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CHAPTER 1

WATER CONSUMPTION BY AGRICULTURAL PLANTS

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I. INTRODUCTION

Water consumption by agricultural plants normally refers to all water evaporated from plant and soil surfaces plus that retained within plant tissues. However, the amount of water retained within the tissue of agricultural plants generally is less than 1% of the total evaporated during a normal growing season. Therefore, water consumption as used in this chapter essentially involves water evaporated from plant and soil surfaces.

Several definitions are presented below to clarify terminology used in this chapter, although it does not differ materially from other terminology in this book.

Transpiration is the loss of water in the form of vapor from plants. All aerial parts of plants may lose some water by transpiration, but most water is lost through the leaves in two stages: (1) evaporation of water from cell walls into intercellular spaces, and (2) diffusion through stomates into the atmosphere. Some water vapor also diffuses out through the epidermal cells of leaves and the cuticle. Small amounts of cuticular transpiration may take place in herbaceous stems, flower parts, and fruits.

Evapotranspiration is the sum of water lost by transpiration and evaporation from the soil or from exterior portions of the plant where water may have accumulated from rainfall, dew, or exudation from the interior of the plant.

Consumptive use is, for all practical purposes, identical with evapotranspiration. It differs by the inclusion of water retained in plant tissues. For most agricultural plants, the amount of water retained by plants is insignificant when compared to evapotranspiration.

II. HISTORICAL ASPECTS

A major stimulus for water requirement studies has been the development of irrigation in the western United States. Irrigation has been practiced for many centuries in other countries, and there is no doubt that some investigations of water requirements can be traced back hundreds of years. Irrigation was also practiced for centuries in the southwestern United States before the Spaniards arrived (Golzé, 1961). The Spaniards began irrigating crops in New Mexico in 1598. Irrigation of small tracts of land began along many rivers of the western United States in the middle of the nineteenth century and expanded throughout this area during the latter part of that century. Numerous studies on water requirements of crops were initiated during this period, reflecting the importance of this information to irrigated agriculture.

The early mechanisms permitting research on water requirements of agricultural crops in the United States were established more than 100 years ago. On May 15, 1862, Lincoln signed "an act establishing the United States Department of Agriculture," and on July 2, 1862, he signed "an act donating public lands to the several States and Territories which may provide colleges for the benefit of American agriculture and the mechanic arts" (Knoblauch *et al.*, 1962). In 1887 the Hatch Act was passed, establishing agricultural experiment stations. This act gave immediate impetus to irrigation research at a number of agricultural experiment stations in the West. These studies frequently involved the assessment of water requirements for agricultural crops.

During the period from 1890 to 1920 the term "duty of water" was used extensively to describe the amount of water being used for irrigation. This term was in general use in the western United States in the 1890's and appears to have originated in Europe, since a number of books on irrigation written in England, France, and Italy during the nineteenth century were cited by Carpenter (1890). Mead (1887) summarized the "duty of water" as determined at Fort Collins, Colorado, where irrigation water applied to wheat, barley, oats, corn, and garden crops was measured during the summer of 1887. Extensive data on water applied to crops such as alfalfa, corn, flax, oats, peas, potatoes, rye, sugar beets, timothy, and wheat, obtained from 1893 to 1898 in Wyoming, were summarized by Buffum (1900). Similar studies were started in Utah in 1890 (Mills, 1895). Such studies expanded throughout the West when funds were provided for irrigation investigations in the Appropriation Act of 1898 (Teele, 1905, 1908). Most of these studies primarily involved the measurement of water delivered to irrigated farms.

Plot and field studies were established during this era to determine the relation between the quantity of water used and crop returns and losses of water by evaporation and percolation through soils (Widstoe *et al.*, 1902; Fortier, 1907; Teele, 1908; Fortier and Beckett, 1912). The primary objective of the plot and field studies was to determine seasonal consumptive use by soil-sampling techniques. Widstoe (1912), e.g., made detailed studies in Utah from 1902 to 1911 on 14 crops. Harris (1920) summarized 17 years of study in the Cache Valley, Utah. Lewis (1919) conducted similar studies near Twin Falls, Idaho, from 1914 to 1916. Hemphill (1922) summarized the studies conducted in the Cache LaPoudre River Valley of northern Colorado. Israelsen and Winsor (1922) made detailed "duty of water" determinations in the Sevier River Valley of Utah from 1914 to 1920. A discussion of the determination of consumptive use by various experimental techniques was presented by Hammatt (1920). An excellent summary of seasonal consumptive use of water can be found in the progress report of the Duty of Water Committee of the Irrigation Division, ASCE "Consumptive Use of Water in Irrigation," presented in 1927 and later published (anonymous, 1930).

Probably the most widely recognized classic investigation of water use by agricultural plants was the transpiration study of Briggs and Shantz (1913, 1914). They initiated extensive experiments at Akron, Colorado, to determine the relative water requirements of crops. These studies were made using small containers in which 44 species and varieties were grown in 1912 and 55 species in 1913. The exposure of these crops was varied. In some experiments a screened area was used to protect the plants from hail and birds. Other experiments were conducted in the open and some with the containers placed in trenches. Because of the observed differences in transpiration, depending on exposure, the data from these studies were not considered as unique values for these plants. Briggs and Shantz (1914) stated that "the water-requirement measurements must therefore be considered relative rather than absolute." This basic relationship between the loss of water through transpiration and the dry matter produced was recognized one-half century ago, but it still is often misinterpreted—even in more recent studies or applications in the 1960's.

