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Influence of Soil Water Status and Meteorological Conditions on Evaporation from a Corn Canopy[1]

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ABSTRACT

In predicting evaporation rates for field crops, it is important to consider the influence of soil water status on the actual evaporation rate relative to the potential rate. This study was conducted to determine actual evaporation rates of corn (*Zea mays* L.) as influenced by soil water status and potential evaporation rate. Actual evaporation rates were measured during the 1972 growing season with a weighing lysimeter. Evaporation rates were found to be practically independent of the soil water status for all existing conditions of potential evaporation. During the season more than 20 cm of soil water was removed from the 120-cm deep profile.

Leaf diffusion resistance and leaf water potential measurements indicated that at least 80% of the extractable soil water was freely available to plant roots. These findings differ from those of Denmead and Shaw (Agron J. 54:385-390, 1962) who found that evaporation reduction in container grown corn plants started when about 20% of the extractable water was removed from the soil for potential evaporation rates above 6 mm/day. The difference between the results from the experiment reported by Denmead and Shaw and this experiment point out that serious errors are possible when using their results for predicting evaporation from corn plants growing under field conditions.

Additional index words: Evapotranspiration, Plant water potential, Leaf diffusion resistance, Root water uptake, Potential evaporation, Available water.

THE actual evaporation rate from a crop surface when a soil water deficit develops in the plant root zone has been the subject of much interest in recent years. A widely quoted experimental study of Denmead and Shaw (1962) indicated that actual transpiration rates of container grown corn (*Zea mays* L.) plants decreased with decreasing soil water content and increasing potential evaporation. In recently published texts on soil-plant-water-atmosphere relationships, the work of Denmead and Shaw has been used to demonstrate the dynamic aspects of factors influencing the transpiration rate (Rose, 1966; Kramer, 1969; Slatyer, 1967).

Relationships drawn from the work of Denmead and Shaw have been used either directly or in a modified form to predict actual field evaporation rates as influenced by soil water status and potential evaporation for corn (Shaw, 1963a; Flinn, 1971; Saxton, footnote 3; Norero, Keller, and Ashcroft 1972), for oats (*Avena sativa* L.) (Shaw, 1963b), and for meadow (Shaw, 1964).

Recent studies of evaporation using precise, well-exposed weighing lysimeters have shown for cotton (*Gossypium hirsutum* L.) and grain sorghum [*Sorghum bicolor* (L.) Moench.] (Ritchie, Burnett, and Henderson, 1972) and for alfalfa (*Medicago sativa* L.) (Van Bavel, 1967) that about 80% of the extractable water from a deep field soil profile can be used before stomatal regulation of evaporation begins. Van Bavel (1967) found that the ratio between actual and potential evaporation from an alfalfa canopy did not decline below unity until 20 days after irrigation under potential evaporation conditions up to 10 mm/day. A decrease in the ratio after 20 days was associated with a decline in soil water potential values below about —4 bars and an increase in measured canopy resistance. Ritchie et al. (1972) found that evaporation rates were independent of soil water status until soil water was depleted beyond a critical threshold and from that point water was extracted at a decreasing rate before evaporation practically stopped. Because alfalfa, cotton, and grain sorghum are crops developed for more arid climates, it was thought that corn might have a more sensitive stomatal mechanism to regulate transpiration at higher soil water contents than the other crops. Therefore, this study was conducted to reevaluate the influence of potential evaporation and soil water status on actual evaporation rates from a corn canopy under representative field conditions.

MATERIALS AND METHODS

The experiment was conducted at Temple, Texas, during the corn growing season of 1972. The field was planted on March 1 in rows spaced 61 cm apart. Plants were approximately 33 cm apart in each row and resulted in a population of approximately 50,000 plants/ha. The soil at the site is Houston Black clay. Half-hourly evaporation rates were measured with a 183 cm square × 120 cm deep weighing lysimeter. Net radiation, temperature, windspeed, and humidity over the cornfield were recorded every half hour. Other details regarding the field site, the lysimeter installation for measuring evaporation, and the general experimental procedures are described elsewhere (Ritchie, 1971; Ritchie and Burnett, 1971; Ritchie et al., 1972; Ritchie and Jordan, 1972).

