

Reprinted from AGRONOMY JOURNAL
Vol. 67, May-June 1975, p. 380-385

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by Soil Matric Potential and Microclimate**

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ABSTRACT

Water stress during critical growth periods is frequently the limiting factor in crop production. However few data are available on the variation of plant water status under field conditions. The object of this work was to quantify the effect of soil matric potential on plant water status. Sweet corn (*Zea mays* L.) was grown on a Varina sandy loam soil to determine the effect of the microclimate and irrigation on leaf water potential. Soil water stress was imposed naturally and by use of automated portable shelters that covered the plots during rainfall.

Leaf-water potential was closely related to the diurnal change of incoming energy. A maximum leaf-water potential of -1.5 bars occurred just prior to sunrise. The minimum value, which occurred during the peak radiation load or stress, was dependent on soil matric potential and stage of plant development. Before tasseling, soil matric potentials of -0.08 and -0.60 bar at the 15-cm depth in irrigated and nonirrigated plots resulted in minimal leaf-water potentials of -12 and -18 bars, respectively. After tasseling, soil matric potentials were -0.07 bar at the 15-cm depth in the irrigated and -3.0 bars in the nonirrigated plots, and the same minimal leaf-water potential of -18 bars developed for both. Under the same radiation load, minimal leaf-water potential of irrigated plants was -12 bars before tasseling and -18 bars after tasseling. The results demonstrate the need to evaluate the influence of environmental stresses

and soil water deficits on leaf-water potential and associated physiological processes.

Additional index words: Plant water status, Incoming radiation, Net radiation, Soil water potential, Irrigation, Water stress, *Zea mays* L.

DIURNAL fluctuations in leaf water potential have been predicted by theoretical analyses (7). Klepper (16) measured marked diurnal variations in water potential of both leaves and fruits and found that during the day variations in the plant water status were closely related to radiation load or stress, while at night the plant water potential reflected the soil water status. Her results indicate that during the day the roots could not absorb water fast enough to replace that lost by transpiration even as the potential gradient increased. Similarly, Waring and Cleary (20) using Douglas fir (*Pseudotsuga menziesii*) with adequate soil water showed that plant water potential reached -20 bar, even when soils were near field capacity, if the radiation load was sufficiently high. They found plant water status may fluctuate rapidly, as much as a 5-bar change per hour, depending on the microclimatic conditions.

Recently, the importance of soil matric potential on the transpiration rate of field plants has been studied intensively. Denmead and Shaw (8, 9, 10) reported that the transpiration rate of corn (*Zea mays* L.) decreased as the soil matric potential decreased.

¹Contribution from the Coastal Plains Soil and Water Conservation Research Center, Southern Region, ARS-USDA, Florence, SC 29501, in cooperation with the South Carolina Agric. Exp. Sta. Received Aug. 30, 1974.

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If evaporative demands were high, the relative transpiration rate decreased rapidly although the soil matric potentials were fairly high, ranging from -0.02 to -0.5 bar. However, if evaporative demands were low, the relative transpiration rate did not decrease until soil water potentials were lowered. These data indicated that meteorological conditions significantly affected the potential evapotranspiration rate. Thomas and Weigand (19) showed that as soil matric potential decreased, water availability and transpiration rate decreased and leaf temperature increased. Yang and De Jong (21) concluded that as the transpiration rate of wheat (*Triticum aestivum* L.) decreased with decreasing soil water potential, soil conductivity was identified as the major limiting factor in the pathway of water from the soil to the plant leaf. This generally agrees with work of Gardner and Ehlig (12, 13) and Lang and Gardner (17) which indicated at low soil water potentials, unsaturated conductivity is the most important factor in controlling the rate of water uptake by plant roots.

Little quantitative data have been reported on the diurnal changes in leaf water potential under various soil water regimes, when both micrometeorological and soil moisture stresses were evaluated simultaneously. The work reported here was conducted under field conditions to quantify the diurnal fluctuations of leaf water potential of corn and relate their magnitude to the microclimate and soil matric potential.

METHODS AND MATERIALS

Sweet corn 'Silver Queen' was grown on a Varina sandy loam soil (Plinthic Normudult) near Florence, S. C., during 1972. The corn was planted on March 30 (emergence completed on April 17) in 51-cm rows and thinned to approximately 30 cm between plants in the row, equivalent to a population of 72,000 plants/ha. The corn was fertilized with 84, 74, and 139 kg/ha of N, P, and K, (5-10-10 fertilizer), respectively, and with 212 kg/ha of N as a slow release fertilizer (26-0-0 Osmocote[®]) at planting time. The fertilizers were mixed into the surface soil by disking to the 10-cm depth.

