

## WATER DYNAMICS IN THE SOIL-PLANT-ATMOSPHERE SYSTEM

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The water problem in agriculture is related both to weather and to the reserves of water in the soil that are available to plants. Water dynamics in the soil-plant-atmosphere system concerns the capacity of the soil water reservoir, its depletion and replenishment, and its efficient management for crop production.

The concept of the soil as a reservoir for water is appealing and useful. Since only a small amount of water can be stored in crop plants relative to the rate of transpiration through them, it is the storage of water within the soil pores that permits transpiration to continue for several days without recharge by rainfall or irrigation. However, water storage in the soil is not similar to that in a bucket. Some water may drain out of the root zone, and not all water remaining in a drying soil can be taken up by the plant as rapidly as it is needed because it is held too tightly by soil particles.

Although methods of determining the capacity of the soil water reservoir available to the plant are not exact, the concept permits calculations of the soil water balance and its impact on crop production.

Water-balance calculations using computers are becoming more common. There should be more emphasis on water-balance technology in the future because it is needed for accurate estimation of crop yields, early warning about food shortages, better farm management, reliable irrigation scheduling and water-resource planning, etc. Because of these urgent needs, it is important to develop models of the water balance that are as general as possible so that local calibrations are eliminated or at least minimized. Models should also not depend on the input of weather records that are difficult to obtain.

The dynamics of the soil-water balance requires separate understandings of the atmospheric, plant and soil-water factors which affect the soil water balance. These factors are interdependent but will be discussed separately for simplicity.

## ATMOSPHERIC INFLUENCE

The accuracy of estimating evaporation from soil and plants is of primary importance for reliable water-balance evaluations. Because climatic variables influence evaporation so strongly when adequate water is available, the proper combination of factors to estimate maximum evaporation ( $E_{\max}$ ) is important. In 1973, the American Society of Civil Engineers (ASCE) evaluated the accuracy of several equations for estimating  $E_{\max}$  from a wide variety of locations. The Society tested energy balance and aerodynamic combination equations, humidity-, radiation-, and temperature-based equations and some miscellaneous equations. The well-known combination equation of Penman and two other equations, somewhat similar to it, were superior because they had small errors, but some other equations were impressive. Although the report did not evaluate daily errors, experience has shown that temperature-, humidity-, or pan evaporation-based calculations give high daily errors but tend to become more accurate when records from several days up to an entire season are included as a single comparison.

One  $E_{\max}$  calculation method which the ASCE report did not discuss and which has gained popularity during recent years is an equation suggested by Priestley and Taylor (1972), based on a correlation found between what Priestley (1959) called equilibrium evaporation ( $E_{\text{eq}}$ ) and  $E_{\max}$ . The equation for  $E_{\text{eq}}$  is the same as the radiation term in Penman's combination equation,

$$E_{\text{eq}} = \frac{\Delta}{\Delta + \gamma} (R_n - G). \quad (1)$$

In this equation,  $\Delta$  is the slope of the saturation vapor pressure curve at mean air temperature ( $\text{mb}/^\circ\text{K}$ );  $\gamma$  is a psychrometric constant ( $\text{mb}/^\circ\text{K}$ );  $R_n$  is the net radiation at the canopy top ( $\text{mm}/\text{day}$ ), and  $G$  is the heat-flux density at the soil surface ( $\text{mm}/\text{day}$ ). Priestley and Taylor found that

$$E_{\max} = \alpha E_{\text{eq}}, \quad (2)$$

where  $\alpha$  averaged about 1.26 for climate with little advection when  $E_{\text{eq}}$  was determined from 24-hour  $R_n$  values and  $G$  was assumed to be zero.

There is little reason to use more complicated equations when the simpler ones such as equation 2 give more accurate and consistent results. However, the main disadvantage of equation 2 is that it does not account adequately for advection. Tanner and Jury (1976), Sumayao *et al.* (1978), and Meyer and Green (1980) have

proposed making  $\alpha$  variable when humidity is below or temperature is above certain threshold values. These empirical modifications provide equations that are somewhat similar to the Jensen and Haise (1963) radiation-based  $E_{\max}$  equations, where temperature is used to modify the radiation term. It is important to understand that  $E_{\max}$  cannot be calculated exactly, and that all equations are empirical and, therefore, need some calibration.