Briggs and Shantz also obtained meteorological data, including minimum and maximum air temperatures, wind speed, rainfall, evaporation, sunshine, sun and sky radiation, and wet-bulb depression. They recognized that solar radiation was the primary cause of the cyclic change of environmental factors (Briggs and Shantz, 1916a). Radiation incident on plants exposed to direct sunlight was corrected to an equivalent horizontal area. Advected energy or heat energy extracted from warm air was determined and recognized as a contribution to the energy utilized in transpiration. They stated that "even on bright days, therefore, other sources of energy such as the indirect radiation from the sky and from surrounding objects and the heat energy received directly from the air, contribute materially to the energy dissipated through transpiration" (Briggs and Shantz, 1916b). Other investigators also began studying the influence of various meteorological factors on evaporation and transpiration (Harris and Robinson, 1916; Widstoe, 1902, 1909, 1912).

This summary illustrates the change in the type of studies underway in the western United States from merely the measurement of water delivered to farms in the late 1800's and early 1900's to studies of factors causing and affecting water loss from 1900 to 1920. During the next two decades emphasis was placed on the development of procedures for estimating seasonal consumptive use of water, using available climatological data.

Some of the problems associated with crop yields and consumptive use relationships were recognized in the 1920's. For example, the ASCE Duty of Water Committee recognized that yields may be reduced by plant diseases and insects without significantly affecting seasonal consumptive use. The difficulty in obtaining the same environmental conditions around pots or containers as exist in ordinary cropped land was recognized. Also, the influence of abnormal environmental conditions on consumptive use was recognized as being great enough to render questionable the pot method of determining consumptive use. Drainage from the soil profile following infrequent heavy irrigations or frequent light irrigations was recognized as a probable source of error when soil sampling methods were used. Many consumptive use data in the literature determined by soil sampling or using the neutron moisture meter obviously include a significant drainage component.

The emphasis on factors controlling transpiration expanded extensively during the middle of the twentieth century. The energy balance concept—applied in estimating evaporation from water surfaces in the 1920's and the 1930's (Bowen, 1926; Cummings and Richardson, 1927; McEwen, 1930;

Richardson, 1931; Cummings, 1936, 1940; Kennedy and Kennedy, 1936)—was applied to crop surfaces in the 1940's by Penman (1948) and Budyko (1948). Penman combined the energy balance equation and an aerodynamic equation into what now is commonly referred to as the combination method (see Chapter 4, Volume I). The Penman equation, or equations of the Penman type, have been evaluated throughout the world. The meteorological measurements required for the combination method are mean air temperature, dew-point temperature, mean wind speed, and net radiation. On a field basis, water losses from soil and plant surfaces can be conservatively approximated more readily by using an energy balance or a combination approach than by any of the other available methods relating the evaporation and transfer of water to the atmosphere, such as the Dalton equation or aerodynamic equations. A detailed discussion of the characteristics of these methods is presented in Chapter 4, Volume I.

This brief summary of progress in assessing water requirements by agricultural crops, beginning with crude measurements of water applied to fields, is not all inclusive, but it illustrates the trend of early studies and progress made throughout the world. The general relationships of consumptive use to climate still need refinement for developing efficient irrigated agriculture and for maximizing the development of water resources. Detailed studies involving the biochemistry and internal processes within the plants as influenced by the state of water within the plant are currently underway.

III. DETERMINING EVAPOTRANSPIRATION

A detailed discussion of evaporation from plant and soil surfaces as related to micrometeorological parameters and a summary of various methods of calculating evaporation using energy balance or mass transfer concepts are presented in Chapter 4, Volume I. Other methods are also used. The most common method of determining water requirements of agricultural plants under natural environmental conditions for 5- to 20-day periods is by soil moisture depletion. This method has been used extensively in irrigated areas of the world and in the western United States for more than 70 years. The major problems encountered in soil sampling are summarized in Chapter 5, Volume I. The precautionary measures needed to minimize errors in evapotranspiration determinations using soil moisture depletion techniques follow: (1) the sampling sites must be representative of the general field conditions; (2) depth to a saturated zone should be much greater than the root zone depth; (3) only those sampling periods where rainfall is light should be used—all others are questionable because drainage may be excessive; and (4) drainage should be minimized by (a) applying the preplant irrigation at least 10 to 30 days before planting, (b) controlling irrigation so as to apply less water than can be retained within the effective root zone, (c) waiting at least 2 days after normal light irrigations before taking the first sample (longer periods are required if excessive irrigations or high soil moisture levels are involved and when evapotranspiration rate is small), and (d) using only the effective root zone depth or the depth to the plane of zero hydraulic gradient (Jensen, 1967a).

