# Site-Specific Analysis of a Droughted Corn Crop: II. Water Use and Stress

E. John Sadler,* Philip J. Bauer, Warren J. Busscher, and Joseph A. Millen

## ABSTRACT

**In the southeastern USA Coastal Plain, spatial variation in soils causes extreme spatial variation in grain yield, as seen in yield maps. Corn (*Zea mays* L.) appears to be particularly susceptible to soil variation, especially during periods of drought. Our objectives were to compare variation in water use and stress of corn within and among soil map units. In one field, at two sites in each of four map units, we measured site-specific effects of soil variation on crop water use from 40 d after planting until after maturity using a time-domain reflectometer (TDR). On 4 d during vegetative growth, drought stress was evaluated on eight transects using infrared thermometer (IRT) measurements of canopy temperature ($T_c$). During the most severe drought, visibly stressed areas had canopy-air temperature differences ($T_c - T_a$) > 10°C, yet other areas remained <2°C. Two days after a 46-mm rain, $T_c - T_a$ was near zero over the whole field, indicating little water stress. The time series of TDR measurements produced estimates of daily evapotranspiration, runoff, and infiltration; site-to-site differences in these dominated the water balance. Water stress, inferred from water use, matched that inferred earlier from yield components. In sum, corn at the eight sites arrived at final water use via fundamentally different paths. Further, variation between sites within soils was significant, indicating that soil map units are not homogenous with respect to water relations. These results underscore the need for within-season observations of crop water use and stress to augment interpretation of site-specific yield maps.**

The new, rapidly expanding field of site-specific, or precision, farming presents a greatly increased demand for agronomic knowledge. However, classical statistical replicated experimental procedures are neither inexpensive nor well-suited to solving spatial problems. This new knowledge of plant–culture–soil relationships on a close spatial scale must be developed using a combination of spatial field measurements and computer simulation modeling (Robert, 1996).

Although the precision farming movement began with fertilizer management (Wollenhaupt and Buchholz, 1993), an increasing body of knowledge suggests that spatial variation in soil water relations may be an important factor in causing spatial variation in grain yield. First, there is the well-known dependence of water holding capacity on texture, which itself is known to vary spatially. Second, despite many attempts, there has been little success correlating spatial grain yield to spatial patterns in fertility (Pierce and Nowak, 1999). Third, the literature is replete with examples of spatial water stress inferred from spatial canopy temperature patterns observed using airborne and satellite remote sensing (Moran and Jackson, 1991; Kustas and Norman, 1996) and handheld infrared thermometers (Sadler et al., 1995). When these observations are considered in the context of the long-known dependence of yield on applied water (e.g., Howell et al., 1990) that gave rise to the concept of water use efficiency, one must conclude that water stress bears increased consideration as a candidate for causing spatial variation in yield.

What is not so easily concluded, however, is a suitable approach to measuring components of water relations with a useful spatial extent. It is not feasible to measure enough sites to fully map water use over the whole area using soil profile water balance measurements with, for instance, a time-domain reflectometer. However, local experiences with recurring patterns in yield often suggest locations from which spatial water use might be inferred, especially if supported by complementary data taken on a more dense spacing.

Thus, the combination of soil water contents and canopy response, coupled with collateral crop measurements reported in a companion paper (Sadler et al., 2000), would provide a comprehensive dataset with which to study spatial variation in crop water relations. However, simple analyses of cause-effect candidates were not expected to succeed because of the multiple, complex interactions among water and energy transfer processes and their dynamics during the season. For this reason, we expect final analysis for these data to require the use of process-level computer models of corn growth and yield. Such is beyond the scope of this paper, but results presented here should indicate processes that are important and should be considered in the models. As a result of the considerations presented above, water stress has been put forth as a candidate cause for site-specific variation in grain yield that should be considered in any explanation on sandy soils. Therefore, our objectives were to compare variation in water use and stress within and among soil map units and to evaluate variation in water relations as a cause for variation in grain yield.

## METHODS

### Overview

This research was conducted during the 12th cropping season of a study designed to document spatial variability of crop yield within a representative Coastal Plain field (Karlen et al., 1990; Sadler et al., 1993, 1995). The study followed a typical conventionally tilled corn–wheat (*Triticum aestivum* L.)–soybean [*Glycine max* (L.) Merr.] rotation. In 1993, the rotation phase was corn. During this season, the plan was to use soil and plant characteristics to evaluate causes of yield variation.

Coastal Plains Soil, Water, and Plant Research Center, USDA-ARS, 2611 West Lucas St., Florence, SC 29501-1242. Received 15 June 1998. *Corresponding author (sadler@florence.ars.usda.gov).

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**Abbreviations:** AW, available water content; DAP, days after planting; DOY, day of year; Et, evapotranspiration; $Et_a$, actual evapotranspiration; $Et_r$, reference evapotranspiration; IRT, infrared thermometer; GPS, global positioning system; $K_c$, crop coefficient; $K_s$, soil coefficient; LAI, leaf area index; $T_a$, air temperature; $T_c$, canopy temperature; TDR, time-domain reflectometer; TSW, total soil water content; WUE, water use efficiency.

