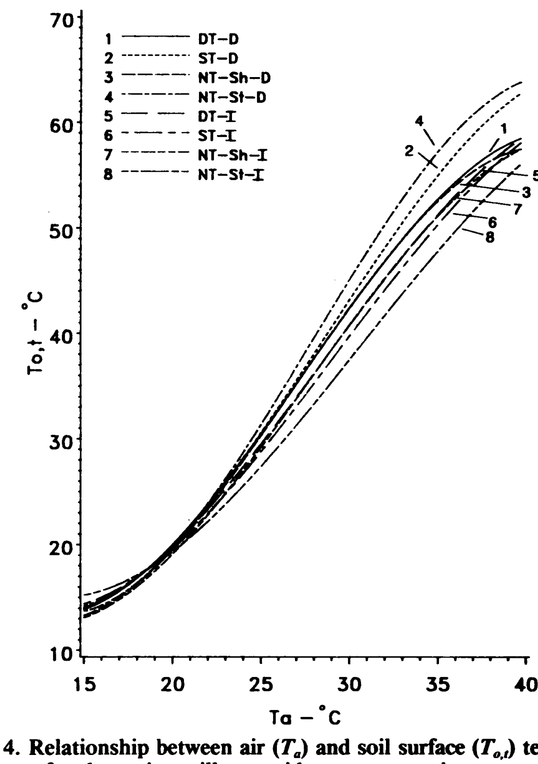

Fig. 4. Relationship between air (T_a) and soil surface ($T_{o,t}$) temperatures for the various tillage-residue treatments in summer 1983 (DY 209–238).

illustrated in Fig. 5. In summer and fall, differences in $\Gamma^*_{o,t}$ were slight. In winter, $\Gamma^*_{o,t}$ for the ST-D treatment lagged behind those for the DT-I treatment. The only appreciable difference in spring resulted from the NT-St-D treatment, for which cooling was faster than for the ST-I treatment. The generally greater differences in $\Gamma^*_{o,t}$ in winter than in other seasons probably resulted from the differences in soil loosening and surface roughness due to tillage, sun angles relative to residue orientation (random due to tillage and shredding vs. standing in rows with the NT-St treatment), and stubble height (irrigated vs. dryland and standing vs. shredded). Maximum and minimum values of $\Gamma^*_{o,t}$ were slightly less than 1.0 and greater than 0.0, respectively. This is expected because the time of daily maximum and minimum temperature varies with a given season.

Differences among seasons in shapes of the curves for the tillage treatments were related mainly to the time of day at which the minimum $\Gamma^*_{o,t}$ occurred. Time of minimum $\Gamma^*_{o,t}$ varied between 0600 h in summer and about 0800 h in the fall and winter periods. The maximum $\Gamma^*_{o,t}$ occurred between 1400 and 1500 h each season. Consequently, the duration of the heating phase was slightly longer during the summer period than during the fall and winter periods. According to Gupta et al. (1983), such slight differences in $\Gamma^*_{o,t}$ curves among seasons can be ignored for modeling purposes without causing large errors in predicting daily maximum, minimum, or average root-zone temperatures. Such prediction is not covered in this paper.

Predicting Soil Surface Temperatures

The relationships between $T_{o,smm}$ and T_a developed in this paper from data for the 1983 to 1984 fallow period were tested by similar data for the 1982 to 1983 fallow period. Although tillage treatments were the same, surface residue amounts were lower in the 1982 to 1983 than in the 1983 to 1984 fallow period (Table 2). For some seasons, however, there were similar surface residue amounts (difference $\leq$1.0 Mg ha^{-1}), mainly when comparing low residue (after dryland wheat) conditions in 1983 to 1984 to high residue (after irrigated wheat) conditions in 1982 to 1983. To evaluate the predictive value of the relationships developed in this paper (Table 4), T_a measured at a 1.5-m height at a weather station located about 1 km from the plot area were used to predict $T_{o,smm}$ for treatments that provided similar surface residue amounts in a given season during the 1982 to 1983 fallow period. The observed and predicted values are given in Table 5. The first-mentioned treatment in the first column in Table 5 was used for the predictions. Most mean differences between observed and predicted values were not significantly different from zero, based on

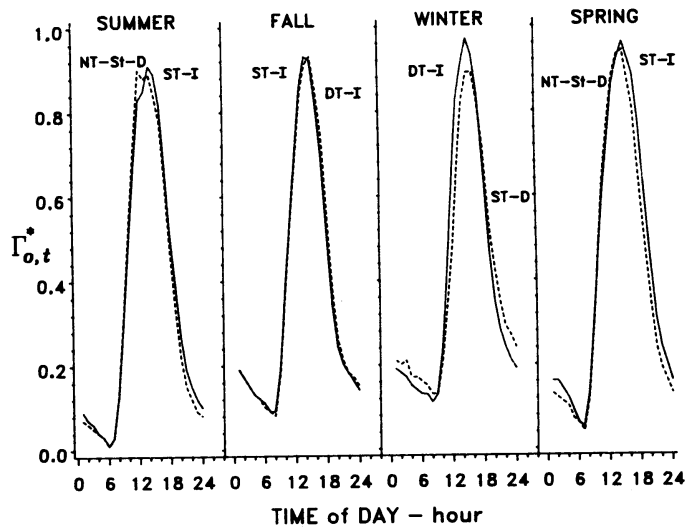

Fig. 5. Average normalized soil surface temperatures ($\Gamma_{o,t}$) in different seasons of the 1983 to 1984 fallow period for treatments resulting in the greatest differences in normalized temperatures.