A summary of lysimeters for measuring evapotranspiration is also presented in Chapter 4, Volume I. The major sources of unreliable data obtained with lysimeters are as follows: (1) the vegetative and soil moisture conditions in the lysimeter may not be comparable to those of the surrounding crop; (2) the effective leaf area for the interception of radiation and transpiration may be greater than the surface area of the lysimeter, i.e., the foliage may extend beyond the perimeter of the lysimeter or extend above the surrounding crop; and (3) the edge of the lysimeter may represent an excessively large proportion of the surface area of the lysimeter, resulting in unrealistic border effects caused by the lysimeter itself, which can influence the microclimate in the plant–air zone. When properly installed, operated, and instrumented, lysimeters provide the most accurate measurement of evapotranspiration. This is especially true under high rainfall conditions, because the probable error resulting from drainage increases with other methods such as soil moisture depletion techniques.

Meteorological methods for determining evapotranspiration are being used increasingly as a result of the tremendous development of electronic instrumentation during the 1950's and 1960's. A thorough discussion of these techniques is presented by Webb (1965) and in Chapter 4, Volume I. In general, the instrumentation and technical skill requirements limit these methods to detailed research studies or comprehensive operational studies at a few locations.

IV. CLIMATIC REGIMES

A. Potential Growing Seasons

The climatic regime and the potential growing season control the type of agricultural crops that are grown and, consequently, greatly influence the annual or seasonal water use by agricultural crops. In general, seasonal water use is greater with long growing seasons than with short ones (Milthorpe, 1960; Penman, 1963).

A detailed classification of climates of the world and their agricultural potential is presented by Papadakis (1966). Three climatic regimes are presented in Fig. 1 to illustrate the range of climatic conditions encountered in agricultural areas. Obviously, the potential growing season at Maiquetia, Venezuela, is all year long primarily because of proximity to the Equator and

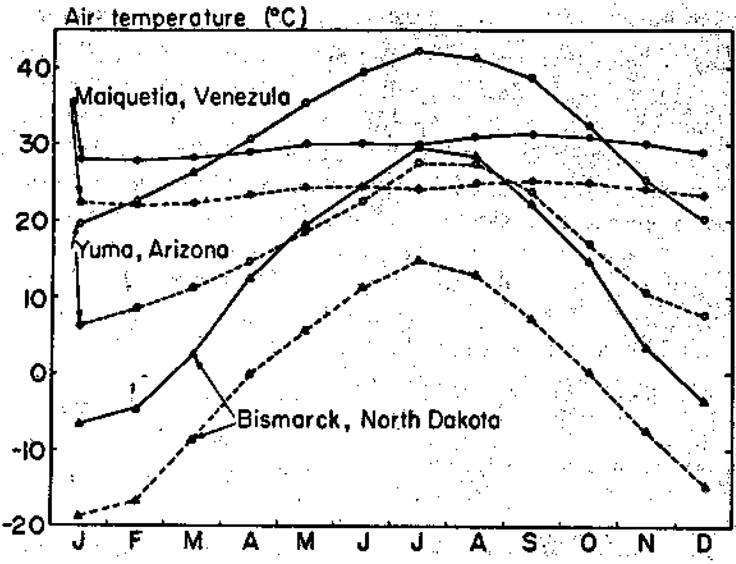

Fig. 1. Monthly mean maximum and mean minimum air temperatures.

the Caribbean Sea. Mean monthly solar radiation at this location varies from a low of 400 cal cm^{-2} day^{-1} in December to 530 in July.

Papadakis classified the climate at Maiquetia, Venezuela, as dry, semi-hot tropical and at Yuma, Arizona, as hot subtropical desert. The latitude at Yuma is 33.7°N as compared to 10.5°N at Maiquetia. Clear skies are common at Yuma; consequently, there is a much greater variation in monthly mean daily solar radiation—varying from a low of 270 cal cm^{-2} day^{-1} in December to 700 in June. The mean minimum temperature at Yuma would indicate that crops may be grown all year long. However, winter temperatures have reached −5°C and, thus, some crops may be subject to frost damage. Monthly mean maximum and mean minimum temperatures at Bismarck, North Dakota (Fig. 1), obviously restrict the potential growing season to the period from mid-April to mid-October. The probability of a late frost in the spring or an early frost in fall further limits the growing season for many farm crops in that area. The usual planting dates for barley and oats in North Dakota range from April 15 to June 5, whereas harvest dates for sugar beets generally range from September 10 to October 20 (Burkhead *et al.*, 1965).

B. Potential Evapotranspiration

Potential evapotranspiration, as used in this chapter, represents the upper limit of evapotranspiration that occurs with a well-watered agricultural crop that has an aerodynamically rough surface such as alfalfa with 30–50 cm of top growth. Potential evapotranspiration so defined occurs in either humid or arid areas in fields that are surrounded by sufficient buffer area so that the edge or "clothes line" effect is small or negligible. The width of the buffer strip required to minimize the edge effect may be only 30 m or less for most short, closely spaced field crops. A detailed theoretical discussion, supported by experimental data, of the horizontal transport of heat and moisture in the 16-m zone is presented by Rider *et al.* (1963). The effect of regional advection of heat or the "oasis" effect would be included in the term as defined because most irrigation projects and most farm fields are subjected to these conditions during parts of the growing season. For comparative purposes, evapotranspiration from well-watered short grass generally would be less than potential evapotranspiration as used here.