#### INFLUENCE OF PLANTS

Actual evaporation may not equal  $E_{\max}$  because of an incomplete crop canopy or a deficiency of water in the root zone. Use of a locally fitted crop coefficient to express the canopy cover through a crop-growth cycle has been commonly used to reduce  $E_{\max}$ , but two problems have prevented generality: (i) growing season times and durations shift because of variable weather and (ii) soil evaporation during partial plant cover varies greatly, depending on the wetness of the soil surface.

It is possible to separate soil and plant evaporation logically when we know the fraction of the energy intercepted by the plant canopy and the critical soil parameters (Ritchie, 1972; Tanner and Jury, 1976). Several attempts to use this logic have been successful, using measurements of leaf area index (LAI) to estimate the energy interception fractions (Al-Khafaf *et al.*, 1978; Kanemasu, 1976).

Measurements of LAI are important, but they are time consuming and many people have no records available. Short-cut procedures are possible for estimating plant-leaf area based on regression of leaf area per plant with more easily measured variables such as plant height, length of a certain leaf, number of leaves, and stem diameter.

An important development in crop modelling is that it appears possible to reasonably calculate plant leaf-area development. Rate of leaf appearance is closely coupled with plant temperature. When leaf sizes, numbers, and growth rates are known, it is possible to develop a logical system for LAI changes during a season, using only weather data required to calculate  $E_{\max}$ . Such a system has been described for development of the grain sorghum leaf (Arkin *et al.*, 1976).

Another possibility for gross evaluation of vegetative cover is through remote-sensing procedures. Allen and Richardson (1968) have proposed a theoretical possibility for remote sensing of LAI on the basis of differences between plant canopy reflectance and soil reflectance. Wiegand *et al.* (1979) demonstrated that three vegetational indexes derived from satellite data were correlated well enough with LAI to provide inputs to evapotranspiration (ET) models for LAI

values  $> 0.3$ . Use of remote-sensing techniques, however, would require frequent overflights during periods of rapid increases in LAI and might not be economically feasible.

#### INFLUENCE OF SOIL WATER

##### *Plant response to soil water deficits*

The response of crop economic yield to water deficits is a dynamic process and general quantitative relations are difficult to establish. Plant water stress can be induced (i) by a deficiency of water supply in the root zone, and (ii) by an excessive atmospheric water demand from leaves. In many crop production systems, variations in soil water deficits are the major cause of year-to-year variation in yield. Although many laboratory experiments and theoretical evaluations have demonstrated that high evaporative demand causes plants growing in a wet soil to show symptoms of water deficiency, such results seldom extrapolate to field conditions because the response often depends on the environmental history of the crop. As a result, experimental measurements of crop canopy photosynthesis, transpiration, or leaf extension growth usually do not show mid-day depressions caused by high evaporative demand at that time, unless the soil water in the root zone is depleted to less than 50 per cent of the total soil water extractable by plants. However, it is generally thought that short periods of high evaporative demand and high temperature during the critical periods of plant pollination or formation of reproductive organs can irreversibly reduce yield regardless of the soil water status, but convincing quantitative evidence is lacking.

The influence of the soil water deficit on crop behavior in the field has been the subject of many agronomic field trials, the results of which are often specific to the location, climate, crop, and soil. It has been almost impossible to generalize about plant response to water deficits using soil measurements such as soil water potential or water content. Consequently, many soil scientists have recently used plant measurements as indicators of crop response to water deficits.