Variation in plant characteristics is examined in Part I (Sadler et al., 2000); this work examines variation in water use and stress.

The 8-ha field, representative both of field size and soil variability in the Coastal Plains, includes 14 soil map units mapped on 1:1200 scale. Much of the variation is associated with two small, shallow depressions called Carolina Bays. The southwest corner of the field is located at 34°14′44″ N, 79°48′34″ W, as determined by averaging differential GPS readings for a period of 1 h.

## Representative Sites

Four soil map units (USDA-SCS, 1986) were selected to represent the range of soils within the field. The descriptions include Goldsboro loamy fine sand (GoA; fine-loamy, siliceous, subactive, thermic Aquic Paleudult), Norfolk loamy fine sand (NkA; fine-loamy, siliceous, subactive, thermic Aquic Paleudult), Bonneau loamy fine sand (BnA; fine-loamy, siliceous, subactive, thermic Aquic Paleudult), and Coxville loam (Cx; fine-loamy, siliceous, subactive, thermic Aquic Paleudult). Two sites were chosen for each map unit (see Fig. 1 in Sadler et al., 2000, for a diagram). After TDR installation (see below), it was discovered that Site 1, which was to represent GoA, was placed by error on the boundary between GoA and Dunbar (Dn), but the difference between these two inclusions is less than between typical pedons of the two soils, and the profile was similar to the other GoA.

## Point Measurements of Soil Profile Water Content

The eight sites were instrumented with TDR probes inserted horizontally at depths selected to represent soil moisture in horizons to a depth of 1 m. To measure all depths at each site, probes were attached to a TDR (Model 1502B, Tektronix,[1] Beaverton, OR) assembled on a two-wheel hand truck with a laptop computer, switching devices, battery, and required cabling (Sadler and Busscher, 1993). The TDR traces from the five or six probes at each site were automatically obtained and reduced to volumetric soil water content (Baker and Allmaras, 1990). Soil water content measurements were scheduled twice a week, with ad hoc measurements just before and after rains. Prediction of both likelihood and timing of rain was done by examining high-resolution radar images. The combination of scheduled and ad hoc measurements resulted in 38 measurement dates during the season.

[1] Mention of trade names is for informational purposes only. No endorsement is implied by the USDA-ARS.

## Soil Water Balance Calculations

Whole-profile water content was obtained by simple rectangular integration of soil water content over depth. The water balance of the profile was assumed to consist entirely of net rainfall and evapotranspiration (Et) during the drought, an assumption that was likely adequate at all sites except possibly Site 8 after the 12 June rain. Rain was measured at a weather station located 300 m from the field. Available water content was calculated using best estimates of drained upper limit and lower limit of plant-available water for each layer at each site. These estimates were obtained by inspection of TDR water contents, supplemented by measurements on similar soils and by literature values (Long et al., 1969; Peele et al., 1970). The rooting depth was estimated by inspection of the TDR traces to judge whether withdrawal occurred from a layer at a given time.

Time series of water content at each site were interpolated to a daily basis using the procedure described below (Schwab et al., 1993) to account for rain and expected evapotranspiration. The procedure used the same basic equation in two ways,