Estimates of potential evapotranspiration E_o for the three locations previously mentioned using solar radiation and mean air temperature are presented in Fig. 2. The curves approximate the mean daily upper limit of evapotranspiration that can occur from a well-watered, aerodynamically rough crop that is actively growing throughout the season. Potential evapotranspiration for a 10-day period in any one year may exceed these mean values for such locations as Bismarck, North Dakota, where climatic conditions may vary widely from one week to the next. In contrast, during the summer months at Yuma, Arizona, there is very little variation in climatic

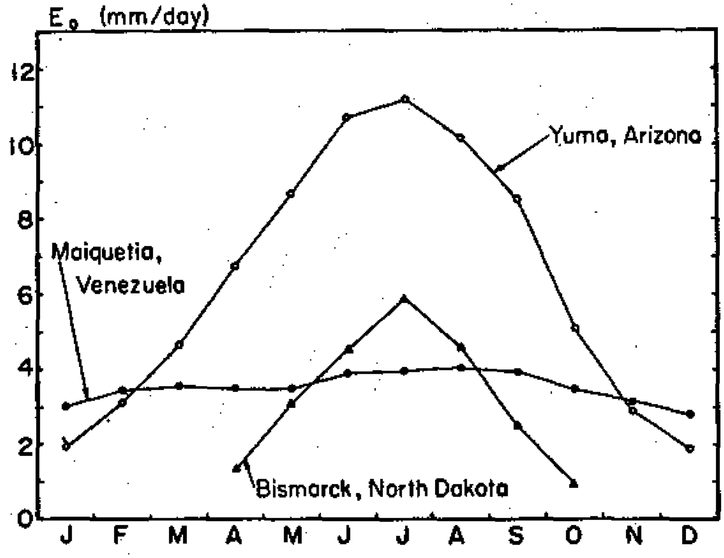

Fig. 2. Monthly mean potential evapotranspiration (E_o). From Jensen (1967b).

conditions from week to week. In general, larger variability in day-to-day solar radiation occurs more often in semihumid and humid areas (oftentimes with only small changes in air temperature) than in arid areas. An analysis of the frequency of daily solar radiation in July for three locations by Jensen (1967b) indicated that daily solar radiation deviated only ±10% from the long-time mean 20 days of the month at Phoenix, Arizona. In contrast, the deviation was ±24% at a Florida location and ±32% in Wisconsin.

Seasonal evapotranspiration for most common farm crops will be less than the potential because the soil may be completely bare for some time prior to planting, leaf area is limited as the seedlings emerge and develop, and the effective resistance to transpiration increases as the crop begins to mature.

Meteorological parameters controlling potential evapotranspiration, as illustrated in Fig. 2, indicate that crops such as small grains would not necessarily require the same amount of water when grown in different regions under widely different climatic conditions or when grown at different times during the year at a given location. Thus water requirements of a crop cannot be discussed without considering the crop season and potential evapotranspiration at various stages of plant growth.

C. AGRICULTURAL CROPS AND POTENTIAL EVAPOTRANSPIRATION

A simple analytical model of evaporation from soil and plant surfaces would be very useful in a discussion of water consumption by agricultural crops. However, even the most elementary model of this system, involving parallel and series hydraulic and diffusive resistances to water flux, heat sinks, and heat and vapor sources, and operating under conditions involving both spatial and time changes as well as "feedback" effects, can be unwieldy, as evidenced by the simplified ohm's law model presented by Cowan (1965). Models of this system, such as those discussed by Monteith (1965) and Tanner in Chapter 4, Volume I, are extremely useful in describing the general influence of diffusive resistance to water vapor transfer from the leaves to the atmosphere on evapotranspiration. As long as the limitations and pitfalls of using simplified one-dimensional models for quantitative inferences and estimates discussed by Philip (1966) are recognized, models can be effectively used for many purposes.

Individuals forced to manage this complex system often must rely on extremely simple but rational relationships for estimating evapotranspiration. One such relationship, which is based on the concept of potential evapotranspiration and a crop coefficient, is presented here. The basic meteorological parameter required is potential evapotranspiration as previously defined. The reference crop must have a root system that is fully developed, sufficient leaf area so as not to materially limit transpiration, and adequate soil moisture so that evapotranspiration is essentially limited by meteorological conditions. Potential evapotranspiration could be calculated by one of several methods discussed in Chapter 4, Volume I, or it could be measured with one or two good lysimeter installations in the general region under consideration. Because of the conservativeness of potential evapotranspiration and areal uniformity (with the exception of areas adjacent to large water bodies or major orographic changes), accurate determinations at a few locations would be preferred over numerous crude determinations throughout the area of interest. Evapotranspiration for a given agricultural crop can be related to potential evapotranspiration E_o as follows:

$$E_t = K_c E_o \tag{1}$$

in which K_c is a dimensionless coefficient, similar to that proposed by van Wijk and de Vries (1954), representing the combined relative effects of resistance to water movement from the soil to the evaporating surfaces, resistance to diffusion of water vapor from the evaporating surfaces through the laminar boundary layer, resistance to turbulent transfer to the free atmosphere, and the relative amount of radiant energy available as compared to the reference crop.

