Predicting Soil Temperatures with Air Temperature and Soil Moisture[1]

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Introduction

Knowledge of soil temperatures is important for making spring planting decisions and for modeling early crop growth and development. Since low soil temperature delays mineralization of soil organic nitrogen and inhibits nitrification of ammonium, soil temperature information is also important for planning nitrogen needs and timing for fertilizer application. Yet soil temperature observations are not available for many areas. Although there are more soil temperature stations in Indiana than in any other state, there are only 12 stations for which daily maximum and minimum soil temperatures are currently published in *Climatological Data, Indiana* (USDC, EDS, 1978). This number contrasts to more than 90 stations for which air temperatures are available.

For planting decisions and modeling corn growth and development 50°F (10°C) generally is used as the critical base soil temperature for corn seed germination and plant growth. At West Lafayette, the mean daily minimum temperature at the 4-in (10-cm) depth for a bare soil reaches 50°F about May 5 (Fig. 1), and most corn planting in Indiana occurs in May. The growing point of the corn plant rises above the ground surface about mid-June. In this paper, several methods are examined for estimating daily maximum and minimum soil temperatures from air temperatures and soil moisture during May and June at West Lafayette, Indiana.

Estimating soil temperature by any method is difficult because of the complex interaction of factors affecting it. Solar radiation is the driving force for both air and soil temperature. Yet, there are even fewer stations observing solar radiation than soil temperature. Soil characteristics which affect its temperature include moisture, ground cover, slope, texture, and organic matter. The nearer the surface, the greater the diurnal range in soil temperatures (Carson, 1961, p. 54-59). Below a depth of about 20 in (50 cm) the diurnal temperature variation is negligible, and only the seasonal trend in soil temperature can be sensed. (Schaal et al., to be published). Since corn is planted and nitrogen is incorporated in the top few inches of the soil, it is this layer near the surface with which we are concerned in this paper. Maximum and minimum air temperatures, soil moisture, and an interaction term of air temperature with soil moisture were included as variables in six regression models to predict maximum and minimum soil temperatures at the 4-in (10-cm) depth in bare soil.

DATA

Weather data were taken from the National Weather Service-Purdue University Agronomy Farm Station, West Lafayette 6 NW,