Early field work on crop water status by agronomists and ecologists centered on the idea that leaf stomatal diffusion should be a primary measurable factor influenced by water deficits since stomatal closing is directly linked to both photosynthesis and transpiration. Diffusion resistance meters were developed (Kanemasu *et al.*, 1969), made commercially available and are now commonly used in many agronomic studies. Penman and Schofield (1951) developed an equation including vapor diffusion resistance to estimate transpiration when stomata were closed or partially closed. The main disadvantage of using stomatal

resistance has centered on the difficulty of deriving an integrated value of resistance for an entire canopy that is generally suitable for use in evaporation equations. Although stomatal resistance measurements have provided quantitative descriptions for research, they are not to my knowledge being used on a widespread operational basis to estimate crop performance characteristics or to determine when to irrigate. One possible reason for the lack of applicability of stomatal resistance measurements to crop performance is that the physiological

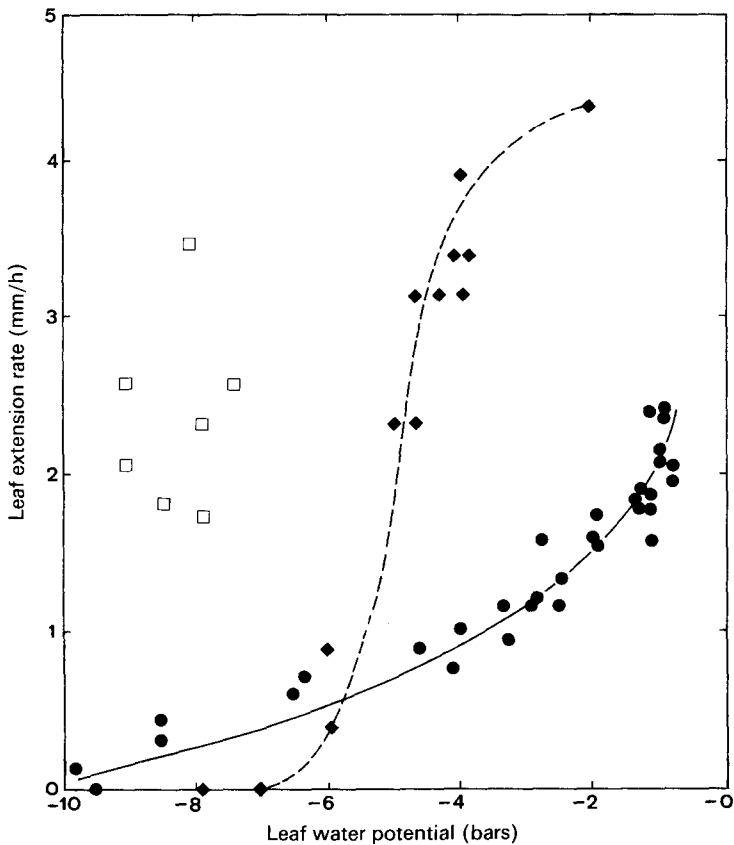


Fig. 1. Relationship between leaf extension and leaf water potential for corn growth in the field ( $\square$ ), or grown in controlled environment in the dark at 28°C ( $\bullet$ ), or in the light at 30°C ( $\blacksquare$ ). From Watts (1974).

processes of plant extension growth are more sensitive to plant water deficits than are the stomatal regulated processes (Hsiao, 1973) + hence, irreversible damage may have occurred in a crop before stomatal resistance measurements clearly indicate a change in plant conditions.

Another physical measurement which is sensitive to crop water deficit is the plant water potential. Like stomatal resistance, agronomists and ecologists began to make this measurement when the pressure chamber (Scholander *et al.*, 1965) was adapted for relatively simple use in the field. Problems in interpreting the results of plant water potential measurements in general, quantitative terms have almost paralleled those of stomatal diffusion. With both measurements, when atmospheric conditions are about constant day by day, little change occurs when soil water is being depleted until some threshold value is reached, following which the values usually change rapidly (van Bavel, 1967; Ritchie, 1973). Therefore, plant water potentials have limited value in estimating the onset of field water stresses for applications such as irrigation scheduling.

Evidence for the lack of a general relationship between leaf extension rate and leaf water potential in corn is shown in Figure 1 from data compiled by Watts (1974), who compared field and controlled environment data. When low night temperature does not reduce extension growth, leaf expansion continues day and night at fairly similar rates despite a usual diurnal change in leaf water potential from about  $-1$  to  $-9$  bars (Watts, 1974; McCree and Davis, 1974). Physiologists have suggested that this phenomenon is the result of a diurnal osmotic potential adjustment in the leaf, causing leaf turgor pressure to remain adequate for extension growth (Begg and Turner, 1976).