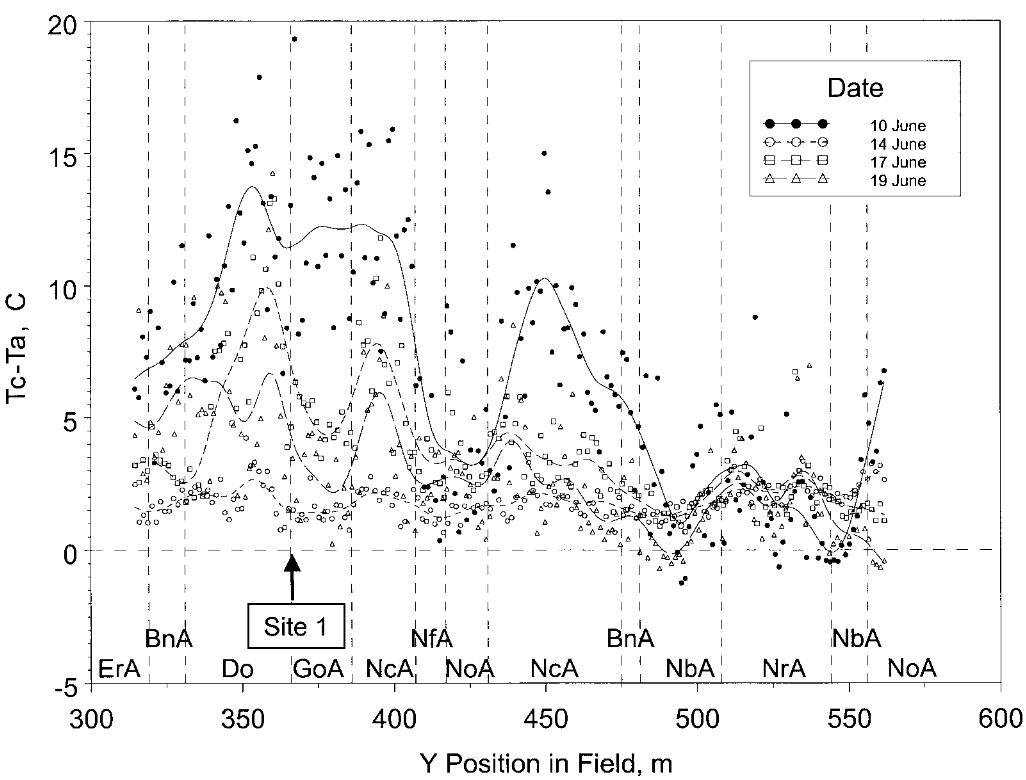


**Fig. 1. Crop temperature measured with an infrared thermometer as a function of distance along Transect 1 for one date before and for three dates after a 46-mm rain on 12 June 1993. The area around Site 1 appeared to be the most stressed in the field.**

depending on whether rain occurred between the TDR measurements.

When there was no rain between measurements, differences in soil profile water contents were used to estimate daily actual evapotranspiration ($Et_a$). Using this value of $Et_a$, a calculated reference Et ($Et_r$), and a soil ($K_s$) factor (see below), we solved for the crop ($K_c$) factor. When rains occurred between measurements, an interpolated value of the crop factor was used to estimate $Et_a$. The definition of the soil and crop factors follows from the equation

$$Et_a = Et_r \times K_s \times K_c \quad [1]$$

In the case without rain, $Et_a$ and $Et_r$ were known, and Eq. [1] was solved for $K_c$, using $K_s$ taken from Haan et al. (1994):

$$K_s = \frac{\ln(AW + 1)}{\ln(101)} \quad [2]$$

where AW is available water content expressed as a percentage. In the case where rain occurred between measurements, so that $K_c$ was not obtainable by direct solution, daily values were interpolated from the seasonal pattern of measured $K_c$ values at each site using a simple cubic polynomial. Then, with $Et_r$, $K_s$, and $K_c$ known, Eq. [1] was used to calculate $Et_a$.

### Transect Measurements of Canopy Temperature

Corn growth during 1993 was extremely variable because of drought. On 10 June, the visibly stressed areas in the field were markedly distinct from others that were not apparently stressed. The plant heights ranged from 0.48 m in stressed areas to 1.34 m in less stressed areas. Other signs included a blue-gray cast and severe leaf rolling. In contrast, the areas with the tallest plants showed no visible stress.

Documenting the spatial patterns of stress was done by measuring canopy temperature on the eight transects with an infrared thermometer (IRT; Model 4000, 4° field of view, Everest Interscience, Tustin, CA). To do this, an IRT was connected to a datalogger (CR21X, Campbell Scientific, Logan, UT) mounted on a platform strapped to an operator's waist. The operator walked along the row at a steady pace, pointing the IRT forward and down at a 45° angle above the row. At 1-s intervals, the datalogger recorded the temperature. A manual switch allowed the operator to start and stop at known locations. Assuming the pace was steady (average was ~1.4 m $s^{-1}$), the time of the individual measurements allowed computation of location. The first such measurements were made on 10 June during the most severe stress period. After the 46-mm rain on 12 June, measurements were made on 14, 17, and 19 June. Sky conditions were clear for all IRT measurements. On the four dates, the series commenced at 1430h, 1445h, 1240h, and 1145h (EST), and the total duration for each day was ≤30 min.

## RESULTS AND DISCUSSION

### Spatial Canopy Temperature

Canopy minus air temperature data are shown in Fig. 1 and 2 for Transects 1 and 5. Transect 1 includes Site 1, which appeared to be the area with the most severe stress. Transect 5 includes the additional Site 11 (NoA) described in Sadler et al. (2000), which never showed visible signs of stress. The four sets of measurements show the severe drought stress on 10 June before the 12 June rain, near total relief of stress on 14 June after the rain, and the development of drought conditions nearly as severe as before on 17 June and 19 June. The