The experimental design was a split-plot with a 6.5×8.2 -m plot size. Main plot treatments were tillage and subplot treatments were water control, replicated four times. The tillage treatments were conventional surface tillage, and conventional surface tillage plus chiseling to a 38-cm depth. The water control treatments were three drought periods imposed at different stages of growth, and a control that was furrow irrigated with 2.5 cm of water when the soil matric potential was -0.2 bar at the 30-cm depth. The first period of drought stress was imposed 36 days after planting by covering the plots with moveable shelters automatically activated by rainfall. The second and third droughts were imposed 55 and 70 days after planting by laying polyethylene sheets on the soil surface between the plant rows and stapling them around the plant base to eliminate infiltration of rainfall.

Leaf water potential (xylem pressure potential assumed \gg xylem osmotic potential), ψ_l , was measured in the field using the pressure chamber technique described by Scholander et al. (18). Plants with fully expanded leaves exposed to full sunlight were selected randomly for determining leaf water potential. The influence of leaf position was not measurable as long as the leaves were not shaded. The leaf was excised approximately 30 cm from the tip, and about 5 cm of the blade was trimmed from the midrib at the cut end for insertion of the midrib into a gland mounted in the wall of the pressure chamber. The chamber was then sealed and pressure applied at the rate of

[®]Trade names are included for the benefit of the reader and do not infer an endorsement or preference of the products listed by the USDA or the South Carolina Exp. Sta.

Table 1. Summary of plant parameters and soil matric potentials on the days of leaf water potential determinations.

Date, 1972	Plant height cm	Leaf area /plant cm ²	Soil matric potential	
			15 cm bar	30 cm bar
May 19	42	1,650	-0.09	-0.10
June 6	114	5,100	-0.17	-0.16
June 23	226	5,800	-0.07	-0.07

0.4 to 0.8 bar/sec. The entire procedure from excision to the final reading required 1 to 2 min. The time between samples varied from 5 to 15 min. The data were smoothed using a 1-2-3-2-1 weighted running average after Jackson et al. (15).

Solar radiation (R_s), net radiation (R_n), wind speed (W), air temperature (T_a), and dew point temperature (T_d) were recorded. Solar radiation was measured with an Eppley[®] pyranometer mounted 4 m above ground level. Net radiation was measured with a Fritschen-type net radiometer (11) placed approximately 110 cm above the crop canopy, which was elevated as the plant height increased. Wind velocity was measured with a 3-cup anemometer mounted 200 cm above the soil surface. The electrical output of the radiation and wind sensors was integrated continuously and recorded hourly. At 200 cm above ground level, both air and dew point temperatures were measured with a nickel wire resistance thermometer and a Honeywell Dew Probe[®], respectively. The ambient vapor pressure and saturated vapor pressure were determined from the temperature-vapor pressure curve. Vapor pressure deficit (VPD) was calculated as the difference between saturated and ambient vapor pressures. All data described above were recorded hourly by an electronic data acquisition system.

The soil water status was monitored with tensiometric and gravimetric measurements. Tensiometers were placed in the soil at 15-cm increments to the 61-cm depth and at 30-cm increments to the 183-cm depth. The tensiometric measurements were recorded between 0800 and 1000 hours (EDT) daily.

RESULTS

Influence of Microclimatological Stresses On Leaf Water Potential

Data for 3 days (May 19, June 6, June 23) were selected to show the influence of the microclimatological variables on the diurnal cycle of leaf water potential of "well-watered" plants. Since soil water stress throughout the experiment was not apparent, any fluctuation in leaf water potential (ψ_l) was assumed due to climatic variables. Leaf area, plant height, and soil matric potential on the selected days are summarized in Table 1.

The diurnal pattern of leaf water potential and microclimatic variables are plotted (Figures 1a, 1b, and 1c) for the selected dates, May 19, June 6, and June 23, respectively. The energy distribution throughout the daylight hours of these days was substantially different. May 19 was heavily overcast and cool with no direct sunlight until about 1400, which represented a low energy day. June 23 was a perfectly clear day with moderate temperatures, and June 6 was clear until about 1430 when a brief thunderstorm occurred adjacent to the experimental area. Only a trace of precipitation was measured and the sky cleared at about 1700 and remained so until sunset.