Leaf potential measurements just before sunrise appear to be generally related to daily extension growth. Pre-dawn potentials should give an idea of the integrated potential of the soil that affects plant extension growth because the plants have had long enough during the night when the transpiration is practically zero to recover to a potential in equilibrium with the root-soil system. Cutler and Rains (1977) found a fairly stable relationship between pre-dawn water potential and daily cotton leaf elongation. There was some variation in the relationship caused by levels of stress conditioning achieved by varying the frequency of irrigation during pretreatment periods.

The response of stomatal regulated processes to plant water deficits has been known for many years. However, it is generally recognized that stomata do not respond directly to leaf water potential until a critical threshold potential has been reached, after which stomata close over a narrow range of potentials and cause no further decrease in plant water deficit. Early work on these relationships implied that the critical potential threshold, when stomata would close, might

provide a species-specific parameter that would be valuable in quantitative evaluation of plant water deficits. However, field work reported in the 1970's has demonstrated that there is no unique leaf water potential causing stomatal closure. Begg and Turner (1976) presented evidence that this threshold leaf potential varies with position of the leaf in the canopy, age of the plant, and growth conditions such as the number of stress cycles or whether plants are grown in the field or in controlled environments. Jordan and Ritchie (1971) found that stomata closed rapidly at  $-16$  bar potential in cotton plants grown in a growth chamber, whereas stomata of field grown cotton plants subjected to a long water-drying cycle, did not close at the lowest measured leaf potential of  $-27$  bar. Similar differences in response have been shown for sorghum (McCree, 1974) and vines (Kriedemann and Smart, 1971). These findings further demonstrate the limitation of leaf water potentials as indicators of plant water deficits.

Thus far, I have pointed out that expansion growth is more sensitive than stomatal processes to plant water deficits. Other important processes such as cell division, leaf wilting or rolling, tillering, leaf abscission or partial death, seed filling, pollination, seed abortion and translocation, all have different sensitivities to plant water deficits, some of which are significant only during specific phases of plant development. Differences in sensitivity of plant processes to water deficits may be related to natural survival mechanisms. Primitive progenitors of modern crop plants were subjected to a great variety of climatic conditions and their adaptive mechanisms prevented extinction. While modern crops are grown in monocultures usually at higher plant populations per unit area than their progenitors, their varying degrees of sensitivity to water deficits show that they have retained the survival mechanism.

The differences in sensitivity of plant processes to water deficits may be the primary reason for the large difference between the responses of small container-grown plants and field-grown plants to soil water deficits. When water stress develops gradually in plants, as when plants grow on stored water from deep soils, the various processes affected at different times by the stress should become evident to the close observer. Unfortunately, there have been few field studies where more than one process has been evaluated during plant water stress (Hsiao, 1973).

However, when plants are grown in containers where watering is required every one to three days to prevent water stress, it is difficult to observe the varying stress responses because of insufficient time for various regulatory mechanisms to express themselves. Consequently great caution should be used when extrapolating the response of plants in containers to field conditions. An example of this

difference is the form of the relationship found between soil water and transpiration obtained experimentally in container-grown corn plants by Denmead and Shaw (1962) and that found for corn grown in a weighing lysimeter with a large soil volume (Ritchie, 1973). In the container study, transpiration was reduced under high evaporative conditions after a small fraction of the soil water was reduced, whereas in the large soil volume, transpiration was not reduced when as much as 70 per cent of the available water was extracted.

Ludlow and Ng (1976) found that the water relations of green panicum (*Panicum maximum*) grown in large pots in a growth room compared favorably with similar plants grown in similar sized pots in a field environment. The chambers were programmed to provide average values of outdoor daylength, maximum and minimum temperature, and relative humidity. Photosynthetically active radiation was 66 per cent of the outdoor value during three weeks without water. Threshold water potentials at which stomatal resistance increased and leaf elongation ceased were similar for both outdoor and growth room potted plants. Thus, it appears that growth room climates *per se* may be satisfactory for plant water deficit studies that may be extrapolated to field conditions if root volume is not restricted much more than under field conditions to ensure that the rate of onset of stress is not accelerated.