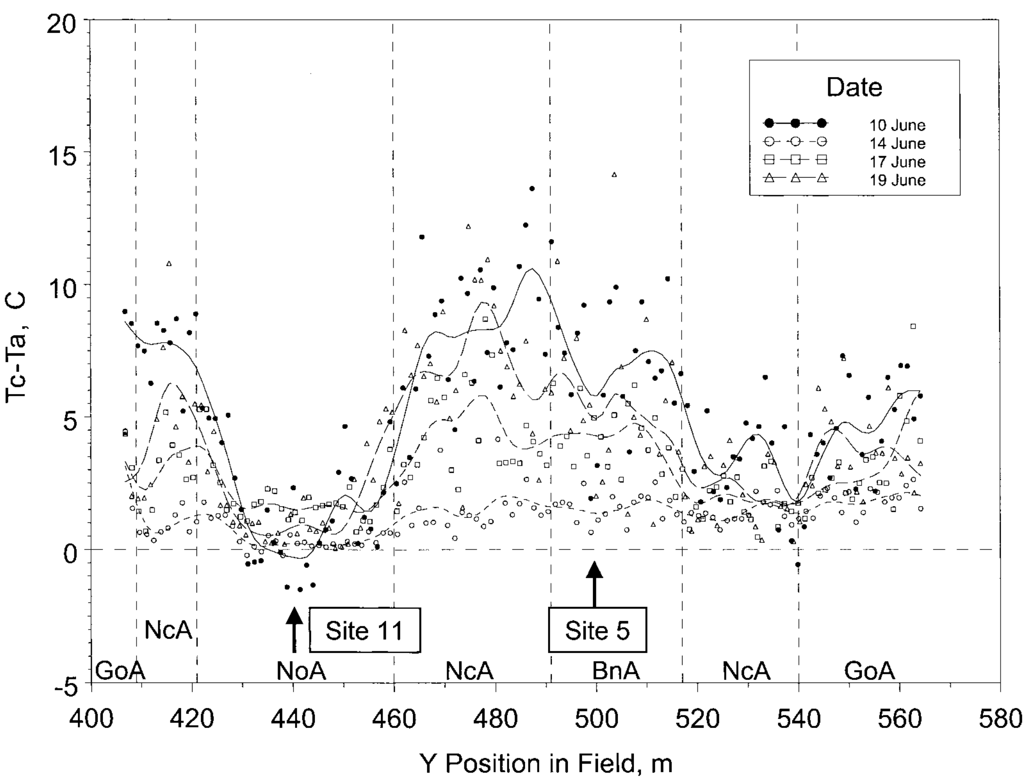


**Fig. 2. Crop temperature measured with an infrared thermometer as a function of distance along Transect 5 for one date before and for three dates after a 46-mm rain on 12 June 1993. The NoA site (Site 11) noted was never observed to be stressed, though final yields were quite low relative to norms.**

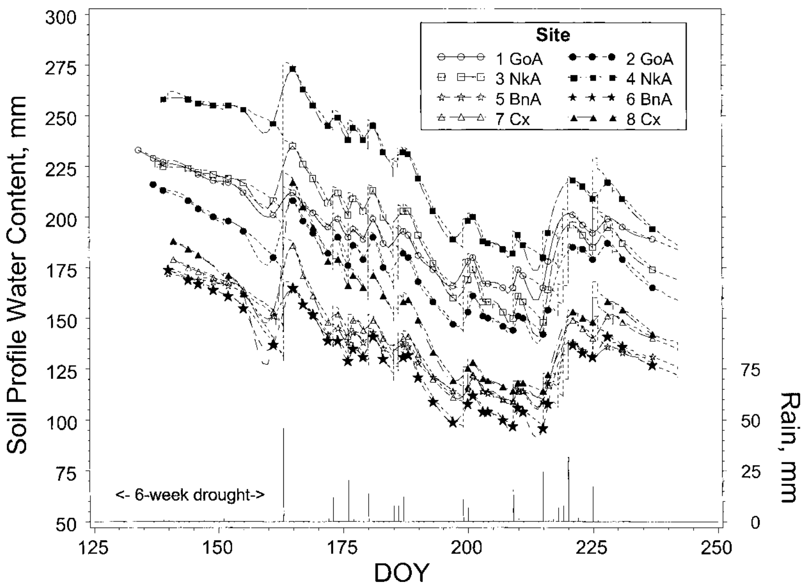


**Fig. 3. Soil water balance at the eight original representative sites as a function of date during the season. Symbols represent measurements; dashed lines indicate the interpolated values using procedures listed in the text. Rainfall is indicated on the right *y*-axis.**

variation in $T_c - T_a$ increased with drought stress. This supports Aston and van Bavel's (1972) assertion that variation in canopy temperature could be used as an early indicator of the need for irrigation. In the humid Southeast, cloudiness may prevent irrigation scheduling using field-scale variation in IRT readings. However, one may choose a limited transect where measurements could be made during cloud-free periods. The first 40 m of Transect 5, which includes the GoA, NcA, and NoA soils, might be such an area because it spans the range of responses observed in the field.

## Seasonal Patterns

Given the water stress measured by IRTs, one would expect to see clear differences in measured soil profile water content, shown in Fig. 3 for the eight sites. The 46-mm rain on 12 June caused the most significant dif-