Leaf area index was used as an indicator of crop growth. Leaf areas were measured every 7 to 10 days from May 1 through July 30. The leaf area of 10 plants removed from the field surrounding the lysimeter was correlated with plant height each time samples were taken until the maximum vegetative stage was reached. The correlation was used to estimate the leaf area of lysimeter plants from measured height of each plant in the lysimeter. When physiological maturity began to cause the green leaf area to decline, leaf area was determined from the number of green leaves on lysimeter plants and from average leaf area of similar leaves measured on plants surrounding the lysimeter. Throughout the season, plants growing in the lysimeter were visibly similar in height and density to plants growing in the surrounding area.

A small plot, 10 rows wide and 20 m long, near one edge of the cornfield was irrigated at 7- to 10-day intervals during rainfall deficient periods as a means of comparing the response of dryland and irrigated plants to the environment.

The water content of the root zone was measured periodically by the neutron scattering method with two access tubes in the lysimeter and two access tubes in the vicinity of the lysimeter. Soil water potential was measured at several depths using thermocouple psychrometers located in the lysimeter and in the irrigated field.

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[3] K. E. Saxton, 1972. Watershed evapotranspiration by the combination method. Ph.D. Dissertation. Iowa State Univ., Ames.

Leaf diffusion resistances were measured with a commercially available porometer[4]. Measurements were made every 2 to 3 days from May 22 to July 10. Resistances were measured during the early afternoon on both the upper and lower leaf surface of three sunlit leaves in the lysimeter and in the irrigated plot. On June 23, leaf resistance was measured at 1- to 2-hour intervals throughout the day on dryland plants growing near the lysimeter. The total resistance, R, of each leaf was calculated using the equation:

$$1/R = 1/R_a + 1/R_b \quad [1]$$

where R_a and R_b are the adaxial and abaxial resistances, respectively.

Leaf water potential was determined by the pressure chamber technique of Scholander et al. (1965) for irrigated plants and for dryland plants growing in the vicinity of the lysimeter. The potential was usually measured on five sunlit leaves of different plants from each area immediately following the leaf resistance measurements.

Estimates of potential evaporation were calculated using a combination equation of Penman (1963):

$$E_o = [\Delta/\gamma\ (R_n + 0.262\ (1 + 0.0061u)\ (e_o - e_a)]\ (\Delta/\gamma + 1)^{-1} \quad [2]$$

where:

R_n = net radiation above the canopy, mm/day (1 mm/day is equivalent to an energy flux of about 59 cal/cm^2 per day);

Δ = slope of the saturation vapor pressure curve at mean air temperature;

γ = constant of the wet and dry bulb psychrometer equation;

u = wind speed at a height of 2 m; km/day;

e_o = saturation vapor pressure at mean air temperature, millibars;

e_a = mean vapor pressure of the atmosphere, millibars.

The empirical wind function in [2] contains an allowance for the extra roughness of a crop as compared with open water.

RESULTS AND DISCUSSION

A summary of the experimental results is given in Fig. 1, A to D. The results shown are only for the growing season after May 1. The leaf area index (LAI) was about 0.7 by May 1, and the plants had begun to grow rapidly. Figure 1A gives the daily measured evaporation rate through the season along with calculated values of potential evaporation.

The evaporation rate during the first 20 days of May was usually below the potential rate because of a lack of complete cover, except on days after rain when the soil surface was wet. After May 20, the daily evaporation rate was usually within ±1 mm of the potential rate until about July 5, when the green leaf area began to decline rapidly as a result of senescence. After July 5, evaporation rates declined rapidly with the decrease in green leaf area.