It is possible to obtain the small-container effect in the field when plants grow in shallow soil with low water-holding capacity because of the possibility of rapid stress. The rate of onset of stress is primarily affected by the water storage of the root zone; transpiration rate is secondary. To demonstrate the effect of the adaptive mechanism of osmotic adjustment, consider a crop canopy fully covering the ground growing in three soils having respectively, 1, 15, and 30 cm of extractable soil water in the root zone. Assuming a constant transpiration rate of 5 mm a day until plants had removed about 70 per cent of the extractable soil water, the water potential to which plants recover overnight (the pre-dawn value) would be expected to have relations similar to those shown in Figure 2a.

In the graph, recovery potentials of about  $-5$  bar represent zero to slight deficit, those between  $-5$  and  $-15$  bar, moderate deficits, and those below  $-15$  bar, severe deficits. The soil with 1 cm extractable water provides one day of no stress conditions, and the onset of stress is very rapid, lasting possibly only two more days until a severe stress. In this case, osmotic adjustment is minimal and plants would likely die because of the lack of time to adapt. For the soils with 15- and 30-cm extractable water, however, there would be a period of 24 and 50 days, respectively, with little stress and about 8 and 11 days with moderate stress. The stomatal-controlled functions for the three soil comparisons might provide patterns as shown in Figure 2b where the threshold leaf water potential for