From an energy balance viewpoint, the crop coefficient represents the relative heat energy converted to latent heat. Thus, K_c is related to the major energy terms of the soil–plant–air continuum as follows:

$$K_c = (R_n + A + G)/(R_{no} + A_o + G_o) \tag{2}$$

in which R_n is net radiation, A is sensible heat flux to or from the air, and G is sensible heat flux to or from the soil. The subscript o designates concurrent values for the reference crop in the immediate vicinity (in this case alfalfa). The energy terms are positive for input to the crop air zone and negative for outflow. Of the energy terms, only sensible heat flux is difficult to determine or predict. However, it is related to the overall effective hydraulic and diffusive resistance of the soil–plant–air system. The energy terms of the energy balance equation can be rewritten using the Bowen ratio approach from which

$$K_c = \frac{1 + \beta_o}{1 + \beta} \frac{(R_n + G)}{(R_{no} + G_o)} \tag{3}$$

where β represents the partitioning of latent and sensible heat flux (the ratio of sensible heat flux to latent heat flux) or the Bowen ratio, A/LE (see Chapter 4, Volume I). The magnitude of $(1 + \beta)$ is largely controlled by the overall resistance to the transfer of soil water to water vapor in the free atmosphere.

The overall resistance to water flow from the soil to plant roots and through the plant, as well as to the soil surface, the resistance to diffusion of water vapor through the leaves and the dry surface layer of soil, the laminar boundary layer, and the resistance to turbulent transfer of water vapor to the free atmosphere all indirectly affect the magnitude of G and to some extent R_n. When evaporation from the soil is negligible compared to transpiration, the hydraulic resistance to water flow to the roots would be inversely proportional to hydraulic conductivity of the soil and the length of roots per unit volume of soil (Gardner, 1966). Visser (1965) and Gardner and Ehlig (1963) presented similar analogies of soil resistance. Monteith (1965) presented a detailed analysis of the influence of the diffusive resistance of a crop on transpiration. Until quantitative values are available for calculating the influence of various soil and crop resistances, crop coefficients K_c can be determined from experimental data for estimating purposes.

A typical example of the influence of growth stage on the crop coefficient where soil water is not limiting is shown in Fig. 3 (Jensen, 1967b). The data in

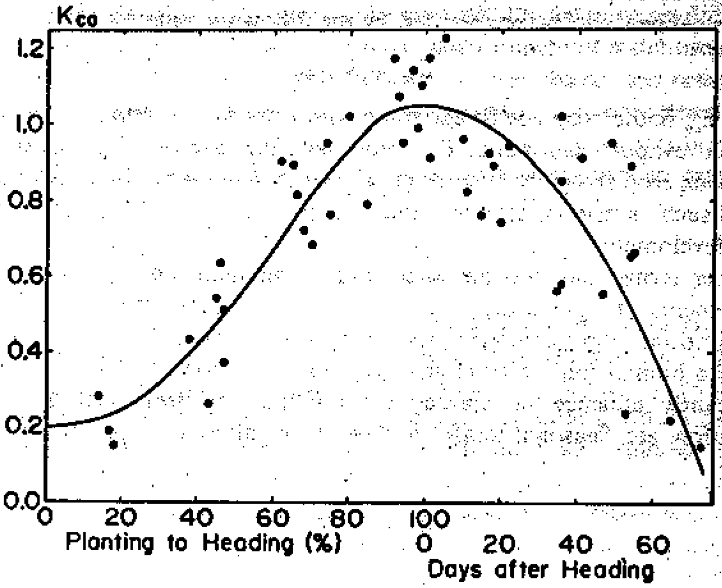

Fig. 3. Crop coefficients (K_{co}) for grain sorghum.

Fig. 3 illustrate primarily the relatively large diffusive resistance of bare soil immediately after planting. The resistance decreases during the period of rapid leaf-area development, approaching an effective overall resistance (and net radiation) similar to that of alfalfa (estimated potential evapotranspiration in this case) near heading and then increases as the crop matures after heading. A similar curve for corn was presented by Denmead and Shaw

(1959) and a curve for soybeans by Laing (1965, from Shaw and Laing, 1966) using evaporation from a pan as an estimate of evaporative demand.

D. Crop Evapotranspiration (Water Nonlimiting)

Since most farm crops do not require as much water during the season as would be needed to meet potential evapotranspiration, even though adequate soil moisture is provided, an additional term is desired to differentiate water requirements of agricultural crops when water is not limiting from water use when soil moisture may be limiting during a portion of the season. This term can be referred to as "crop potential evapotranspiration," E_{oc}. The magnitude of this term generally will be less than potential evapotranspiration during much of the season, as previously indicated, primarily because of limited plant canopy during a portion of the season and the overall increase in resistance to evaporation as the crop matures. Crop potential evapotranspiration, as defined, can be represented by the following equation:

$$E_{oc} = K_{co} E_o \tag{4}$$

where K_{co} is the crop coefficient when soil water is *not* limiting. Thus, crop potential evapotranspiration, E_{oc}, represents the rate of evapotranspiration for a given crop at a given stage of growth when water is not limiting and other factors such as insects, diseases, and nutrients have not materially restricted plant development.