The daily soil water content for the May through July period is given in Fig. 1B. Increases in soil water represent rainfall and decreases represent evaporative loss. During the May through July period, no drainage from the lysimeter was necessary to maintain water content values approximately equal to field water content values. The water present in the soil is referred to as the extractable water and is defined as the quantity of soil water in the entire profile in excess of the minimum quantity observed in the soil when plant evaporation practically stops because

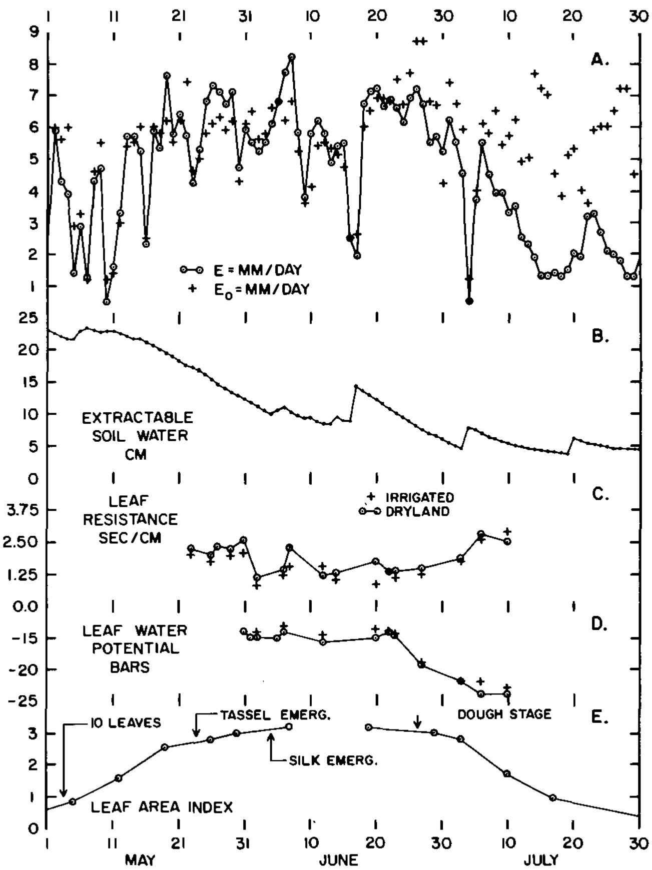

Fig. 1. Seasonal variations in (A) daily actual and potential evaporation rate; (B) extractable soil water in the root zone; (C) early afternoon average leaf resistances for irrigated and dryland plants; (D) early afternoon average leaf water potentials for irrigated and dryland plants; and (E) leaf area index and physiological stage of development; 1972.

of dry soil. Unfortunately, the lower limit of extractable water was not reached during this test; therefore, the amount of water extractable by corn roots was assumed to be the same (25 cm) as found for cotton and grain sorghum in earlier studies (Ritchie et al., 1972). Water content measurements made in years with greater soil water deficits than occurred in 1972 have not indicated that corn can extract more soil water than grain sorghum or cotton for soil similar to the one in this study. Extractable soil water declined to 10 cm by June 8 and remained below that value for the remainder of the season except for a 7-day period following a 5.7-cm rain received on July 17. Extractable soil water was about 5 cm throughout most of July.

Average afternoon leaf diffusion resistance and leaf water potential for irrigated and dryland plants are given in Fig. 1, C and D. Leaf diffusion resistance for dryland plants growing in the lysimeter averaged about 2.5 sec/cm throughout most of the period of active growth of the crop. Because evaporation was not reduced appreciably below the calculated potential rate during this period, these results indicate that daytime leaf resistance values of 3 sec/cm or less for corn cause no stomatal regulation of transpiration. These results agree with data of Kanemasu and Tanner (1969) for snap bean (*Phaseolus vulgaris* L.)