Table 5. Observed and predicted soil temperatures based on daily maximums and minimums for different seasons of the 1982 to 1983 fallow period as affected by tillage-residue treatments.†

Seasons and treatments compared	Observed Mean	Observed SE‡	Observed Range	Predicted Mean	Predicted SE	Predicted Range	Differences means Value	Differences means SE	t§
	°C								
Summer									
DT-D vs. DT-I	25.8	1.9	6.9–51.8	27.4	1.9	13.4–52.8	1.6	1.0	1.56NS
ST-D vs. ST-I	26.6	2.0	7.4–55.1	28.1	1.9	13.8–55.0	1.5	1.1	1.45NS
NT-Sh-D vs. NT-Sh-I	25.4	1.9	6.8–50.7	27.1	1.9	12.7–52.6	1.7	1.0	1.74NS
NT-St-D vs. NT-St-I	25.8	1.9	7.7–52.7	29.0	2.1	13.5–57.2	3.2	1.1	2.87**
Fall									
ST-D vs. ST-I	16.9	2.0	−6.7–49.0	16.3	1.8	1.7–41.3	−0.6	0.9	−0.64NS
NT-Sh-D vs. NT-Sh-I	15.9	1.8	−5.2–37.1	16.2	1.9	1.4–40.6	0.3	0.8	0.39NS
NT-St-D vs. NT-St-I	15.8	1.7	−4.5–35.4	17.5	1.9	1.7–43.9	1.7	0.8	2.05*
Winter									
DT-D vs. DT-I	3.8	0.9	−1.7–29.0	3.8	1.5	−9.8–28.5	0.0	0.9	0.00NS
ST-D vs. ST-I	4.6	1.0	−2.7–31.9	4.0	1.3	−6.7–26.6	−0.6	0.8	−0.83NS
NT-Sh-D vs. NT-Sh-I	4.0	1.0	−3.3–27.7	4.3	1.5	−9.1–29.3	0.3	0.9	0.37NS
NT-St-D vs. NT-St-I	4.3	0.9	−1.2–25.8	3.8	1.5	−8.6–29.8	−0.5	0.9	−0.56NS
Spring									
DT-D vs. DT-D	18.3	2.2	−7.1–46.1	17.4	2.2	−0.8–42.7	−0.9	1.1	−0.87NS
DT-D vs. DT-I	18.2	2.2	−7.2–45.2	17.4	2.2	−0.8–42.7	−0.8	1.1	−0.80NS
DT-I vs. DT-I	18.2	2.2	−7.2–45.2	16.5	2.1	−1.1–40.6	−1.7	1.1	−1.70NS
ST-D vs. ST-I	18.3	2.2	−7.7–45.6	16.7	2.1	−1.1–41.3	−1.6	1.0	−1.66NS
NT-Sh-D vs. NT-Sh-I	20.3	2.5	−6.9–50.9	17.8	2.3	−1.3–42.3	−2.5	1.0	−2.67**

*,** Significant at the 0.05 and 0.01 probability levels, respectively.
† The first-mentioned treatment in the first column was the one used for the prediction. All comparisons are based on 60 data points.
‡ SE = Standard error of the mean.
§ t-value based on paired "t" test. NS = not significant. Observed and predicted populations checked for normal distribution by SAS (1985) procedure.

paired *t*-test analyses. Exceptions were for the NT-St-I treatment in summer and fall when predicted means were higher than observed means and for the NT-Sh-I treatment in spring when the predicted mean was lower than observed mean.

The significant differences between predicted and observed means may be related to such factors as amount and distribution of precipitation, residue orientation, and uniformity of surface coverage by residues. Examination of precipitation records, however, revealed no definite relationships between precipitation amount and distribution and the observed and predicted temperatures. Information on residue orientation and uniformity of surface coverage is not available. Another possible reason is the use of unshielded thermocouples at a 2-m height in the field, whereas temperatures at the weather station were measured at a 1.5-m height with shielded thermocouples. Temperatures at 1- and 2-m heights in the field differed only slightly, however. The effect of thermocouple shielding was not determined.

Although statistically significant, the maximum difference between predicted and observed means was 3.2 °C for the NT-St-I treatment during the summer period. The generally good agreement between predicted and observed means indicates that $T_{o,t}$ prediction from T_a is possible, provided that appropriate coefficients for the relationships between $T_{o,t}$ and T_a have been established. These coefficients, however, must be established for the climatic region under consideration because the coefficients for this study varied greatly from those established by Gupta et al. (1983) for conditions in Minnesota. Relationships between $T_{o,t}$ and T_a (Fig. 4), along with the $\Gamma^*_{o,t}$, provide a method for estimating upper boundary temperatures for various tillage and residue conditions in the southern Great Plains. These values, when used in a finite difference or Fourier Series model, could be used to estimate root zone temperatures.

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