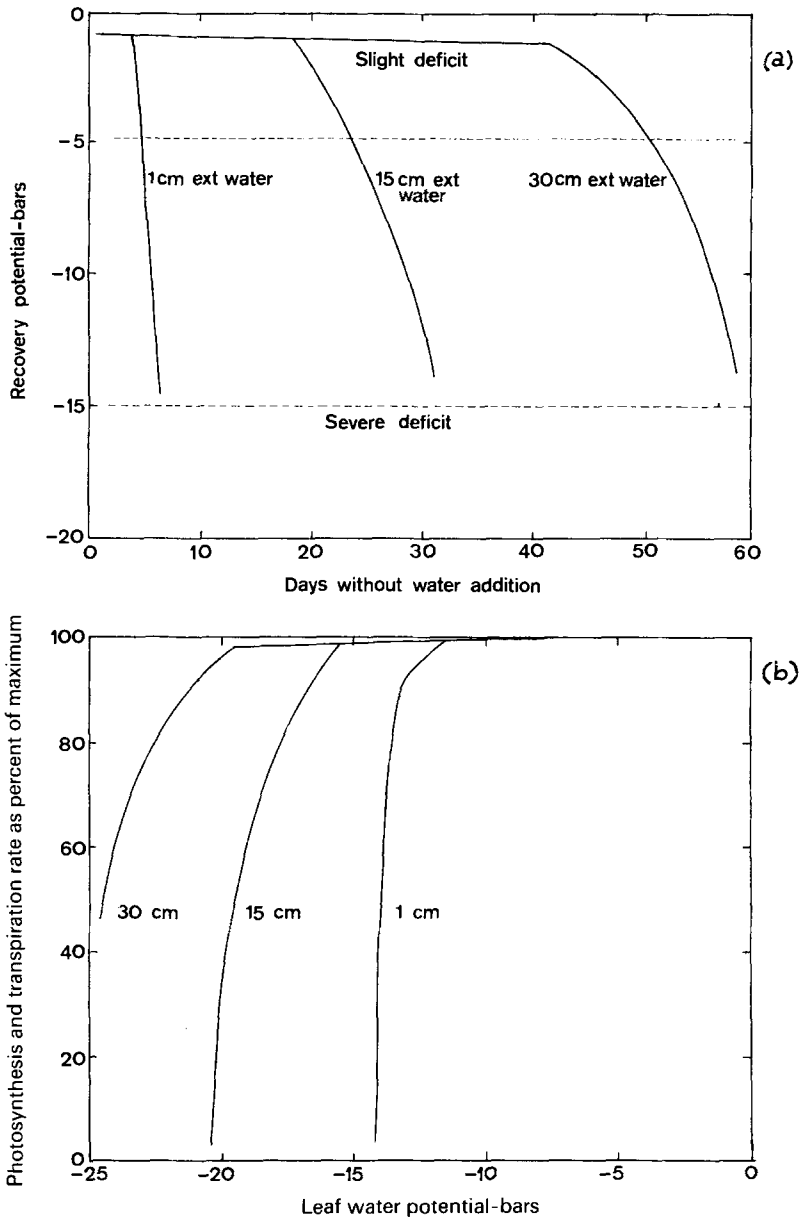


Fig. 2. Estimated plant water relations of a crop growing on stored soil water amounting to 1, 15 and 30 cm extractable water;  
 (a) the pre-dawn recovery potential as a function of time after water addition as related to extractable soil water and  
 (b) the influence of leaf water potential on relative photosynthesis and transpiration.

stomatal closure is at progressively lower values for larger soil water storage capacities. Evidence for such relationships is found in Jordan and Ritchie (1971) and Brown *et al.* (1976). Absolute threshold potential values where stomatal closure is obtained would be expected to vary with such things as species and leaf age, and the amount of adjustment should vary between drought-tolerant and drought-susceptible plants.

Because of the difficulty of using plant stomatal resistance or water potential measurements for operational purposes to determine the effect of water deficit on crop performance, empirical evaluation of various processes as related to soil water deficits should continue to be a useful option. However, recognizing that water stress causes variable responses for different physiological processes, a set of relationships needs to be established for each process for predictive purposes. Figure 3 represents a possible template for such an evaluation. The type of relationship shown in this figure is often used to estimate evapotranspiration (ET) reduction in response to soil water deficits. The general concept is that there is no reduction in the process being considered until the amount of extractable water in the entire root zone falls to some threshold value, following which the process is reduced in proportion to the extractable water.

From several analyses of the type shown in Fig. 3, it appears that threshold values for various physiological processes are about the same for many crops and soils. The diagram shows that the process of leaf elongation is more sensitive to

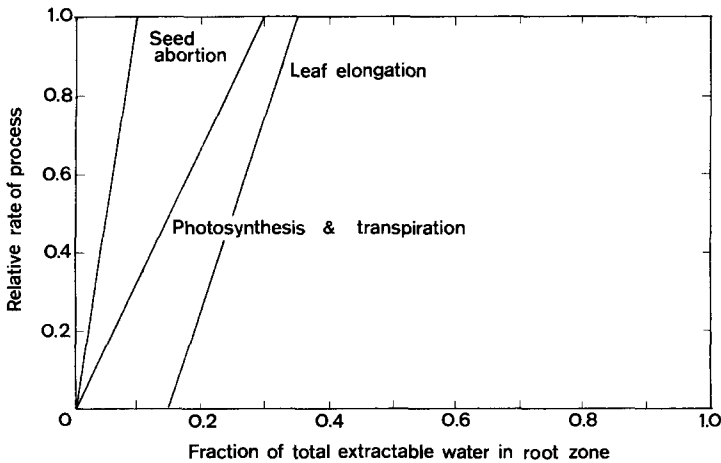


Fig. 3. Suggested possibilities for expressing the influence of extractable soil water on the relative rate of various physiological processes.

soil water deficits than other processes and that elongation stops even when some soil water remains. The sensitivity of processes regulated by stomata is less than that of elongation. Processes like seed abortion occur only under a very severe stress. Other processes such as seed filling, leaf senescence, tillering and root extension can be similarly evaluated but the rate of some processes is reduced in very wet soil when aeration is poor.