Other terms that become important in planning and discussing water requirements of agricultural crops are seasonal totals of potential evapotranspiration, crop potential evapotranspiration, and actual evapotranspiration with limited soil moisture at some stages of growth or other factors that significantly influence the characteristics of the crop itself, such as diseases, defoliation, etc. Seasonal totals for these three values are represented by Eqs. (5)–(7):

$$W_o = \int_{t_1}^{t_2} E_o \, dt \tag{5}$$

$$W_{oc} = \int_{t_1}^{t_2} E_{oc} \, dt = \int_{t_1}^{t_2} K_{co} E_o \, dt \tag{6}$$

$$W_{ct} = \int_{t_1}^{t_2} E_t \, dt = \int_{t_1}^{t_2} K_c E_o \, dt \tag{7}$$

When considering seasonal totals, t_1 and t_2 in Eqs. (5)–(7) represent the dates of planting and harvest. The totals for a portion of a growing season, or for periods including evaporation from the soil before and after the crop growing season, can be obtained by integrating over the entire time interval. The seasonal total potential evapotranspiration will vary with the meteorological conditions during a given growing season. The total crop potential evapotranspiration will also vary with seasonal meteorological conditions, but in addition it will be influenced by the date of planting within the growing season and date of harvest or freeze near the end of the season. Water use by barley, e.g., is about 40 cm in North Dakota and about 55 cm in Arizona (Haise, 1958; Woodward, 1959).

V. CROP CHARACTERISTICS AND EVAPOTRANSPIRATION

A. Plant Effects

Characteristics of agricultural plants, such as number and distribution of stomata, leaf coatings, etc. discussed in Chapters 6 and 7, Volume I, can affect evapotranspiration for a given crop primarily by influencing diffusive resistance. For example, in a recent analysis and estimate of water use by an orange orchard, van Bavel *et al.* (1967) concluded that the canopy resistance to evaporation is considerable in citrus orchards, resulting in evapotranspiration much below the potential rate. Similarly, other plant characteristics such as wilting and maturation can influence the effective resistance to evaporation.

B. Root and Soil Effects

The volume of soil occupied by plant roots and the number of roots within this volume can significantly influence effective soil resistance to water movement. This subject is discussed in detail in Chapter 5, Volume I. Obviously, evapotranspiration with a deep-rooted crop such as alfalfa would not be influenced as much by the removal of a given amount of soil water as with a shallow-rooted crop such as grass. Characteristics of the soil profile that may severely restrict the volume of soil occupied by a dense root system would also result in greater changes in the crop coefficient as soil moisture decreased. Shaw and Laing (1966) presented data illustrating the relative transpiration rate as a function of soil suction in Colo silty clay loam. These data indicate that the relative transpiration rate, or K_c, for corn was also influenced by the evaporative demand. This effect is also represented in Eq. (3). For example, the turgor loss point at low potential evapotranspiration rates occurred at higher soil water matric potentials than at high potential rates. Loss of turgor would increase the effective diffusive resistance and the Bowen ratio. Also, if the evaporative demand were large, the effective soil resistance would increase more rapidly with a limited root system as compared to a crop with a deep, dense root system such as alfalfa.

C. PRECIPITATION EFFECTS

For a row crop with a partial canopy, the effective diffusive resistance would be large when the soil surface is dry. However, immediately following a light rain, the plant surfaces and the surface of the soil between plant rows would be wet and effective diffusive resistance would be greatly decreased. In addition, the albedo of the wet soil surface would decrease, thereby increasing relative net radiation. Obviously, the crop coefficient as given by Eq. (3) would not remain constant at a given stage of growth under these conditions. Under arid conditions, experimentally determined mean crop coefficients at given stages of growth can be effectively used to estimate water use by various crops because of infrequent light rains. Even when rains occur, the soil surface dries within 3 days or less. Crop curves representing K_{co} at various stages of growth would be similar for semihumid areas except for the mean value under partial cover, and as the crop matures K_{co} might be larger than those under arid conditions because of more frequent rains and smaller variations in the Bowen ratio.

D. PERENNIAL CROPS

The effective diffusive resistance for perennial crops decreases in the spring when new growth begins, or when new growth begins after a period of dormancy. The effective diffusive resistance during dormancy, or when climatic conditions are such that growth does not take place, will generally be much higher. Consequently, the potential crop coefficient for a perennial crop would be small during a period of dormancy.

Other factors also influence water use by perennial crops. A common cultural practice, e.g., that significantly affects water use is cutting. Cutting alfalfa drastically changes the effective diffusive resistance, although for a short time period after cutting evaporation from the soil surface may compensate for the decrease in transpiration. Bahrani and Taylor (1961) found that evapotranspiration decreased following the cutting of alfalfa. The decrease in this case was attributed to less net radiation as surface soil temperature increased. Irrigation of alfalfa that had previously been cut increased net radiation.