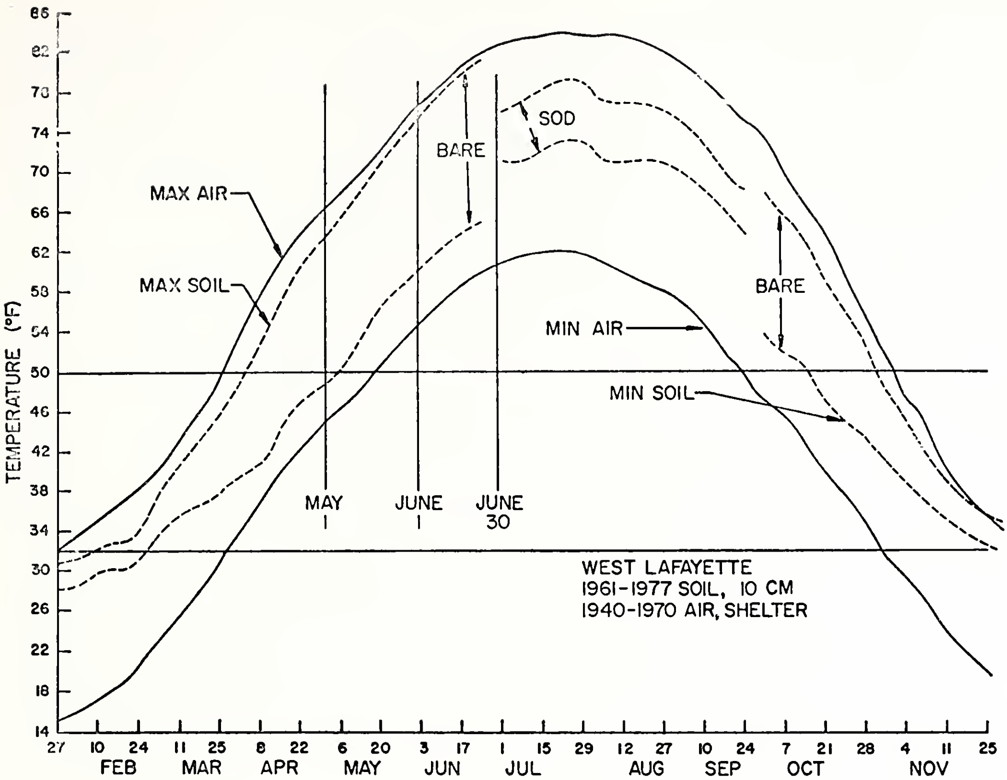

FIGURE 1. *Weekly mean maximum and minimum soil and air temperatures from January 27-November 25, West Lafayette, Indiana. Soil temperatures 4 in (10 cm) under grass sod are plotted for July-September, the period when a corn canopy generally covers the ground.*

Indiana (USDC, EDS, 1962-1966, 1977-1978). The soil temperatures used were measured with a Palmer thermometer with a mercury bulb at a 4-in (10-cm) depth under a bare soil surface, in a Udollic Ochraqualf, Toronto silt loam. Air temperatures were measured with liquid-in-glass max and min thermometers in a standard cotton region shelter. Because the observation time was 8 AM, maximum soil and air temperatures were set back one day to agree with their likely date of occurrence. Precipitation and evaporation values were used in a soil moisture program (Stuff and Dale, 1978) to estimate the daily percent plant-available soil mosture (PAV_{15}) in the top 6 in (15 cm). Precipitation was measured with a standard 8-in rain gage and evaporation from a standard Class A pan.

The regressions were developed over a five-year period, 1962-1966. In these years the soil thermometers were most frequently checked and calibrated, and also the data were already on computer files. Data for 1977 and 1978 were used for all independent tests, although soil temperature data were missing for June 2-12, 1977.

Air and soil temperature normals were based on the 1941-1970 and 1961-1977 periods, respectively. Soil temperatures averaged 3°F above normal in both May and June 1962-1966. Air temperatures were 2°F and 1°F above normal in May and June 1962-1966, respectively. The 1977 and 1978 test years provided a greater range in air and soil temperatures than that used to develop the models. In 1977 there was a dry, early spring and in 1978 a wet, late spring. Monthly mean temperatures and departures from normal are shown in Table 1. May 1977 was unusually warm. May daily maximum air temperatures averaged 81°F, almost 10°F above normal, and daily maximum soil temperatures averaged about 8°F above normal. June continued above normal. In contrast, 1978 soil temperatures averaged below normal.

Surface soil moisture generally decreases as the spring season progresses. There were a lack of low PAV_{15} values in the regression development years. The mean daily PAV_{15} for May 1962-1966 was 90% and for June 84%. May had many 100% PAV_{15} values, i.e., the top 6-in (15-cm) soil layer was at its water holding capacity. There were only 19 days with PAV_{15} less than 80% and one day less than 70% out of 155 (31 x 5 yrs) days. The range in PAV_{15} was greater in June, but still there were no days with less than 50% and only three days with less than 60% plant available soil moisture.

There was less precipitation and lower soil moisture in spring 1977 than in spring 1978. May 1977 had 3.96 inches of rain, but most of it occurred during the first week, allowing considerable soil drying during the last three weeks of May. June 1977 had only 1.87 inches of precipitation. The daily PAV_{15} averaged 85% for May and June 1977. By contrast, May and June 1978 had 4.26 and 5.92 in. of precipitation, respectively. Rain fell on 26 days in the two months. Daily PAV_{15} averaged 94%, and was below 80% on only one day.

TABLE 1. *Daily soil and air temperature means and departures from normal at West Lafayette, Indiana, May and June, 1977 and 1978.*

	Bare Soil Temperature 10-cm Depth				Air Temperature			
	Mean		Departure		Mean		Departure	
	1977	1978	1977	1978	1977	1978	1977	1978
May Daily Maximum	77.4	63.8	+7.9	—5.7	80.8	67.0	+9.6	—4.2
May Daily Minimum	59.7	51.5	+5.5	—2.7	56.5	49.0	+7.1	—0.4
June Daily Maximum	83.8	78.2	+3.8	—1.8	81.9	81.3	+1.3	+0.7
June Daily Minimum	66.7	62.4	+2.8	—1.5	60.2	59.3	+1.8	+0.9