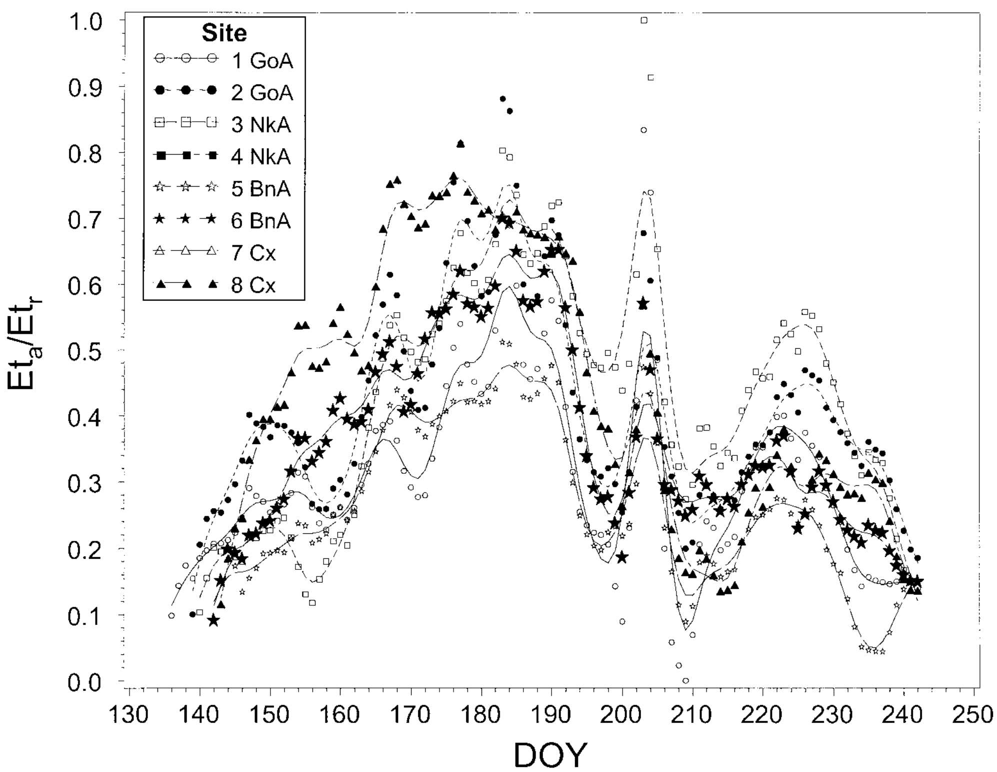


**Fig. 4. Ratio of actual evapotranspiration ($Et_a$) to reference evapotranspiration ($Et_r$) as a function of date during the season for six of the eight sites (Sites 4 and 7 were close to 2 and 6, respectively). The lines were fit using the cubic spline smoothing interpolation feature (SM25) of PROC GPLOT (SAS Inst., 1990).**

ference among the soil types. As seen in Fig. 3, Site 8 showed a greater increase in profile soil water than average (about twice as great), and Sites 1 and 5 showed a smaller increase (about half as great). After correcting for $Et_a$ on days between the measurements, the best estimates of infiltration (Schwab et al., 1993) ranged from 21 and 33 mm for Sites 1 and 5 to 98 mm for Site 8. The last indicated a run-on to the site, with infiltration more than twice the rainfall amount. Site 7, at 50 mm, also had a net increase larger than the rainfall amount. The remaining four sites ranged from 38 to 41 mm. Subsequent $Et_a$ from the eight sites (Fig. 4) showed faster losses from Site 8 and slower losses from Sites 1 and 5. The differences in the ratio $Et_a/Et_r$ among sites are somewhat difficult to interpret because of the combined effects of the soil and the crop.

To separate the effects, Eq. [2] was combined with the measured soil water content, which allowed calculation of the $K_s$ values (Fig. 5). Removing $K_s$ from the $Et_a/Et_r$ ratio isolated the values for $K_c$, which are shown in Fig. 6 along with cubic polynomial trends for Sites 3, 5, and 8. The polynomial equations for all 8 sites had $R^2$ ranging from 0.39 for Site 2 and 0.58 for Site 1 to 0.75 for Site 3. Despite the scatter in the measured points, Site 8 clearly used more water earlier in the season ($R^2 = 0.74$) than the other sites, and Site 3 clearly used more water later in the season ($R^2 = 0.75$). Both these sites obtained higher $K_c$ values than the other six sites. A plot of $K_c$ as a function of leaf area index (Fig. 7) showed that a rectangular hyperbola explained 70% of the variation. The sole constraint on the rectangular hyperbola was that the intercept was forced to 0.2 to conform with convention (Schwab et al., 1993). Despite having no data points higher than an LAI of 1.5, the curve approached an asymptote of 1.15, about as expected for corn. Given the scatter in these data points, there appears to be no justification for pursuing other explanations for the timing of water use.

The seasonal water use (Fig. 8) is illustrated using cumulative $Et_a$. The early-season water use for Site 8 and the late-season water use for Site 3 produced a nearly equal season total. Because of the nearly equal grain yields (the sites were ranked 1 and 2), the two sites had essentially equal water use efficiencies (WUE), defined here as grain yield divided by seasonal Et. On