For ET estimation, all daily records of  $ET/E_{max}$  from accurate, weighing lysimeters in the field fit within the concept shown for transpiration in Fig. 3, with some deviation in the threshold soil water fraction where  $ET/E_{max}$  falls below 1 (see van Bavel, 1967; Priestley and Taylor, 1972; Ritchie *et al.*, 1972; Nkemdirim and Haley, 1973; and Meyer and Green, 1980). The exact point of the threshold water content is difficult to distinguish and is usually extrapolated from measurements taken when  $ET/E_{max}$  is clearly reduced by drought. The zero point for extractable soil water usually has to be extrapolated from measurements above that point because plants are likely to lose much of their leaf area within the extremely dry range and soil evaporation may then become a significant part of ET. In this dry range, plants undergo drastic changes in their natural adaptation for survival.

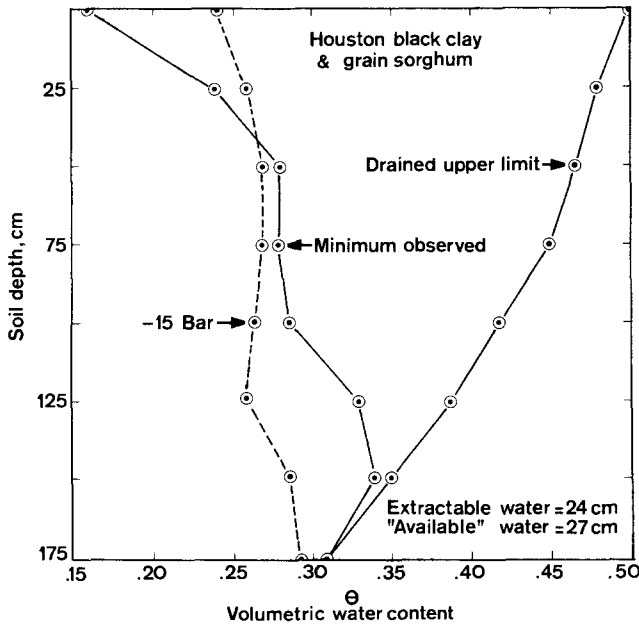


Fig. 4. Graphic representation of the relationship between extractable soil water and the ratio of actual evapotranspiration (ET) to maximum evaporation ( $E_{max}$ ).

A practical problem concerned with establishing relationships of the type shown in Fig. 3 is the evaluation of the soil extractable water. Traditionally, agronomists use water available in the root zone between field capacity and wilting point. Problems associated with this definition include determining values for root zone depth, field capacity, and wilting point, and soil bulk density for all soil depths in the root zone where physical properties change. When soil water potentials measured in the laboratory are used to define field capacity and wilting point, there are uncertainties about which potential to choose for the limit, especially for field capacity.

The concept of extractable water was introduced as a practical means of eliminating some of the problems of the available water concept. The extractable water is defined as the difference between the highest measured volumetric water content in the field (after drainage) and the lowest measured water content when plants are very dry and leaves are either dead or dormant. Extractable water thus defined is preferred to the traditional available water lower limit because it weights root distribution. This definition eliminates the need for doing soil water content/potential relationships for each soil depth where physical properties change. Field measurements of the total extractable water are often less variable spatially than available water estimated from water content-potential measurements.

Fig. 4 illustrates the distinction between extractable water and available water for Houston Black Clay. Available water integrated for the entire profile gave 3 cm more water than measured, about half of the water used during the phase of decreasing ET.

Another problem of using soil water in the root zone to estimate  $ET/E_{max}$  occurs when the soil water reservoir is partially refilled after a very dry condition and the additional water does not fill the root zone reservoir above the threshold water content where  $ET/E_{max} = 1$ . In this case, the added water remains near the surface where root density is greatest and provides a soil water status which is satisfactory for good plant turgor, although the entire root zone water content is low.

When  $ET/E_{max} < 1$ , estimating transpiration from the type of relationship shown in Fig. 3 implies that ET is a function of extractable soil water and  $E_{max}$ . In practice,  $E_{max}$  becomes less important the drier the soil, and factors affecting water transport in the soil-plant system become more important limitations on transpiration. The analysis of this dynamic problem has received much theoretical and experimental attention. None of the proposed models has been widely used and several technical problems must be clarified before general models can be developed. Some technical problems include (i) quantification or estimation of

the root density in soil, (ii) accurate evaluation of water flow to roots with large soil conductivity and potential differences surrounding roots, (iii) quantification of radial and axial root conductivities, (iv) role of the gap between the soil and root surface, and (v) quantification of the water potential in the root xylem system and at the root surface.