Another situation that is encountered is a two-stage agricultural crop such as a deciduous orchard with an alfalfa cover crop. The potential crop coefficient K_{co} would be small because of high effective diffusive resistance before the trees leaf out and before alfalfa begins to grow in the spring. However, as the season progresses the effective diffusive resistance would decrease markedly with the development of leaves and growth of the cover crop. The two-crop combination would probably increase the effective aerodynamic roughness of the surface, thus decreasing the effective resistance to turbulent transfer of water vapor. Analysis of evapotranspiration data from an apple orchard with an alfalfa cover crop indicates that the crop coefficient may be as high as 1.2. The increase in the crop coefficient above 1 can be attributed largely to a smaller resistance to turbulent transfer, resulting from greater aerodynamic roughness of the two-level crop, and a smaller effective diffusive resistance because of the larger leaf-area and distribution of evaporating surfaces above the soil surface as compared to alfalfa alone.

E. ANNUAL CROPS

The discussion in Section V, A–D covered various aspects of perennial crops and their influence on resistance to evapotranspiration. These effects can be grouped into three broad categories: (1) The influence of degree of crop cover or canopy that influences diffusive resistance. (2) The maturation of the crop, including the development of seed heads above a crop that can influence evapotranspiration by decreasing the proportion of net radiation converted to latent heat of vaporization. For example, Fritschen and van Bavel (1964) reported that absorption of net radiation by the seed head protruding above a crop of Sudan grass resulted in a greater portion of net radiation being converted to sensible heat. (3) Cultural practices such as the frequency of irrigation can influence the effective diffusive resistance. Frequent light irrigations of a row crop that keep the soil surface moist decrease the effective diffusive resistance. One would expect the crop coefficient to be larger on widely spaced row crops under these conditions as compared with infrequent heavy irrigations where the soil surface may remain dry for extensive periods of time.

The spacing of row crops can also affect the crop coefficient during early stages of leaf development. Porter *et al.* (1960) reported that more water was used early in a season with narrow row spacings than with wide row spacings. Differences in total water use among either the spacing or planting rate means for the entire season were insignificant.

VI. EVAPOTRANSPIRATION WITH SOIL WATER NONLIMITING

A. FULL-SEASON CROPS

A brief summary of water use by alfalfa in two widely different climatic regimes is presented in Table I to illustrate the small effects of limited leaf area early in the spring and cuttings during the season on seasonal evapotranspiration. The sample data indicate that seasonal water use by a perennial crop such as alfalfa may be about 90% of potential evapotranspiration.

The decrease primarily results from higher diffusive resistance when growth first begins in the spring and immediately following a cutting as compared to a reference crop without cutting.

TABLE I

MEAN WATER USE BY ALFALFA AND POTENTIAL EVAPOTRANSPIRATION

Location	W_{et} (cm)	W_{e} (cm)	$\frac{W_{et}}{W_{e}}$
Bismarck, North Dakota[a]	58	66	0.88
Phoenix, Arizona[b]	188	214	0.88

[a] Haise (1958).
[b] Erie *et al.* (1965).

B. PART-SEASON CROPS

Grain sorghum is an example of a crop that is planted after the potential growing season begins and is harvested before the potential growing season ends. Jensen and Sletten (1965) reported mean seasonal evapotranspiration (from planting to harvest) for grain sorghum at Bushland, Texas, to be 55 cm, whereas potential evapotranspiration for the same period averaged 84 cm. The data for a row crop such as grain sorghum, which undergoes large changes in leaf area along with changes in crop characteristics as the seeds develop, fill, and mature, indicate that seasonal evapotranspiration may be only 65% of potential evapotranspiration. Similarly, data presented by Ripley (1966) indicate that seasonal water use by many farm crops may range from 55 to 75% of potential evapotranspiration if alfalfa water use is 90% of the potential.

C. CITRUS CROPS

Water requirements of citrus orchards are generally much lower than for crops such as alfalfa, providing the soil surface is kept bare (Jensen and Haise, 1963). Van Bavel *et al.* (1967) evaluated canopy resistance of an orange orchard near Tempe, Arizona, by direct and indirect techniques. They found that the resistance may vary from 3.4 to 7.6 sec cm^{-1} as compared with 0.3 to 0.5 sec cm^{-1} for field crops reported by Monteith (1965). Mean annual evapotranspiration for clean-tilled grapefruit orchards in Arizona was estimated as 115 cm (Jensen and Haise, 1963). Thus, annual evapotranspiration for a high-resistance canopy crop may be only 55% of mean annual potential evapotranspiration.

D. OFF-SEASON LOSSES

Loss of soil water before planting and after harvest of an annual crop may vary greatly, depending on cultural practices involved. For example, weeds allowed to grow following the harvest of a crop such as winter wheat (approximately June in the southern Great Plains) can significantly increase the amount of water lost prior to preparation of a seed bed and planting of the next crop. The causes for these losses are obvious and are discussed in Section V. The loss of water with weed growth is normally greater than under fallow conditions as a result of (1) smaller diffusive resistance and (2) smaller effective soil hydraulic resistance because of weed roots. Losses of water under fallow conditions also may be high because of high rates of evaporation from the soil surface immediately following light rains. Numerous data in the Great Plains from Texas to Canada indicate that the amount of water remaining in the soil after a fallow period may be only 15–30% of the total precipitation received during the period.