The variation of leaf water potential on May 19 is shown in Fig. 1a. The scatter around the smoothed data ranged from 1 to 4 bars, representing plant to plant variation. Leaf water potential was approximately -1.5 bars from 0600 to 0900 hours and gradual-

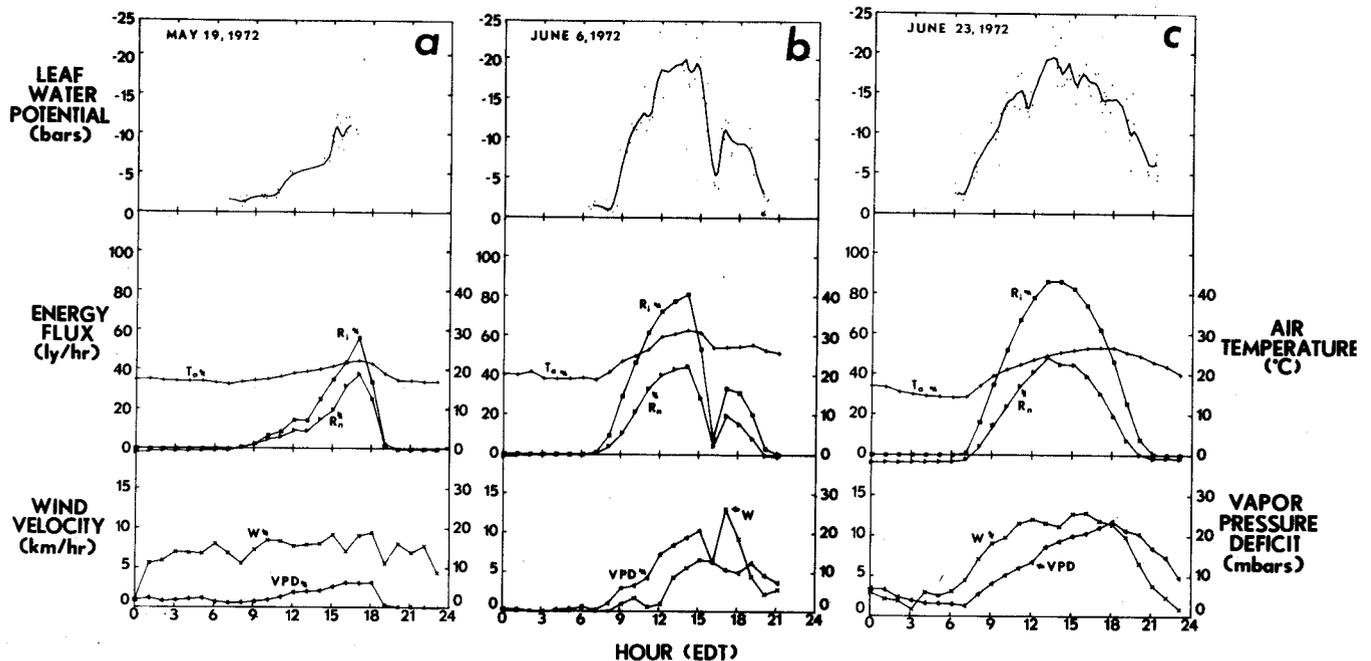


Fig. 1. Diurnal variation of microclimate data and leaf water potential of well-watered corn plants: a, May 19; b, June 6; c, June 23.

ly decreased (more negative) until 1600. Dew covered the plant leaves up to 0900. On May 19, no Ψ_1 data were collected after 1700, but accompanying data indicate Ψ_1 increased rapidly at sundown. The energy flux data reflect the extent of cloud cover as indicated by both the incoming and net radiation. The net radiation slowly increased to about 10 ly/hour at 1300 and rapidly increased to 35 ly/hour as the cloud cover decreased. The relationship between Ψ_1 and the energy flux, whether net or solar radiation, was strikingly close.