[4] Lambda Instruments Co., Inc., 2933 North 36th, Lincoln, Nebraska 68504. Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the U.S. Department of Agriculture.

leaves. The leaf resistance of irrigated plants varied little from dryland plants. Afternoon leaf water potentials averaged about —15 bars for dryland plants and about —14 bars for irrigated plants until June 23. After June 23, leaf potential values declined gradually to about —22 bars. Some physiological factor was the likely cause of the leaf potential decrease because it was observed in both dryland and irrigated plants.

The seasonal variation in leaf area index of green leaves is given in Fig. 1E along with the details about the physiological stages of development of the plants. Throughout the season, there was no visible difference in plant height and leaf area index between the irrigated and dryland plants although measurements were made only in the dryland area of the field. Leaf senescence at the latter part of the season was not visibly different between the irrigated and dryland plants.

A summary of the diurnal changes in evaporation and plant water status on June 23 is given in Fig. 2. This particular analysis was made to determine if there was a midday reduction in evaporation that might not be indicated in the daily totals of Fig. 1A. The upper part of Fig. 2 shows that the measured evaporation rates were approximately equal to the calculated potential evaporation rates throughout the day, including the period of maximum water use from 1100 hours to 1500 hours. The leaf water potential was —5 bars at the beginning of the day and decreased in approximate proportion to the increase in evaporation rate to about —15 bars during maximum water use.

Adaxial and abaxial leaf resistance responded between 0500 and 0600 hours to the light intensity increase at sunup and remained at 2 to 4 sec/cm throughout most of the day until late afternoon. The slightly higher adaxial resistance when compared to the abaxial resistance is similar to the findings of Turner (1969). The increase in adaxial resistance beginning after 1500 hours caused no apparent reduction in evaporation.

The extractable soil water on June 23 was about 10 cm (Fig. 1B). About 15 cm of the extractable water storage for this soil had been depleted. Average soil matric potentials for June 23 were approximately —8, —4, —1.5, and—0.4 bars at depths of 25, 50, 75, and 100 cm, respectively. These results, along with water content changes with depth and time, indicated that the root water uptake rate was greatest from the 50 to 100-cm soil depth on June 23 and was great enough to satisfy the atmospheric demand.

Figure 3 summarizes the results of this study in a manner comparable to relationships drawn from the literature of Denmead and Shaw (1962), Van Bavel (1967), and Ritchie et al. (1972). The results shown represent the actual to potential evaporation ratio as a function of the percentage extractable soil water calculated for each study. Soil water data of Van Bavel (1967) were calculated from the amount of water extracted from a profile during a drying cycle following flood irrigation until evaporation practically stopped. Soil water data of Ritchie et al. (1972) represents the amount of water extracted by plant roots of full-grown canopies of cotton and grain sorghum from