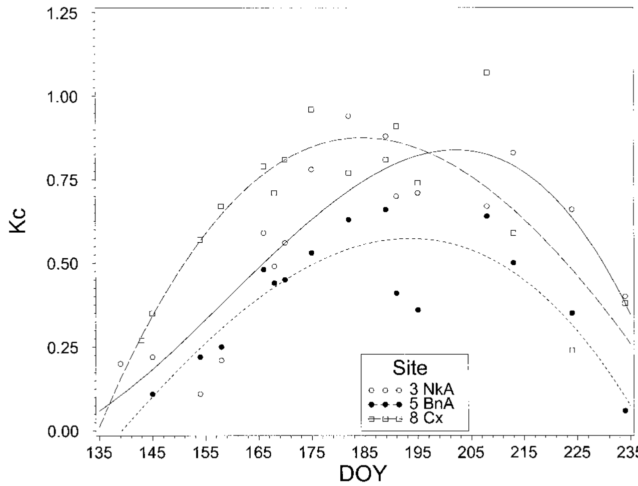


**Fig. 6. Plot of crop coefficient ($K_c$) as a function of day of year (DOY). Curves are cubic polynomials.**

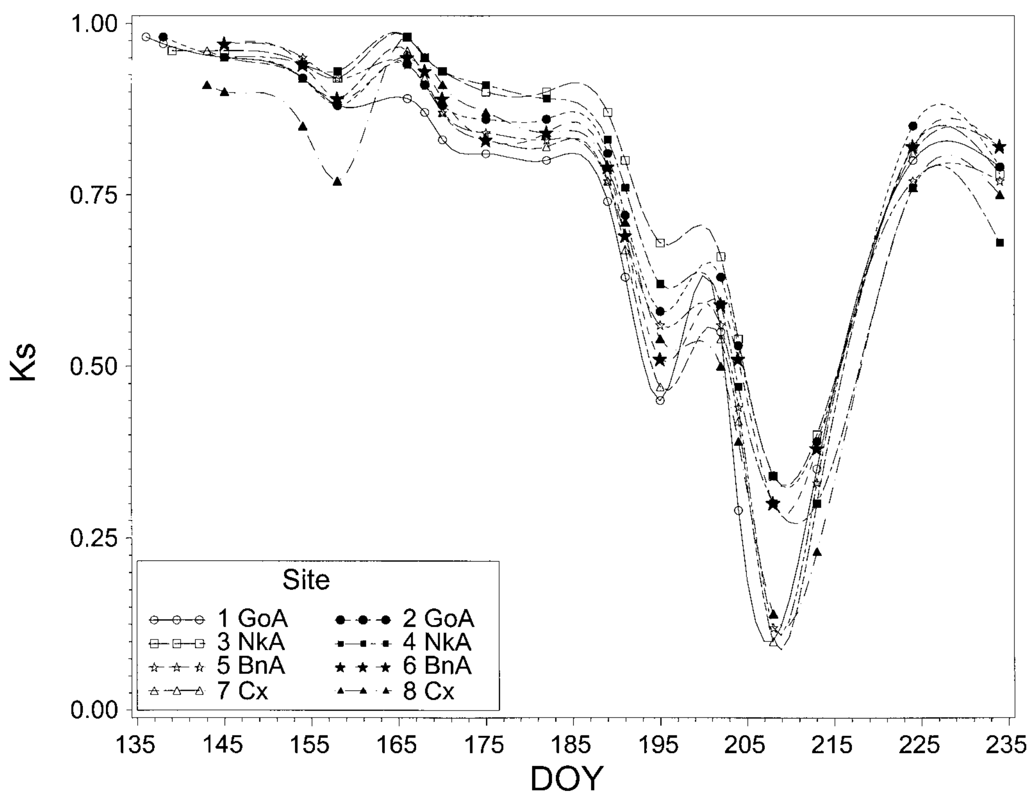


**Fig. 5. Plot of soil coefficient ($K_s$) as a function of day of year (DOY). Points are connected by spline interpolation.**

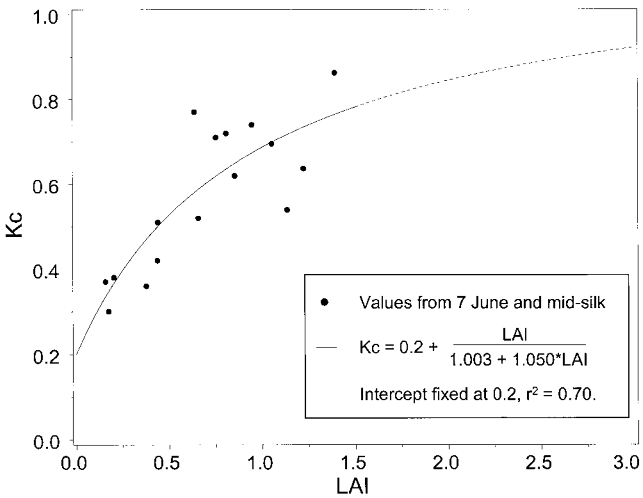


**Fig. 7. Plot of crop coefficient ($K_c$) as a function of leaf area index (LAI). Curve is a least-square fit rectangular hyperbola with the intercept forced to 0.2 by convention and the asymptote left unconstrained.**

the other hand, Sites 2 and 4 had water use nearly as high, but ranked near the bottom in grain yield, so WUE ranked 7 and 8. Sites 6 and 7 followed close behind in water use and ranked 6 and 7 in grain yield, and so had the next-lowest WUE pair. Site 5 had the third-ranked grain yield and the lowest water use, producing the highest WUE. As expected from the variation in WUE, there was no significant relationship between grain yield and seasonal water use under these conditions.

