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EVAPOTRANSPIRATION AND SOIL WATER MOVEMENT BENEATH THE ROOT ZONE OF IRRIGATED AND NONIRRIGATED MILLET (*PANICUM MILIACEUM*)

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ABSTRACT

We estimated a water balance for irrigated and nonirrigated millet grown in a Varina sandy loam, which we harvested periodically during the 1970 growing season. Evapotranspiration (ET) was calculated using the water balance equation; all elements, except the subsurface drainage, were measured directly. The subsurface drainage was estimated, using the Darcy equation, to determine the net soil-water flux into and out of the root zone. The ET calculated from the irrigated plots agreed reasonably well with potential ET values computed using the combination equation. Hydraulic gradient data in nonirrigated plots showed that water moved upward for most of the season. During one drought, the upward flux accounted for about 34 percent of the calculated ET. Although the total amount of water moving upward was small, it provided enough water for the crop to subsist until rainfall was adequate.

INTRODUCTION

The effect of crop-water use on deep drainage or percolation is related to the evapotranspiration (ET) rate and the soil depth. Rose and Stern (1965) indicated that drainage below a given depth is a function of the water content at that depth. As ET increases without irrigation or rainfall, the soil water content will rapidly decrease until drainage becomes negligible. With frequent large irrigations, ET will affect total soil water content little. Conversely, with small, infrequent irrigations and large ET, less water will be available for deep drainage.

Soil-water depletion under crop conditions is often equated with ET, and the loss or gain of water, due to flow into or out of the root zone, is often considered negligible, an assumption that may not be valid under field conditions (Miller and Aarstad 1971). Wilcox (1960, 1962) recognized that ET measured by the soil-water depletion method contained an unknown quantity of profile drainage. Rose and Stern (1965), LaRue et al. (1968), and van Bavel et al. (1968a) discussed the magnitude of deep profile water movement and the error involved when this movement is not considered in plant-water use studies.

Van Bavel et al. (1968a) found that when a grain sorghum (*Sorghum vulgare Pers)* depleted water from the principal root zone, the upward flux was as large as 0.4 cm/day at the 170-cm depth in a silty clay loam soil. The magnitude of the upward flux into the root zone will depend on the soil water potential gradients and soil hydraulic properties and cannot be ignored as a source of water contributing to the total ET from field-grown plants.

Stone et al. (1973a, 1973b) reported that the upward flow of water in the soil began in the 15- to 30-cm depth, 3 days after irrigation, and at the 150-cm depth, 19 days after irrigation. The upward flux into the root zone reached a maximum of 0.2 cm/day near the end of a drought period at the 150-cm depth. During the 31-day study, ET depleted about 65 percent of the total water and downward soil water flow from the root zone about 35 percent. These data showed the significance of the net soil water flux below the root zone for determining ET rates using the depletion methods.

Miller and Aarstad (1971) found that the downward flux of water at the bottom of the root zone decreased as ET increased. Under

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similar environmental conditions, ET decreased drainage sufficiently to allow actual available water to be estimated from conventional field data. Their data showed that large erros were probable in field measurements of ET rates if deep drainage is ignored. In further work Miller and Aarstad (1973) found that as the ET rate increased, drainage after irrigation decreased and the effective available water increased. The increase in the effective available water, due to the high ET rate, was greater in the sand than in the finer-textured soils.

In many Southeastern Coastal Plains soils, the surface layers are characterized by low water-holding capacities because of their sandy texture and other physical properties. In this semihumid region, annual rainfall is normally adequate but poorly distributed, so soils become very droughty a few days after rainfall. We conducted this study to evaluate the contribution of the subsurface drainage component to the ET of irrigation and nonirrigated millet (*Panicum miliaceum*).

MATERIALS AND METHODS

The experimental design consisted of irrigated (nonstressed) and nonirrigated (stressed) treatments replicated four times. Pearl millet (var. Millex-22) was planted in 51-cm rows in plots (6.1 m wide by 8.5 m long). The soil was Varina sandy loam (Typic Paleudult) with less than a 1 percent slope near Florence, South Carolina. The initial fertilization rate was 1064 kg/ha of 10-10-10 fertilizer surface-incorporated by disking. Seedbed preparation and planting were completed on May 8, 1970. Subsequent application of 784 kg/ha of 15-0-15 was hand-applied after each harvest, which resulted in a total amount of 799 kg/ha of N, 46 kg/ha of P, and 641 kg/ha of K.