### *Infiltration*

Accurate water-balance modelling also requires an estimate of the amount of water infiltration into the soil from precipitation or irrigation. The amount of water that infiltrates into the soil is governed by a diversity of variables; the major ones being the amounts and rates of precipitation, soil type, amount and type of vegetative cover, land slope, surface roughness, and initial soil water content. Frozen soils add another variable to infiltration problems. The most commonly used approach to estimating infiltration is through statistical models fitted to experimental data. These models are usually developed with the sole aim of optimizing the prediction by use of appropriate regressions.

Infiltration has also been studied through physical models. Physicists usually seek to advance understanding of hydrologic processes through use of models which embody, as fully as possible, our knowledge of the physical processes. The statistical strategy may yield a useful predictive system, but such an approach ignores the physical processes and is often useless for extrapolation outside the area where experimental data have been taken. The physical strategy often leads to an intolerably complicated model with limited usefulness and high labor requirements to characterize the real system and its initial stage.

I believe that a general and useful infiltration model must take advantage of the statistical strategy by fitting 'rationally' empirical expressions to functions with physical meaning. A promising possibility for a relatively simple physically based model for infiltration is the optimal prediction of the time between initiation of rainfall and the initiation of surface runoff, or ponding time (Smith and Parlange, 1977). The technique requires inputs of soil conductivity at saturation and sorptivity.

Infiltration equations that require precipitation data for less than 24-hour periods may not be useful for many operational models because of the lack of short term rainfall data. Because of this constraint, it may not be possible to model infiltration accurately with a single general approach.

#### INCREASING AVAILABLE SOIL WATER THROUGH MANIPULATION OF ROOTS

Incomplete extraction of apparently available soil water can result in limitations of productivity in many rainfed agricultural regions. Enhancement of deep rooting is a possibility for increasing the availability of soil water. Genetic variability in root growth rates and field rooting patterns has been demonstrated in several crops (Hurd, 1974; Jordan *et al.*, 1979; Jordan and Miller, 1980; O'Brien, 1979; Taylor *et al.*, 1978). If deep rooting genetic materials can be combined with high yielding ones, the result could have a beneficial impact on production in areas where deep soil water is available and replenishable on an almost annual basis. If additional photosynthate is necessary to form and maintain deeper root systems, the trade-off for higher yields may not be possible. Also, the water status of plants taking up water from deep in the soil may be adversely affected and thus reduce production potential.

There have been no clear field demonstrations of benefits derived from breeding plants for deeper root water extraction. Measurement of roots and receipt of rainfall during the drying cycle causes experimental difficulties. However, in my opinion, the possibilities of increasing available water through developing plants with deeper root systems deserves considerable additional research as a means of increasing production in dry regions.

#### CONCLUSIONS

Although precise definitions of the two concepts for the upper and lower limits of soil water availability are limited by the dynamics of the soil-plant-atmosphere system, the use of these rough limits helps greatly in evaluating the impact of soil water balance on crop production. Estimates of extractable water determined in the field overcome several problems associated with definitions of the upper and lower limit and provide a measure of the soil water reservoir which is useful in estimating the influence of soil water deficits on important processes coupled with plant growth and yield.

Physical measurements such as stomatal conductance and water potential, while they are sensitive to plant water deficits, have proven to be of limited value in operational use because they lack sensitivity under marginal conditions of stress when some growth processes are restricted.

Much is yet to be learned about the dynamics of water in the soil-plant-atmosphere system. A specific strategy to guide research to meet future production demands requires close linkage between scientists of several disciplines, especially plant breeding, plant physiology, climatology, and soil and crop

management. Multidisciplinary teams will be required to meet the challenge of the future to produce optimum crop production systems that avoid or tolerate plant water stress.

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