The timing of water use and the inferred water stress together invite comparison to the yield component data shown in Part I of this series (Sadler et al., 2000). The clearest example comes from the contrast between Sites 3 and 8. Site 8 used water early in the season and had the highest value for number of kernels per ear. Site 3 appeared to be stressed early and had an intermediate value for kernels per ear. Later in the season, Site 3 had both the high value for $Et_a/Et_r$ and the highest mass per kernel. Also late in the season, Site 8 had both an intermediate value for $Et_a/Et_r$ and an intermediate value for mass per kernel. Thus, these results obtained using independent methods supported the same conclusions.

## Comparison of Paired Samples

The 38 dates for which TDR values were measured for all sites provide a dataset amenable to evaluation of the variation within sites. Total soil water content (TSW), compared using a *t*-test, was significantly different ($\alpha$ = 0.05) between the two GoA sites (1 and 2) and also between the two NkA sites (3 and 4), as seen in Table 1. The Cx and BnA sites were not different according to this criterion. However, because of the large contrast between soil water retention curves for sand and clay, site-to-site differences in depth to clay would be expected to cause large differences in TSW. These can easily be accounted for using linear regression of seasonal mean TSW against depth to clay, which explained 70% of the variation in TSW. When this line was subtracted from TSW for each site, thus eliminating the known effect of depth to clay, differences between the Cx sites went from marginally insignificant to significant, NkA remained significant, BnA went from nonsig-

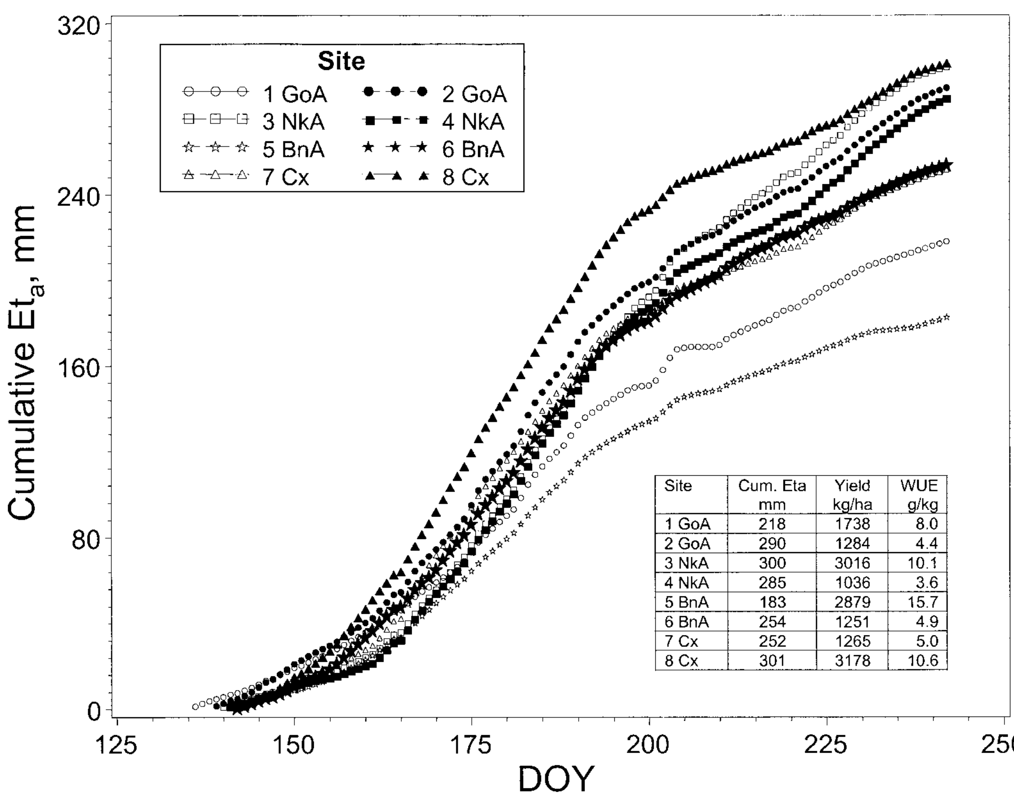


**Fig. 8. Plot of cumulative actual evapotranspiration ($Et_a$) as a function of day of year (DOY). End-of-season values for cumulative $Et_a$ and grain yield (dry weight) were used to derive water use efficiency (WUE).**

**Table 1. SAS PROC TTEST (SAS Inst., 1990) comparisons between sites within soils. Values are Prob> |T| values.**

| | Soil | | | | |
|---|---|---|---|---|---|
| **Parameter** | **BnA** | **Cx** | **GoA** | **NkA** | ***n*** |
| **Total soil water, TSW** | **0.2121** | **0.0614** | **0.0003*** | **0.0000*** | **38** |
| **TSW adjusted for depth to clay** | **0.0550** | **0.0000*** | **0.9949** | **0.0105*** | **38** |
| **$T_c - T_a$ 10 June (closest 5 m)** | **0.2707** | **0.0176*** | **0.0217*** | **0.2561** | **6–8** |
| **$T_c - T_a$ 14 June (closest 5 m)** | **0.1087** | **0.2439** | **0.0085*** | **0.1704** | **6–7** |
| **$T_c - T_a$ 17 June (closest 5 m)** | **0.0002*** | **0.0012*** | **0.0000*** | **0.2156** | **6–8** |
| **$T_c - T_a$ 19 June (closest 5 m)** | **0.3440** | **0.0061*** | **0.9731** | **0.9466** | **7–8** |

*** Significant at the 0.05 probability level.**

nificant (0.21) to nearly significant (0.055), and GoA went from significant at 0.0003 to insignificant at 0.9947. Thus, essentially all differences between the two GoA sites were accounted for by the differences in depth to the clay horizon. In the final analysis, the NkA sites were different, the Cx sites were different if adjusted for depth to clay, the GoA sites were different until adjusted for depth to clay, and the BnA sites were not different in either case.