Irrigation was applied when the average matric potential at the 30-cm depth was −0.4 bar. A total of 38 cm of water was applied in 11 irrigations to the irrigated treatment. All irrigation water was measured volumetrically and applied in furrows with closed ends. Irrigation consisted of 2.5 cm of water applied in 20 min and generally infiltrated in 3 to 4 h. The distribution of water was constantly observed and dikes built as necessary to insure uniform distribution in the furrows. After infiltration was completed the dikes were removed to permit runoff from rainfall. A dry period without any significant rainfall for 32 days, starting on 12 June and ending on 14 July 1970 (harvest periods 2 and 3), caused a drought that provided an opportunity to study the effects of soil water stress on the growth of stressed and nonstressed millet.

Soil matric potential was monitored with tensiometers, soil moisture blocks, and gravimetric sampling throughout the experiment. Tensiometers attached to mercury manometers were installed at 15-, 30-, and 45-cm depths in all plots and additional tensiometers were installed at 61-, 91-, and 122-cm depths in two replications. The tensiometers were usually read between 0800 and 1000 h (EDT).

Pan evaporation and rainfall were measured about 350 m from the field site. Total and net radiation, wind speed, air, dew point, and soil temperature at the experimental site were recorded and used to calculate potential ET, using the combination equation (van Bavel 1966). Since the wind function in the original Penman equation (Penman 1962) does not adequately account for differences in the surface roughness, the wind function, as suggested by Businger (1956), was incorporated into the calculation of the potential ET. The roughness coefficient, Z_0, was chosen as 1.0 cm, based on the data of Tanner and Pelton (1960).

The millet was harvested when the plants within any treatment reached an average height of 76 cm. At each harvest, the four center rows of the 12-row plots were sampled for the vegetative yield. Total fresh weight was determined at the plot, with subsamples taken and oven-dried, and total fresh weight converted to dry matter yields.

We calculated ET using the water balance equation as follows:

$$P + I - R = ET \pm \Delta S + D$$

where P = precipitation, I = irrigation, R = runoff, ET = evapotranspiration, ΔS = the change in storage, and D = the subsurface drainage component, in centimeters of water. We determined P, I, and R by direct measurement; ΔS by gravimetric sampling and by inference from the tensiometer readings and the moisture desorption curves. Subsurface drainage, D, was determined by the Darcy equation.

The method of Rose et al. (1965) was used to determine the unsaturated hydraulic conductivity as a function of water content in the field.

Briefly the method involves measuring the change in soil water content and the vertical hydraulic gradient across the depth increment of interest. The method implicitly assumes that the change in water content (when no plant roots are present) is a result of flow out of the volume element. Using this assumption and the hydraulic gradient data, the hydraulic conductivity is calculated from the Darcy equation. To evaluate the hydraulic conductivity-water content relation, a plastic-covered plot (3 × 3 m) was surrounded with twin dikes with the water level between the dikes maintained at the same level as the water on the plot to minimize border effects. The plot was instrumented with duplicate sets of eight tensiometers at the 15-, 30-, 46-, 61-, 91-, 122-, and 152-cm depths. The change in soil water storage was measured from the difference in water content between consecutive water-content profiles. The hydraulic gradient was the time-averaged value at the 107-cm depth over the range of hydraulic conductivity and matric potential encountered under field conditions. Data from the plastic-covered plot were used to calculate the hydraulic conductivity, assuming negligible soil evaporation.

The hydraulic gradient in the field plots was determined from the tensiometer readings between the 91- and 122-cm depths (or 107-cm mean depth which we determined from field observation as the depth below the root zone of millet). Soil water flux was plotted as a function of time, and the area between the curve and the zero line measured with a planimeter to estimate the total water moving into or out of the root zone during a given harvest. When D is positive, water is moving downward out of the root zone.

RESULTS AND DISCUSSION

The rainfall and irrigation data are summarized in Fig. 1 for the 1970 growing season. The limited rainfall in May, June, and the first part of July caused an extremely dry period that decreased millet growth. However, rainfall from the latter part of July to the end of the growing season was more than adequate for millet growth. The water table was 2.5 m below the surface on May 1 and gradually dropped to 4.0 m at mid-July. Daily irrigation amounts applied during the drought ranged from 2.5 to 5.1 cm.