Methods and Procedures

Daily maximum and minimum soil temperatures were estimated with the following regression models:

$$T_s = b_0 + b_1(T) + b_2(CD) \quad [1]$$

$$T_s = b_0 + b_1(T) + b_2(CD) + b_3(PAV)_{15} \quad [2]$$

$$T_s = b_0 + b_1(T) + b_2(CD) + b_3(T)(PAV_{15}) \quad [3]$$

$$T_s = b_0 + b_1(T) + b_2(CD) + b_3(PAV_{15}) + b_4(T)(PAV_{15}) \quad [4]$$

$$T_s max_t = b_0 + b_1(Tmax_t) + b_2(CD) + b_3(Tmin_t) \quad [5a]$$

$$T_s min_t = b_0 + b_1(Tmin_t) + b_2(CD) + b_3(Tmax_{t\text{-}1}) \quad [5b]$$

where: T_s = bare soil temperature at 4-in (10-cm) depth, maximum or minimum, °F.

T = air temperature, maximum or minimum, corresponding to that for T_s, °F.

CD = climatological day number.

PAV_{15} = percent available moisture in the top 6 in (15 cm) of soil.

$T_s max_t$ = maximum soil temperature on day t, °F.

$T_s min_t$ = minimum soil temperature on day t, °F.

$Tmax_t$ = maximum air temperature on day t, °F.

$Tmax_{t-1}$ = maximum air temperature on day t–1, °F.

$Tmin_t$ = minimum air temperature on day t, °F.

The parameters in models [1] through [5b] were fitted to the weather data for 1962-1966 at West Lafayette, Indiana. Separate regression equations were developed for the months of May and June.

Climatological day number (CD) was included to consider the "normal" upward temperature trend in May and June. The CD is 1 on March 1st and increases daily by one. Although the upward trend in air and soil temperatures tends to level off at the end of June, CD was included in all regression equations.

To compare the significance and goodness of fit of the models, F-tests and R^2 (coefficient of determination) values were calculated for each equation. The regression models also were tested independently with the 1977 and 1978 data. Mean daily absolute errors of prediction, $\overline{\left| T_s - \hat{T}_s \right|}$, were calculated, where T_s is the observed soil temperature and $\hat{T}_s$ is that predicted. As a control the mean daily soil temperature for the respective CD was also used to predict the daily soil temperature for the two test years.

Results and Discussion

The F and R^2 values for the five regression models are shown in Table 2. All equations were highly significant. Including PAV_{15} in the regressions did not significantly increase the R^2 values. Only for the May daily maximum soil temperatures was the R^2 for model [2] more than 0.01 greater than that for model [1]. Nor did including the inter-

TABLE 2. *Goodness of fit tests for indicated T_s and regression model, 1962-1966.*

Reg. Model	May Daily Maximum F	May Daily Maximum R^2	May Daily Minimum F	May Daily Minimum R^2	June Daily Maximum F	June Daily Maximum R^2	June Daily Minimum F	June Daily Minimum R^2
[1]	185	.71	252	.77	228	.76	167	.69
[2]	159	.76	178	.78	158	.77	113	.70
[3]	162	.76	175	.78	157	.76	113	.70
[4]	121	.76	136	.78	122	.76	85	.70
[5a]	123	.71			151	.76		
[5b]			220	.81			132	.73

actions in models [3] and [4] improve upon the R^2 compared with the more simple models [1] and [2]. Model [5b] had the highest R^2 when estimating May and June daily minimum T_s.

The fitted regression coefficients and standard errors of estimate are shown in Table 3 for [1], [2], [5a] and [5b]. The air temperature coefficients in [1] and [2] were relatively stable, and their standard errors of estimate ranged from 5% to 8% of the computed coefficient. The PAV_{15} coefficient was negative in [2] for all four cases. In [5b] both air temperature coefficients, b_1 and b_3, were important for estimating minimum soil temperatures, but in [5a] the b_3 coefficient was not significant when predicting maximum soil temperatures.

A scatter diagram of soil temperature on air temperature for indicated PAV_{15} is shown in Figure 2 for May 1-5 daily maximum soil temperature. The fitted regression equations [2], [3], and [4] for *all* May daily maximum temperatures, evaluated for CD = 64 (May 3), are shown for PAV_{15} values of 100% and 80%. PAV_{15} was negatively correlated to soil temperature. For example, a 20% decrease in PAV_{15} resulted in a 4-5°F increase in T_s at a constant air temperature in May. A comparative PAV_{15} decrease in June yielded a 2-3°F increase in T_s. The effect of soil moisture was similar in models [2], [3], and [4], as shown in Figure 2.