The relationship between Ψ_1 and the energy flux is even more striking on June 6 (Fig. 1b). Net radiation increased rapidly, as the sun angle increased, until 1430 hours, and then decreased sharply as a small thunderstorm moved over the area. The sky cleared by 1700 and again R_n was related to the sun angle. Leaf water potential did not change substantially until 0800 when the decrease in Ψ_1 was closely related to the energy flux. The rapid decrease in Ψ_1 from 1500 to 1600 was related to the decrease in energy flux, because no precipitation fell until 1605 and the trace amount that fell evaporated within the hour. Although the daily trends of Ψ_1 and VPD were similar, the relationship was not as dramatic as that between Ψ_1 and R_n . The air temperature extremes were 21 and 31 C, and the wind velocity was very low during the early morning hours but increased briefly to 13 km/hour during the thunderstorm.

These results suggest that Ψ_1 of well-watered plants can respond to energy changes within 5 to 15 min. Each sampling, measuring, and recording required 5 to 7 min and did not permit sufficiently rapid sampling for more precise evaluation of the Ψ_1 time response. However, these results support the observations of Boyer (3) that Ψ_1 can change as much as 50 % in 4 min when a step change in stress is imposed.

Data for June 23 are summarized in Fig. 1c. The radiation data represent a clear day. There was a very close relationship of energy flux and Ψ_1 . Under peak energy loads, Ψ_1 decreased to -19 bars even when the soil matric potential was -0.07 bar at the 15-cm depth. The VPD showed a diurnal swing with a minimum at 0700 and a maximum at 1800 that lagged behind the minimum Ψ_1 by 5 hours.

On June 23 plant leaves had no dew and Ψ_1 decreased at sunrise, about 0630, while on June 6 with a heavy dew, Ψ_1 did not decrease until 0800 hours. The VPD around sunrise on June 23 ranged from 3 to 6 mb while it was less than 1 mb on June 6. These data indicate the influence of dew on the duration of plant water stress in the humid regions and suggest that mist irrigation may be beneficial during periods of minimum Ψ_1 .

Influence of Soil Matric Potential on Leaf Water Potential

The two soil moisture treatments tested on May 16, June 1, and June 15 to show effects of soil matric potential on Ψ_1 will be identified as stressed and nonstressed plants. The term "stress" reflects only the relative difference between the two soil water treatments. The nonstressed plants were irrigated as described earlier.

The leaf water potential and the microclimatological variables on May 16 are summarized in Fig. 2a. Since differences between tillage treatments were not evident, Ψ_1 and soil matric potential data for both treatments were combined. The stressed plants were sheltered from rainfall for 11 days while the nonstressed plants received a total of 34 mm of precipitation the preceding 2 days.