VII. EVAPOTRANSPIRATION WITH LIMITED SOIL WATER

As the soil water content decreases and is not replenished by rainfall or irrigation the effective hydraulic resistance increases greatly. This increase in hydraulic resistance results in various degrees of plant water stress, depending on the evaporative demand and plant characteristics. At high plant water stress, diffusive resistance also increases, illustrating the interdependence of hydraulic and diffusive resistances. Seasonal water use is related to the soil water available at planting, seasonal precipitation, and root penetration. Dreibelbis and Amerman (1964) presented data illustrating the importance of root penetration on water use under dryland conditions. These aspects are covered in Chapters 5 and 7, Volume I and are discussed by Black (1966) and Viets (1962, 1966).

A simple expression linearly relating effects of plant water stress caused by inadequate soil water on yields would be desirable for two general types of crops: (1) those having a determinate type of flowering such as a grain crop and (2) crops such as grass that can tolerate severe stress for a period of a week during the growing season and completely recover following application and maintenance of adequate soil water during the remainder of the season with only a small decrease in total dry matter production. A detailed discussion of the effects of water stresses on physiological processes within the plant is presented in Chapter 3.

A. DETERMINATE CROPS

The effects of limited soil moisture (resulting in reduced water use during a growth stage) on the development of the marketable product of a determinate flowering crop can be linearly related to yields by the following expression, providing other factors such as plant nutrients are not limiting:

$$\frac{Y}{Y_o} \simeq \prod_{i=1}^{n} \left(\frac{W_{et}}{W_{ec}}\right)_i^{\lambda_i} \tag{8}$$

where Y/Y_o represents the relative yield of the marketable product from an agricultural crop (Y_o is the yield when soil moisture is not limiting); $(W_{et}/W_{ec})_i$ represents the relative total evapotranspiration during a given stage of physiological development, e.g., the boot stage or heading stage of a crop such as small grain or sorghum (W_{et} is the actual use of water and W_{ec} is the use if soil moisture was not limiting); and λ_i represents the relative sensitivity of the crop to water stress during the stage of growth i. The right side of Eq. (8) is a product. Therefore, severe water stress, as indicated by reduced water use, during a single growth stage could reduce the yield of the marketable product severely. The magnitude of λ for specific growth stages would depend primarily on the sensitivity of plant growth to water stress during each growth period. The primary implication of Eq. 8 is that the yield of the marketable product of a farm crop may not be linearly related to total water use when plants are stressed. Jensen and Sletten (1965) found that delaying irrigations of

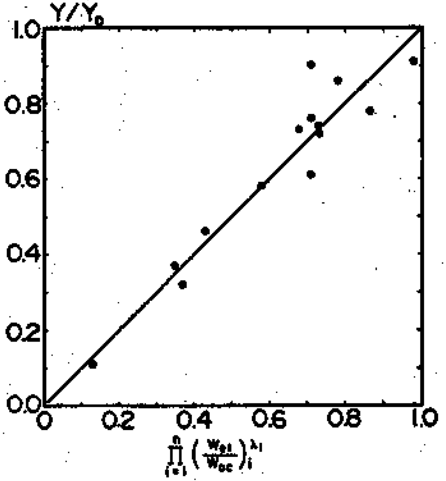

Fig. 4. Relative yield of grain sorghum (Y/Y_o) vs. the product of relative water use (W_{et}/W_{ec}) during various growth periods.

grain sorghum reduced yields an average of 35% but reduced water use only 20%. Similarly, delaying irrigations so that yields were reduced 70% reduced water use only about 40%. Equation (8) was evaluated using the same data with values of W_{et}/W_{oc} approximated from soil moisture data, precipitation, and irrigations (see Fig. 4). Three periods were used: (1) emergence to boot stage with $\lambda = 0.5$, (2) boot to milk stage with $\lambda = 1.5$, and (3) milk to harvest with $\lambda = 0.5$. The results indicate that Eq. (8) may adequately represent the effects of water stress as indicated by reduced water use on yields of a determinate crop. A detailed discussion of water stress during various physiological stages of growth on reproduction and grain development is presented by Shaw and Laing (1966).

The yield of other crops that must meet minimum quality characteristics, e.g., potatoes and lettuce, and for which specific growth stages may have significant effects would be also, probably, linearly related to relative water use by Eq. (8). Detailed discussions of water stress and physiological processes are also presented in Chapter 3.

B. INDETERMINATE CROPS

An expression linearly relating the marketable yield or dry matter produced by an indeterminate crop, such as grass, to water use when soil moisture is limiting, providing other factors such as plant nutrients are not limiting, is as follows:

$$\frac{Y}{Y_p} \simeq \frac{\sum_{i=1}^{n} \lambda_i (W_{et})_i}{\sum_{i=1}^{n} \lambda_i (W_{oc})_i} \tag{9}$$

DeWit (1958) presented a detailed analysis of dry matter production vs. relative transpiration (transpiration/free water evaporation) that generally would substantiate Eq. (9) even though W_{oc} is used in Eq. (9) instead of free water evaporation. The primary difference between Eqs. (8) and (9) is that in Eq. (9) the effects of water stress on yield during a specific growth stage are independent of other growth stages.

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