A second dataset amenable to *t*-test comparisons was developed by extracting the IRT measurements within 5 m of the eight sites on the four dates. On three of the four dates, mean temperatures were different between the two Cx sites and between the two GoA sites. On one date, the two BnA sites were different, and the NkA sites were not different from each other on any date. In 7 of 16 possible comparisons, individual pairs of sites within soils differed according to the *t*-test at $\alpha = 0.05$.

## Evaluation of Transect Data

Attribution of the IRT data to soil map unit provided a dataset amenable to analysis of variance using soil map unit as a class variable. The simple model, $T_c - T_a$ = soil map unit, though significant for all dates at $P > F = 0.0001$ ($n = \sim800$), explained only 30, 7, 35, and 21% of the field variation in $T_c - T_a$ for the four dates. Even in the first, third, and fourth dates, where 20 to 35% of the variation was explained, 65 to 80% of the variation occurred within soil map units.

Examination of the dataset of $T_c - T_a$ within 5 m of the eight sites allowed an examination of variance attributable to soil map unit differences, to site-to-site differences, and to within-site differences. The simple model $T_c - T_a$ = soil map unit on the four soil map units at the sites was always significant at $\alpha = 0.05$ ($n = \sim56$) and explained 38, 23, 20, and 19% of the variation for the four dates. However, the model $T_c - T_a$ = site for the eight sites explained 56, 40, 71, and 35% of the variation, which indicates that 18, 17, 51, and 16% of the variation occurred between sites within soils. Even so, there remained 44, 60, 29, and 65% of the variance unexplained, and thus attributable to either measurement error or variation in $T_c - T_a$ within the 10-m distance at each site.

## Linking $T_c - T_a$ and Soil Water

Given the relative ease of obtaining canopy temperatures, either with handheld IRTs or by remote sensing in thermal wavebands, it would be quite useful to have a relationship between $T_c$ or $T_c - T_a$ and soil water content, measurement of which is both difficult and time-consuming. The subset of $T_c - T_a$ values within 5 m of each of the eight sites allows such a relationship to be examined for the range of soil water contents that existed on the four IRT measurement dates. The TDR measurements were conducted on 10 June, 14 June, 16 June, 18 June, and 21 June, so direct use of the first two dates was possible. Values corresponding to 17 June and 19 June were obtained by linear interpolation. Linear regression showed that nearly 60% of the variation in $T_c - T_a$ was explained by fraction of available water content (Fig. 9). Although not conclusive, this result certainly suggests that this concept merits further study.

## SUMMARY AND CONCLUSIONS

The 1993 results allow us to reach several conclusions. First, under drought stress, large differences occur in most measurable parameters, both within and among map units. The water balance showed both measurable differences in rainfall–runoff partitioning for single storms and noticeable variation in rate of water use. The IRT measurements documented spatial variation in canopy temperature, the recovery after rain, and the subsequent rapid recurrence of stress.

By inspection, *t*-test, and analysis of variance, it was shown that significant differences in total soil water content and $T_c - T_a$ exist between sites for some soil map units, and also in short distances (<10 m) for $T_c$ −

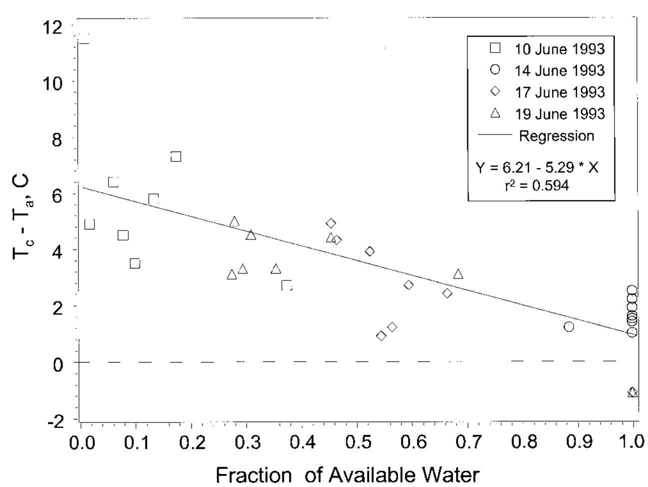


**Fig. 9. Plot of $T_c - T_a$ as a function of fraction of available water content for the four infrared thermometer measurement dates.**

$T_a$. Thus, reliance on a single soil description for an entire soil map unit, even one obtained on 1:1200 scale, will likely mean that variance in the field cannot be explained.

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