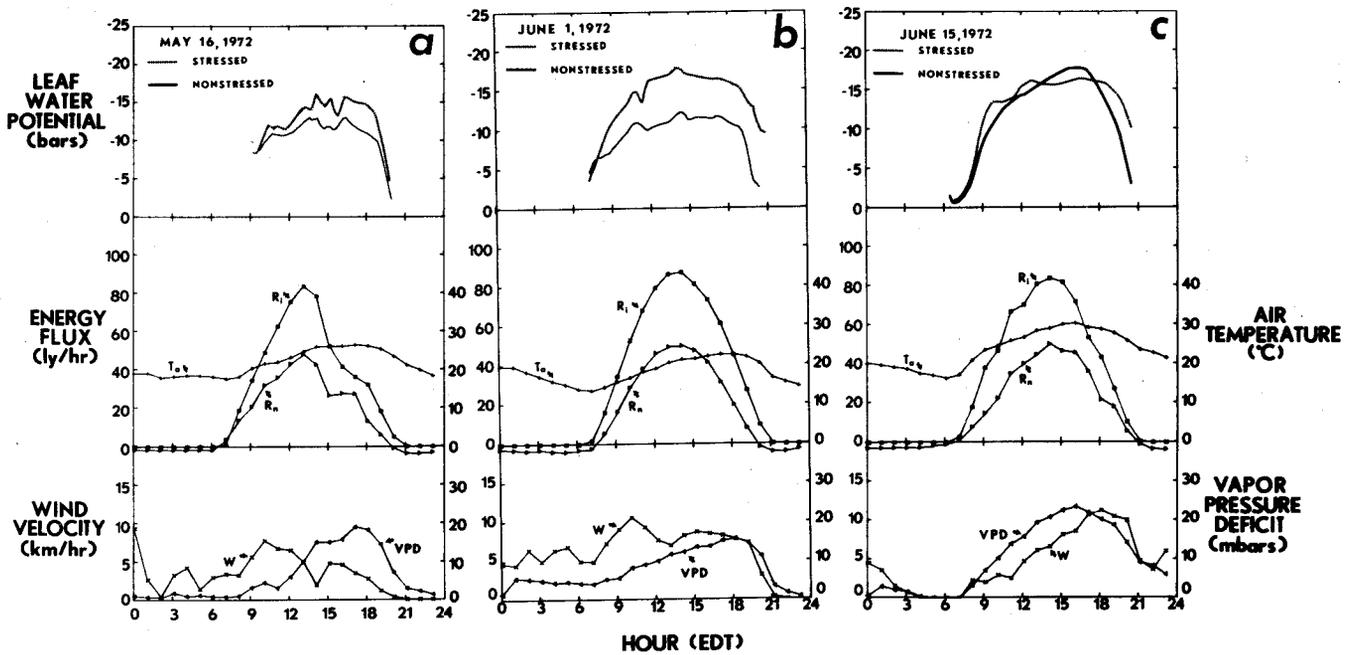


Fig. 2. Diurnal variation of microclimate data and leaf water potential of stressed and nonstressed corn: a, May 16; b, June 1; c, June 15.

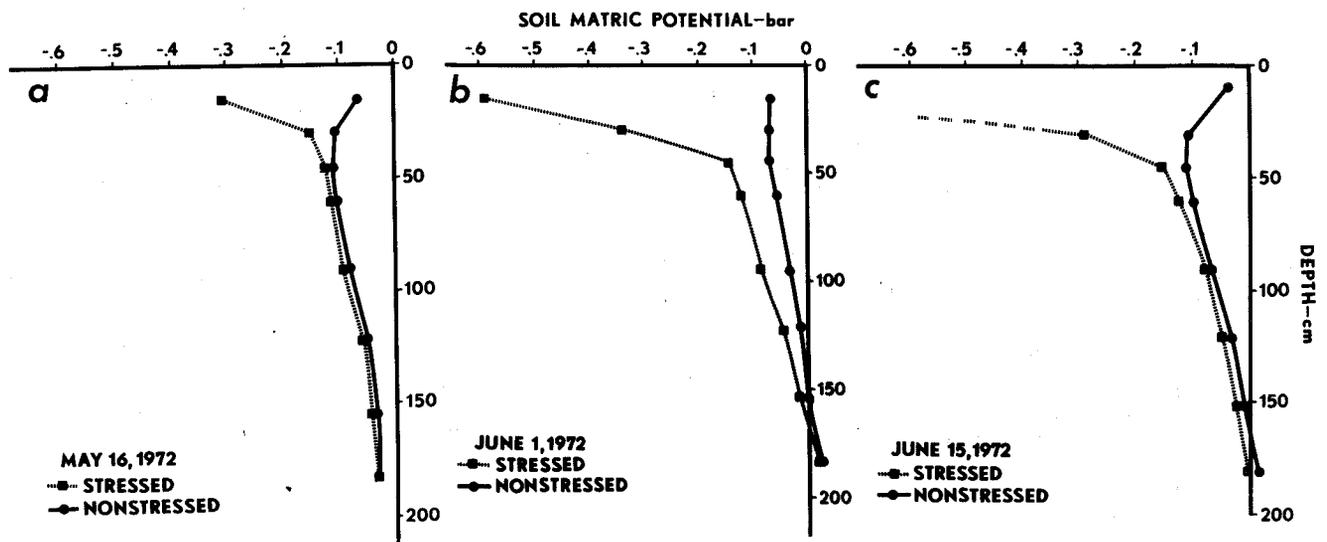


Fig. 3. Soil matric potential distribution for the stressed and nonstressed plots on dates corresponding to Fig. 2.

The Ψ_1 of both the stressed and nonstressed plants decreased rapidly at sunrise, reached a minimum at approximately midday, and rapidly increased at sunset. The Ψ_1 for the stressed and nonstressed plants exhibited a plateau during midday that apparently was unrelated to incoming radiation. The diurnal fluctuation in the VPD lagged behind R_n and R_n fluctuations and did not seem to markedly affect the magnitude of Ψ_1 . The small difference of the leaf water potential of the stressed and the nonstressed plants, under these environmental conditions, was unexpected because of the drastic difference in visual stress symptoms. The minimum Ψ_1 was about -13

bars for the nonstressed plants, whereas that for the stressed plants was approximately -16 bars. This difference obviously was important since the stressed plants wilted severely at solar noon while the nonstressed plants exhibited no visible wilt symptoms. Stomatal resistance data (not shown) indicated complete closure only when the leaves were severely wilted.