Desorption curves for the Varina sandy loam are shown in Fig. 2. The volumetric water content is plotted as a function of matric potential

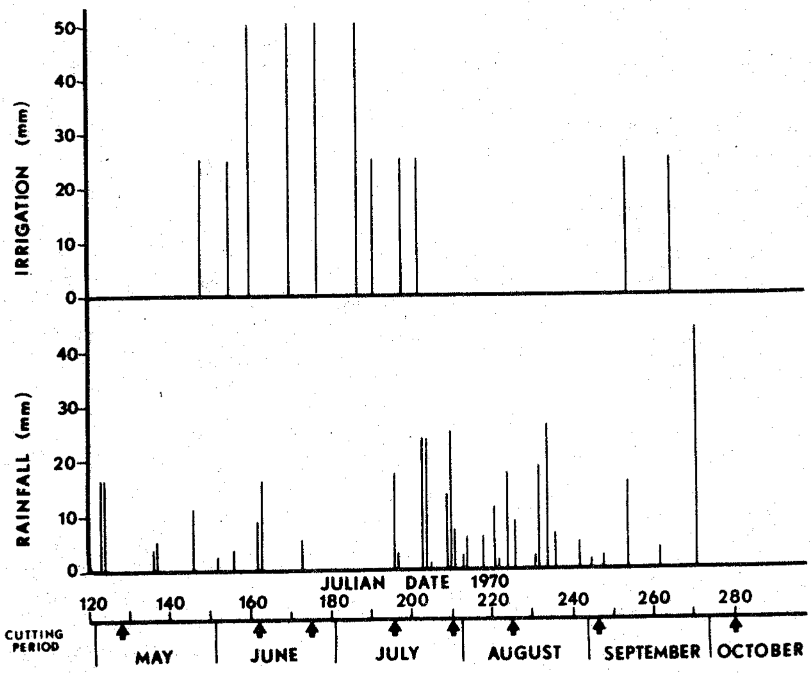

Fig. 1. Summary of rainfall and irrigation for the 1970 crop year.

from -0.01 to -15 bars. The desorption curve for the A_1 layer shows the water content rapidly decreased when the matric potential was between -0.08 and -0.2 bar and then decreased less rapidly to -15 bars. The water content of the B_1 and B_2 layers (30- and 60-cm depths) more gradually decreased down to about -0.2 bar and then decreased very little with a decrease in matric potential to -15 bars. The shape of the desorption curves reflects the sandy clay loam texture of the subsoil. Since the desorption curve for the A_2 horizon in this soil was nearly the same as that for the A_1 horizon, it is not shown.

The hydraulic conductivity-water content relationship in the subsoil is summarized in Fig. 3. The hydraulic conductivity values ranged from 5 cm/day at a water content of 0.37 cm³/cm³ to 2×10^{-2} cm/day at a water content of 0.30 cm³/cm³. The line drawn through the data points was fitted to the data by regression analysis and extrapolated to lower water contents.

The soil-water flux data calculated at the 107-cm depth are plotted as a function of time in Fig. 4. Early in the growing season, the soil water flux in both the nonstressed and stressed treatments decreased rapidly to near zero. In early June, due to the drought, the stressed plots had an upward flux that remained until September when adequate rainfall replenished storage, after which the soil water flux became positive. The nonstressed treatment showed essentially the same trend but the values of the soil water flux were negative only for a short time in July when water demand of the plants was extremely high. Most of the season, the soil water flux in the irrigated treatment was positive resulting in a net downward flow.

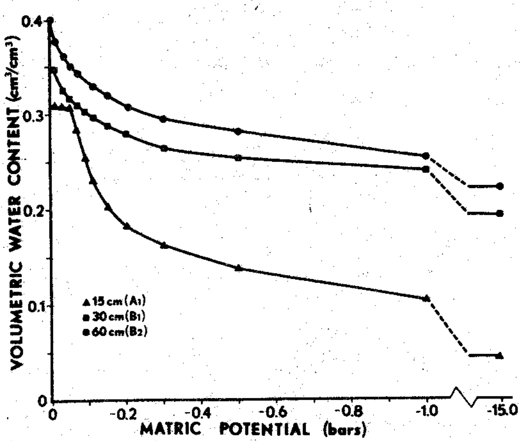

FIG. 2. The moisture desorption curves for the A1, B1, and B2 horizons of the Varina sandy loam at Florence, South Carolina.