The mean daily absolute prediction errors for the independent test years, 1977 and 1978, for equations [1], [2], [5a] and [5b] are shown in Table 4. Results for models [3] and [4] were similar to those for model [2] and are not shown. The regression models predicted T_s better in 1977 than in 1978. In 1977 the mean daily absolute errors were between 2.2°F (June daily min, [5b]) and 4.2°F (June daily max, [1] and [5a]), and averaged 3.1°F. The results for the models with soil moisture [2] were disappointing. Model [2] had slightly higher prediction errors than did [1] in May 1977. Including the previous day's maximum temperature ([5b]) lowered minimum temperature prediction errors in all four cases. To be of value, the regression models must do better predicting T_s, than does the daily climatological mean. They did so in 1977. Absolute daily prediction errors with models [1], [2], [5a], and [5b] were 4-5° lower in May and 0-2° lower in June. Climatology provided better results in June than in May because in 1977 soil temperatures departed less from normal in June.

The regression model prediction errors were greater in 1978 than in 1977, probably because temperature conditions in 1977 were more similar to those during the 1962-1966 period used to develop the regression equations than were temperature conditions in 1978. Mean absolute prediction errors in 1978 averaged 4.1°F for the regression models, up 1°F from those in 1977. In contrast to 1977, [2] had slightly lower prediction errors than [1] in 1978. Again, [5b] did better than [1] when estimating minimum soil temperatures, but [5a] did no better than [1] in predicting maximum soil temperatures. The regression models estimated T_s much better than climatology in May 1978. However, climatology (daily $\overline{T_s}$) did better than [1], [2,] [5a], or [5b] in June 1978. In June, and if temperatures average near normal, cli-

TABLE 3. *Fitted regression coefficients and standard errors of estimate for indicated T_s and regression model, 1962-1966, e.g.,* $T_s = b_0 + b_1(T) + b_2(CD) + b_3(PAV_{15})$ *for Model [2].*

Reg. Model	b_0 (Const.)	b_1 ($Tmax_t$)	b_2 (CD)	b_3 (PAV_{15})	b_3 ($Tmin_t$)	b_0 (Const.)	b_1 ($Tmin_t$)	b_2 (CD)	b_3 (PAV_{15})	b_3 ($Tmax_{t-1}$)
		May Daily Maximum						May Daily Minimum		
[1]	— 5.95	0.592	0.287			10.41	0.513	0.254		
	± 3.72	± .036	± .039			± 2.43	± .026	± .028		
[2]	36.02	0.515	0.249	—0.239		20.40	0.495	0.238	—0.088	
	± 6.34	± .035	± .036	± .043		± 4.32	± .027	± .028	— .032	
[5a]	5.52	0.576	0.283		0.036					
	± 3.75	± .039	± .039		± .040					
[5b]						5.09	0.322	0.232		0.226
						± 2.35	± .039	± .025		± .037
		June Daily Maximum						June Daily Minimum		
[1]	— 1.14	0.591	0.335			8.86	0.463	0.276		
	± 4.02	± .046	± .037			± 3.42	± .035	± .031		
[2]	12.40	0.558	0.289	—0.070		16.09	0.464	0.241	—0.042	
	± 7.07	± .047	± .041	± .003		± 5.69	± .035	± .037	± .026	
[5a]	— 1.22	0.591	0.334		0.003					
	± 4.19	± .046	± .038		± .038					
[5b]						3.56	0.312	0.217		0.248
						± 3.43	± .047	± .032		± .056

TABLE 4. *Mean daily absolute error for indicated predicted soil temperature, and regression model, 1977 and 1978, West Lafayette, Indiana.*

Reg. Model	$\lvert T_s - \hat{T}_s \rvert$, °F							
	May Daily Maximum		May Daily Minimum		June Daily Maximum		June Daily Minimum	
	1977	1978	1977	1978	1977	1978	1977	1978
[1]	2.6	4.1	2.9	3.7	4.2	5.1	2.7	4.5
[2]	3.4	4.0	3.2	3.3	3.9	4.5	2.7	4.3
[5a]	2.6	4.1			4.2	5.1		
[5b]			2.8	2.5			2.2	4.1
Daily $\overline{T}_s$	8.2	8.4	7.1	4.6	6.1	3.5	2.8	3.9