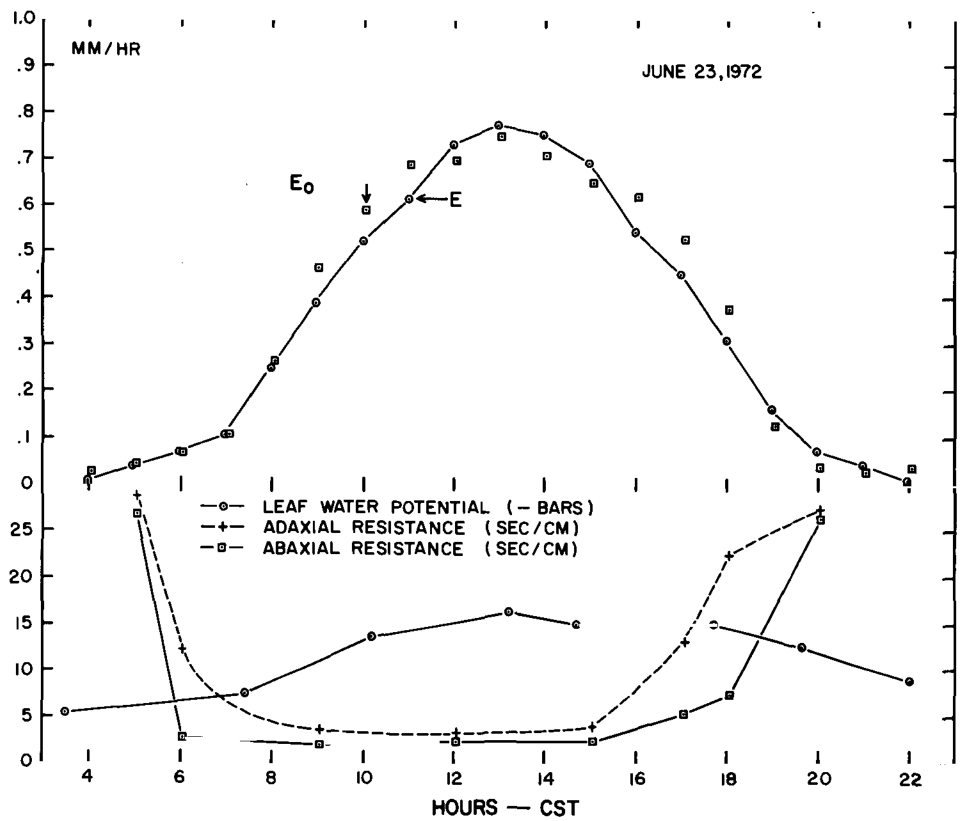

Fig. 2. Diurnal variation in actual and potential evaporation (upper part) and leaf water potential, adaxial resistance and abaxial resistance (lower part); June 23, 1972.

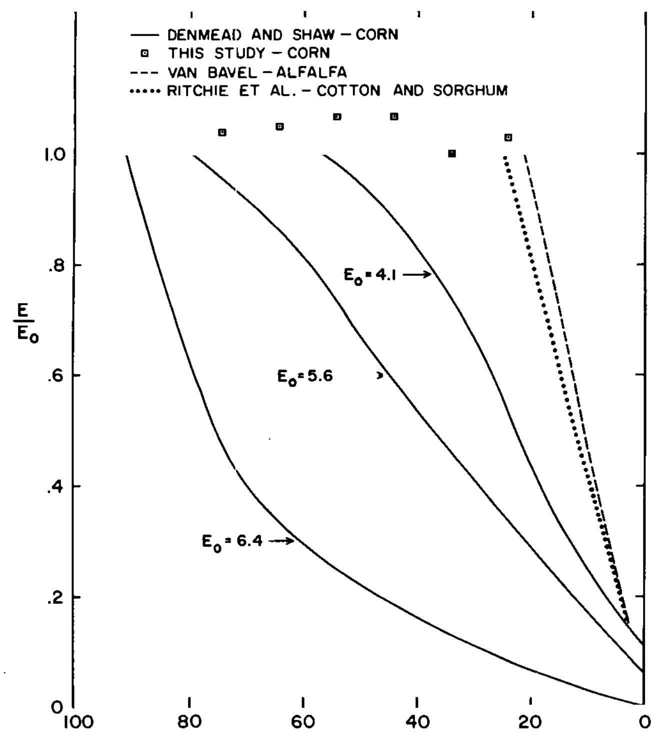

Fig. 3. Ratio of actual to potential evaporation (E/E_0) as influenced by the percentage of extractable soil water for four different crops (Denmead and Shaw, 1962; Van Bavel, 1967; Ritchie et al., 1972).

an initially wet soil profile until evaporation had practically stopped.