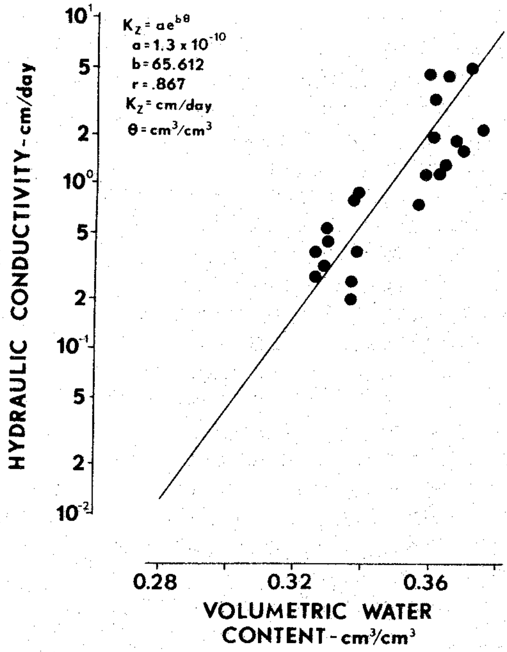

FIG. 3. The hydraulic conductivity-volumetric water content relationship for the Varina sandy loam subsoil.

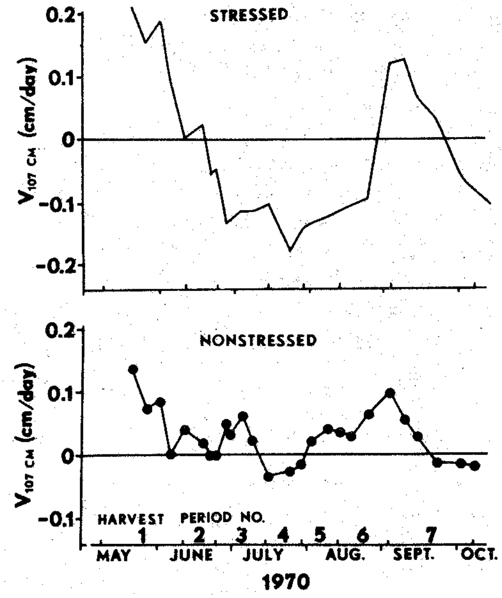

FIG. 4. Soil water flux at the 107-cm depth vs. time for the stressed and nonstressed treatments.

Estimates of the net soil water movement into or out of the soil zone are summarized in Table 1 for each period between harvests. The data indicated that as much as 3.1 cm of water was lost from the root zone during a given harvest, and as much as 2.3 cm was gained. The net upward soil flux was largest during the third harvest period when there was a drought. Even after some rainfall druing the fourth and fifth harvest periods, the hydraulic gradient at the 107-cm depth was still negative. The small amount of rainfall and its distribution caused considerable surface evaporation and did not completely recharge the profile until late in the season.

Figure 5 shows the water content profiles for selected times during the drought. The data show the progressive drying of the profile as the drought extended into the third and fourth harvests. Desorption data indicated that the matric potentials in the upper portion of the stressed profile were near −15 bars during the drought. The soil water storage with time is summarized in Fig. 6 for the nonstressed and the stressed treatments. The total storage ranged from 25 to 37 cm of water throughout the season. Irrigation effectively maintained a high level of stored water throughout the growing season.

The ET, potential ET, and pan evaporation are also summarized in Table 1. Generally, ET from the stressed plots was less than pan evaporation during the first three harvests. The ET values for the nonstressed plots varied somewhat, but were much closer to pan evaporation and potential ET than were those for the stressed plots during the drought. Later in the growing season, the ET values varied considerably, because of the variability in the subsurface drainage and in the soil water storage components of the water balance equation. Even though there were probably some experimental errors in the data in this type of analysis, the data were reasonable for the two different field water regimes.

The net soil water movement, estimated from the upward and downward flux at the 107-cm depth, indicated considerable upward flow into the root zone. Comparing the magnitude of the subsurface drainage component with other components of the water balance equation, the upward flux contributed as much as 34 percent of that water lost by ET for the stressed plots when there was no rainfall. Although the subsurface drainage component contributed significantly to the total ET under the stressed treatment, the subsurface drainage component was relatively small as compared with the ET of the nonstressed treatment. The results indicated that while water was inadequate under stressed conditions for optimum crop growth, the amount of water that moved into the root zone from below was significant and enabled the plant to subsist until rainfall was adequate.

Irrigation increased the vegetative yield of millet during the drought but had essentially little beneficial effect from the fourth harvest to the end of the growing season.