The 3-bar difference in Ψ_1 between the stressed and the nonstressed plants reflects differences in soil matric potential (Fig. 3a). The soil matric potential at the 15-cm depth for the nonstressed plots was approximately -0.07 bar. On the stressed plots the soil matric potential at the 15-cm depth was -0.30 bar.

Soil monoliths indicated that at this time most of the roots were located in the top 30 cm of the soil profile of both the stressed and nonstressed plots. A difference of 0.23 bar at the 15-cm depth resulted in a 3-bar difference in Ψ_1 . These data indicate that soil matric potential had a small effect on the magnitude of Ψ_1 .

The diurnal fluctuation in leaf water potential on June 1 is presented in Fig. 2b. Water was withheld from the stressed plants for 27 days by the portable shelters, while the nonstressed plants received 118 mm of precipitation during this period (23 mm occurred May 29 and 30). The day of June 1 was cloudless, and R_1 totaled 727 ly. Leaf water potential rapidly decreased, starting at sunrise, to a minimum at approximately 1400 and then rapidly increased after 1700 as the sun was setting. Leaf water potential of both stressed and the nonstressed plants was essentially the same from 0600 to approximately 0800 when they began to diverge. The minimal Ψ_1 of the nonstressed plants was approximately -12 bars at 1400. The stressed plants followed a similar trend with the minimal Ψ_1 approaching -18 bars. The time lag of the stressed behind the nonstressed plants, in terms of increasing leaf water potential, apparently represented a resistance (rhizosphere resistance) to the flow of water in the soil-plant system. These results indicated that Ψ_1 of the stressed plants lagged about 1 to 2 hours behind that of the nonstressed plants shortly after sundown.

The soil matric potential distribution on June 1 is shown in Fig. 3b. The soil matric potential of the nonstressed plots was greater than -0.10 bar throughout the entire depth of the profile. However, the soil matric potential of the stressed plots was -0.60 bar at the 15-cm depth, -0.13 bar at the 45-cm depth, and then gradually increased with depth to 180 cm. The water table was approximately 160 cm below the soil surface at this time. The soil matric potential difference of 0.5 bar between the stressed and nonstressed plots at the 15-cm depth is reflected in the 6-bar difference in the leaf water potentials (Fig. 2b). Apparently, the low soil matric potentials of the stressed plots and the resultant decrease in the hydraulic conductivity were the major factors causing the difference between the leaf water potentials of the stressed and the nonstressed plots. Estimates of the hydraulic conductivity values for the surface layer of this soil indicate the difference between the stressed and the nonstressed was three orders of magnitude. This agrees with the theoretical predictions of Lang and Gardner (17).

The diurnal fluctuations of the leaf water potential and the microclimatological data for June 15 are presented in Fig. 2c. The general diurnal patterns were closely related to incoming energy and seem independent of soil matric potential. Leaf water potential changed from -1 bar before sunrise to approximately -16 bars at 1500, and then increased as the sun set for both the stressed and nonstressed plants. The difference in the matric potential distribution between the stressed and nonstressed plots as a result of irrigation is shown in Fig. 3c. The nonstressed plots were irrigated June 14 with 5 cm of water. The soil matric potential was -0.07 bar

at the 15-cm depth, slightly decreased at the 30-cm depth, and then paralleled the stressed plots throughout the rest of the profile. The soil matric potential at the 30-cm depth of the stressed plots was approximately -0.30 bar. The difference in soil matric potential in the surface layers on June 15 did not substantially affect Ψ_1 . These results indicate that Ψ_1 at this stage of growth and in this range of soil matric potential was essentially independent of the soil matric potential and more dependent on R_1 . On June 15 at 1600, a vapor pressure deficit of 22 mbars was measured. The combination of the large VDP and R_1 masked the influence that the soil matric potential might have had on the magnitude of Ψ_1 . However, the effect of plant maturity on Ψ_1 cannot be discounted, because these data were collected 13 days after tassel emergence.