The results shown in Fig. 3 represent daily data taken only during the period when the leaf area index was 2.7 or greater. When the leaf area index is below 2.7, potential evaporation rates will not be obtained because of the partial canopy unless soil water is freely available at the surface (Ritchie and Burnett, 1971). The extractable water percentages in Fig. 3 were derived from the soil water amounts given in Fig. 1B and were based on a total of 25 cm of extractable water. The relative evaporation rates were averaged for each 10% soil water range and did not vary appreciably below unity, even when only 25% of the extractable soil water remained in the root zone. Potential evaporation may have been somewhat underestimated by equation [2], resulting in the average relative evaporation rate being slightly above unity during part of the season. Calculated potenital evaporation rates during most of this period were greater than 6 mm/day. These results, when compared with the curves of Denmead and Shaw (1962) for various potential evaporation rates varying from 6.4 to 4.1 mm/day, show that the amount of extractable soil water did not influence the evaporation rates nearly as much as the results of Denmead and Shaw's results implied. Unfortunately, the conditions of my study did not allow for measurement of the relative evaporation rate for extractable soil water below 20% when the leaf area index was greater than 2.7. However, the results imply that soil water deficit influenced corn evaporation in a manner similar to cotton and sorghum evaporation for the clay soil at Temple and to alfalfa evaporation for the clay loam soil in the study of Van Bavel (1967).

There are several possible reasons for a discrepancy between the results of this study and those of Denmead and Shaw. Experimental techniques for measuring actual and potential evaporation were different. In their tests, four plants were grown in 80-liter containers filled with topsoil. The containers were covered to prevent soil evaporation. Plant evaporation rates were inferred from change in soil water content of the container as measured with the neutron scattering technique. Potential evaporation rates were inferred from actual evaporation rates that were measured using containers of plants that were watered frequently. Even though their method of measuring evaporation was less precise than those in my study, it is doubtful that those experimental techniques accounted for the difference in plant evaporation response to soil water deficit as shown in Fig. 3.

In my opinion, the most probable reason for the difference between the results of these two tests on corn was the root-system differences. Because of the limited rooting volume in the study of Denmead and Shaw, the root density was likely to be greater than would be expected for field plant-root systems. At the planting density used by Denmead and Shaw, the average volume of soil supporting each plant root system was about $^1/_{12}$ the field soil volume with a rooting depth of 120 cm. Therefore, water uptake rate per unit soil volume was considerably greater from the container root systems and may have caused a plant water deficit to develop at a higher soil water content than would be expected for field root systems. The container roots were probably rather equally distributed throughout the soil volume and could be considered a static root system. In the field, root systems are more dynamic, unless a shallow water table or other barrier exists, and continually change their water uptake patterns in response to soil water deficits in the root zone. The roots of annual plants usually expand into deeper soil depths during rapid vegetative growth and take up water where resistance of soil water movement to root surfaces is least. Therefore, when much of the soil water has been used from the upper layer of soil, water uptake by the deeper roots is sufficiently great for potential evaporation rates to be obtained.

Another important reason for discrepancies between studies in containers and in field conditions is the possibility of upward water movement into the root zone from soil that is not or only slightly permeated with roots. Van Bavel, Brust, and Stirk (1968) found that when a sorghum crop was depleting water from the principal root zone, upward flux was as much as 4 mm/day at the 170 cm depth in a silty clay loam soil. The magnitude of the upward water flux into the root zone will depend on the soil hydraulic properties but cannot be ignored as a source of water contributing to evaporation from field grown plants.

When the threshold at which the soil water status begins to limit evaporation is reached, the resistance to water flow in the soil around each individual root (rhizosphere resistance) (Newman, 1969) becomes too great to allow sufficient root water uptake. When soil water deficits reach this threshold, the principles established by Denmead and Shaw are expected to be true, i.e., the rhizosphere resistance may limit evaporation on days when the potential evaporation is high, but not when the potential evaporation is low.