Figure 7 shows the relationship between cumulative vegetative yield and comulative ET. The relationship between the yield and ET was linear for the nonstressed and stressed treatments which agreed with results of Hanks et al. (1969) for millet. The slopes of the regression lines for the irrigated and stressed treatments were almost the same, although the stressed curve began at a much lower value. Transpira-

TABLE 1

Net soil water gain (or loss), evapotranspiration, pan evaporation, and potential evapotranspiration for seven harvest periods[1]

Harvest period	Starting date-1970	Stressed		Nonstressed		Pan evaporation	Potential evapotranspiration
		Net gain	Evapotranspiration	Net gain	Evapotranspiration		
1	May 8	+3.08	1.61	+1.54	10.80	14.86	12.59
2	June 11	−0.12	5.99	+0.26	9.41	9.88	7.77
3	June 24	−2.31	6.89	+0.43	15.11	16.23	12.74
4	July 15	−2.10	5.40	−0.35	9.21	8.48	7.77
5	July 29	−1.95	9.16	+0.45	7.95	8.56	6.57
6	Aug. 13	−1.10	7.29	+0.44	3.35	10.11	9.66
7	Sept. 3	+1.44	5.36	+0.05	11.62	14.78	13.25

[1] A positive sign in columns 3 and 5 indicates movement out of the root zone.

tion ratios calculated from these data were 215 for the nonstressed and 193 for the stressed treatments. These results suggest that the stressed treatment was slightly more efficient than the nonstressed treatment in utilizing water. Possibly surface evaporation in the nonstressed treatment exceeded that of the stressed treatment. Also, transpiration of stressed plants may have been reduced more than growth was reduced.

The maximum upward soil water flux for the stressed treatments was about −0.15 cm/day (25 percent of potential ET). On a daily basis this magnitude is relatively small, but when considered over a large portion of the growing season, it can account for a considerable amount of water. Even though the cumulative upward flux was small as compared with the total ET for the nonstressed treatments, it was sufficient to enable the plants to subsist at a decreased growth rate during the drought.

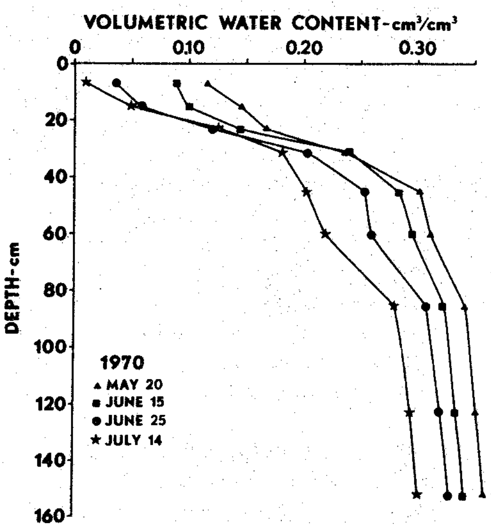

FIG. 5. Volumetric water content profiles for the nonirrigated treatment at selected times during the growing season.

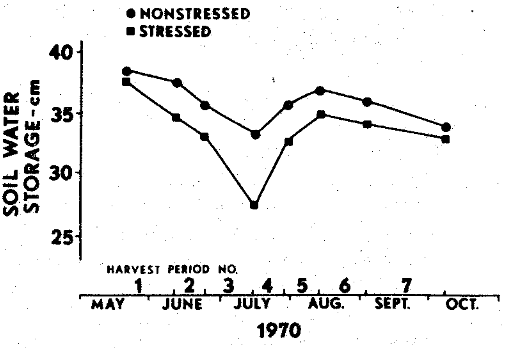

FIG. 6. Soil water storage vs. time for the nonstressed and the stressed treatments.

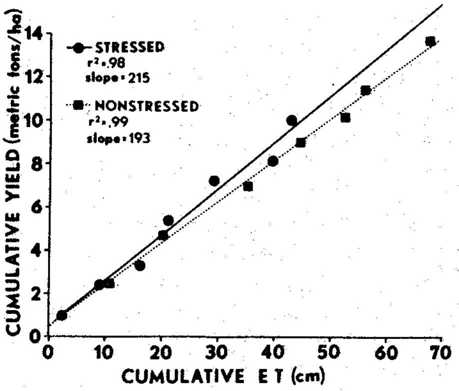

FIG. 7. Cumulative yield as a function of cumulative evapotranspiration for the nonstressed and stressed treatments.

The ET values estimated from the water balance equation were usually near those for potential ET for the nonstressed plots during the early part of the season. In the stressed plots, ET was considerably lower during the same period. During the latter part of the growing season the variation in ET between the nonstressed and stressed treatments was quite large. The data show the influence of irrigation on vegetative yield of millet and the depressing effect of drought.

These results generally agreed with those of LaRue et al. (1968) and van Bavel et al. (1968a and b) who demonstrated upward flow can provide a significant amount of water, even without a water table. The data show some water loss from the root zone of nonstressed crops and that to accurately assess water use with the water-balance method the soil water flux out of or into the root zone must be considered.

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