DISCUSSION

The data show the dependence of leaf water potential on the energy flux which, in turn, influences the rate of transpiration. Because the resistance to water movement in the plant and the soil are finite, the plant did not absorb water fast enough to replace that lost by transpiration, although the water potential gradient in the plant increased and the soil matric potential was very high. This gradient reflects the balance between environmental demand and the rate of water extraction which is controlled by the root system. At sunset when the evaporative demand was low, the large gradient decreased as water moved into the leaf and Ψ_1 increased quite rapidly.

Since Ψ_1 controls growth (cell elongation), the diurnal pattern of the growth rate is apparent. These results confirm that most corn growth is at night when the radiation load is minimal and growth essentially stops during the daylight hours. Acevedo, Hsiao, and Henderson (1) have shown that the elongation rate of the corn leaf decreased linearly as Ψ_1 decreased and was essentially zero at $\Psi_1 = -7.0$ bars. Boyer (4) and Hsiao, Acevedo, and Henderson (14) have shown that corn leaf elongation ceased at approximately this same Ψ_1 .

Based on this value of Ψ_1 , the corn leaf growth rate decreased considerably as the sun rose, almost stopped by 0800, and did not resume till almost sunset. Using these data, a representation of the diurnal changes in Ψ_1 , similar to that for sunflower (*Helianthus annuus* L.) by Boyer (2), can be schematically developed for corn. The upper limit of Ψ_1 for a well-watered plant is probably about -1.5 bars and the lower limit between -18 and -20 bars under high radiation loads, and the growth rate zero at $\Psi_1 = -7.0$ bars. The influence of light intensity on leaf elongation of a well-watered corn plant has been shown by Hsiao et al. (14). The decrease in growth rate at high light intensities is probably due to increased transpiration that changes leaf water balance and Ψ_1 .

These data show a wide diurnal range of Ψ_1 even for well-watered plants. Minimal values of -18 to -20 bars, at midday after tasseling, indicate the importance of radiant energy flux when soil water stresses are minimal. Leaf water potentials of this magni-

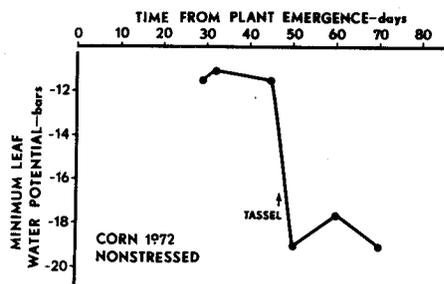


Fig. 4. Minimum leaf water potential of well-watered corn as a function of plant age.

tude have had a substantial effect on certain physiological processes (4, 5). Although laboratory and field data may differ quantitatively, the qualitative relationships are probably valid. These results indicate that microclimatological stresses can dominate the magnitude of Ψ_1 with soil water conditions having a small effect.

Little information is available on the influence of the stage of plant development on Ψ_1 . The relationship of minimal Ψ_1 for the nonstressed corn plants has been plotted as a function of time (Fig. 4). Prior to tassel emergence, the minimal Ψ_1 at the same energy flux for the nonstressed plants was approximately -11 bars. But after the tassel appeared, the minimal Ψ_1 for the nonstressed plants was -19 bars. Unfortunately, minimum Ψ_1 was not collected daily so as to characterize adequately the transition from the vegetative to the reproductive stage. The lower minimum Ψ_1 after tasseling could not be related to leaf number because some of the same leaf numbers were sampled before and after tassel emergence. The difference in Ψ_1 was apparently associated with a physiological change from the vegetative to the reproductive stage of development. When the tassels emerged, the plants had attained approximately 55% of the final dry matter yield and 85% of the maximum leaf area. These observations, in general, agree with those of Boyer (6) that leaf water potentials for soybeans and corn during the reproductive stages may not indicate the same levels of stress as Ψ_1 during the vegetative stage. Based on these results, Ψ_1 , during the vegetative stage of corn growth, is a good indicator of plant water stress. However, due to the independence of Ψ_1 over a wide range of soil matric potentials during the reproductive stage, interpretation of the Ψ_1 data is uncertain. This is perplexing, because during the reproductive stages most agricultural crops are sensitive to soil water stress. These observations indicate the need for careful evaluation of plant water stress throughout the entire growth cycle.

ACKNOWLEDGEMENTS

The authors acknowledge the helpful comments of Drs. E. R. Perrier, M. G. Huck, and J. T. Ritchie in the preparation of this manuscript.

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