The results from this study, when combined with earlier work on cotton and grain sorghum at Temple by Jordan and Ritchie (1971) and Ritchie et al. (1972), point out the difficulty of attempting to use a single soil water content or soil water potential to describe the entire root environment of field plants. Because the rhizosphere resistance is dependent on 1) the density of water-absorbing roots, 2) the unsaturated hydraulic conductivity of the soil near the absorbing roots, and 3) the evaporative demand, these three factors interact to influence the actual evaporation rate. The first two factors are difficult to measure in the field. Ritchie and Jordan (1972) suggested an empirical equation that can be used for predicting evaporation rates when rhizosphere resistance becomes important. Coefficients in the equation were derived from field measurements of the soil and plant water status and from potential evaporation rates. There is a real need, however, for a more quantitative means of defining rhizosphere resistance under field conditions.

LITERATURE CITED

Denmead, O. T., and R. H. Shaw. 1962. Availability of soil water to plants as affected by soil moisture content and meteorological conditions. Agron. J. 54:385-390.

Flinn, J. C. 1971. The simulation of crop-irrigation systems. *In* J. B. Dent and J. R. Anderson (ed.) Systems analysis in agricultural management. John Wiley & Sons, New York.

Jordan, W. R., and J. T. Ritchie. 1971. Influence of soil water stress on evaporation, root absorption, and internal water status of cotton. Plant Physiol. 48:783-788.

Kanemasu, E. T., and C. B. Tanner. 1969. Stomatal diffusion resistance of snap beans. I. Influence of leaf-water potential. Plant Physiol. 44:1547-1552.

Kramer, P. J. 1969. Plant and soil water relations. A modern synthesis. McGraw-Hill Book Company, Inc., New York.

Norero, A. L., J. Keller, and G. L. Ashcroft. 1972. Effect of irrigation frequency on the actual evapotranspiration for various crop-climate-soil systems. Trans. Amer. Soc. Agr. Eng. 15:662-666.

Newman. E. I. 1969. Resistance to water flow in soil and plant. II. A review of experimental evidence on the rhizosphere resistance. J. Appl. Ecol. 6:261-272.

Penman, H. L. 1963. Vegetation and hydrology. Tech. Comm. 53, Commonw. Bur. Soils, Harpenden, Herts., England. 124 p.

Ritchie, J. T. 1971. Dryland evaporative flux in a subhumid climate. I. Micrometeorological influences. Agron. J. 63:51-55.

————, and Earl Burnett. 1971. Dryland evaporative flux in a subhumid climate. II. Plant influences. Agron. J. 63:56-62.

————, ————, and R. C. Henderson. 1972. Dryland evaporative flux in a subhumid climate. III. Soil water influence. Agron. J. 64:168-173.

————, and W. R. Jordan. 1972. Dryland evaporative flux in a subhumid climate. IV. Relation to plant water status. Agron. J. 64:173-176.

Rose, C. W. 1966. Agricultural physics. Pergamon Press, New York.

Scholander, P. F., H. T. Hammel, E. D. Bradstreet, and E. A. Hemmingsen. 1965. Sap pressure in vascular plants. Science 148:339-346.

Shaw, R. H. 1963a. Estimation of soil moisture under corn. Iowa State Univ. Sci. Tech., Res. Bull. 520:969-980.

————. 1963b. Prediction of soil moisture under oats for the spring period. Iowa State J. Sci. 37:417-424.

————. 1964. Prediction of soil moisture under meadow. Agron. J. 56:320-324.

Slatyer, R. O. 1967. Plant-water relationships. Academic Press, New York.

Turner, N. C. 1969. Stomatal resistance to transpiration in three contrasting canopies. Crop Sci. 9:303-307.

Van Bavel, C. H. M. 1967. Changes in canopy resistance to water loss from alfalfa induced by soil water depletion. Agr. Meteorol. 4:165-176.

————, K. J. Brust, and G. B. Stirk. 1968. Hydraulic properties of a clay loam soil and the field measurement of water uptake by roots. II. The water balance of the root zone. Soil Sci. Soc. Amer. Proc. 32:317-321.