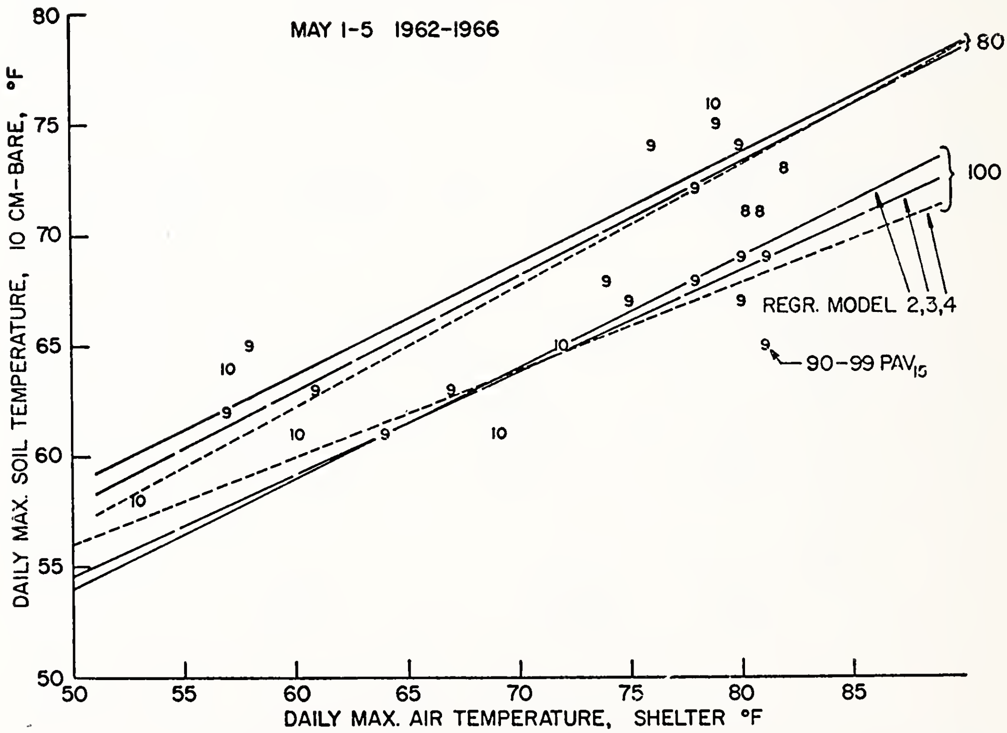

FIGURE 2. *Scatter diagram of soil temperature on shelter air temperature for indicated percent plant available-soil moisture (PAV_{15}) in the top 6 in (10 cm), May 1-5, 1962-1966, West Lafayette, Indiana. Regressions [2], [3], and [4] plotted for 100% and 80% PAV_{15}. Soil temperatures taken at 4-in (10-cm) depth under bare soil.*

matology may be as good an estimator of daily soil temperatures as the regressions. The regressions did better predicting T_s when air temperatures departed more from normal.

Soil moisture was not as effective in the regression equations as expected for several reasons. The biggest problem was a lack of low soil moisture values. A wider range in soil moisture would possibly have resulted in a better relation with soil temperature. Estimates of PAV_{15} may also be in error. Verification of the soil moisture model has been done principally with soil moisture for the top 3.5 ft (105 cm) of soil, not for the top 6 in (15 cm).

Conclusions

The linear regression models discussed in this paper were reasonably accurate predictors of daily soil temperatures in May and June. Model [1], because of its simplicity and comparable accuracy, was the best model choice for predicting daily maximum soil temperatures. Minimum soil temperatures were best predicted with [5b], which included the preceding day's maximum air temperature as a variable. Including soil moisture terms in the regression equations did not improve them, perhaps because of the narrow range in PAV_{15} available for parameter estimation. Further testing is needed with a greater range in both soil moisture and temperature. Solar radiation should also be examined as a predictor variable in the regression equations. If monthly air temperature were near normal, the climatological mean daily maximum and minimum soil temperatures were good estimators of ambient soil temperatures.

References

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