CHAPTER

28

Potential Evapotranspiration

The term *potential evapotranspiration* (PET) must be defined when we talk of evapotranspiration (ET). *Evapotranspiration*, as defined by the Soil Science Society of America (2008), is the "combined loss of water from a given area, and during a specified period of time, by evaporation from the soil surface and by transpiration from plants". The concept of PET was put forth by Thornthwaite (1948), an American, and Penman (1948), an Englishman. We will use the definition of Rosenberg (1974, p. 172), noting that his definition is similar to that of Penman. (For a biography of Penman, see the Appendix, Section 28.5.)

28.1 DEFINITION OF POTENTIAL EVAPOTRANSPIRATION

Rosenberg says that potential evapotranspiration (abbreviated as ETP by him, but as PET by most others) is "the evaporation from an extended surface of [a] short green crop which fully shades the ground, exerts little or negligible resistance to the flow of water, and is always well supplied with water. Potential evapotranspiration cannot exceed free water evaporation under the same weather conditions".

In fact, we know that real (actual) ET differs from the potential under most circumstances. The reasons for these differences are best explained by reference to the conditions imposed by the definition of PET and by an analysis of the reality of these conditions. We follow the discussion of (Rosenberg 1974, pp. 172−178), even though we could use other references (e.g., Chang, 1968; pp. 129−144).

28.2 FACTORS THAT AFFECT POTENTIAL EVAPOTRANSPIRATION

First, let us look at the influence of *extended surfaces* (or what is called the influence of *fetch*) on PET. An extended surface has great

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(if unspecified) fetch. Fields should be at least 20 m from their centers in any direction from which the wind blows. However, in some experiments, it has been found that temperature profiles to 5 m, even at 200 m from the edge of a field, are not fully adjusted to the new surface. Any visible difference in plant growth along the border of a field is evidence of inadequate field size for measuring PET within the meaning of the phrase "extended surface" (Rosenberg, 1974, p. 172).

Second, let us look at the influence of crop height. Many of the important crops grown worldwide are not short: corn, sorghum, winter and spring grains, cotton, and trees. The taller the crop, the more effective is its exchange of energy with the ambient air. Alfalfa (called lucerne in England) should fit the definition of a "short crop", but studies have shown that the quantities of water evaporated by this crop increase with increasing crop height (Figure 28.1). We know also that the type of leaf influences the ET rate and that, all things being equal, broad-leaved plants will transpire more than the grasses (Rosenberg, 1974, p. 172).

Third, let us look at the influence of crop cover. Row crops do not normally shade the ground fully except in some cases at advanced stages in their development. Nor do the broadcasted crops such as alfalfa shade the ground for some time after periodic cuttings. We know that water use may continue to increase with increasing leaf area, even when leaf area great enough to shade the ground completely has been achieved. Brun et al. (1972), for example, showed that in soybean and sorghum fields the

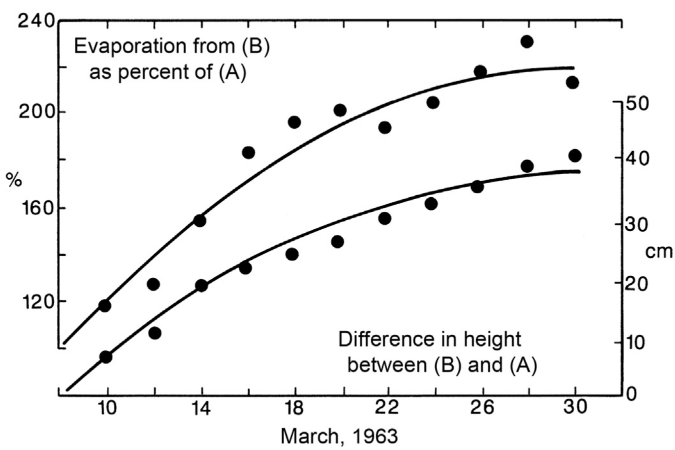

FIGURE 28.1 Evapotranspiration from lysimeters, with similar exposures, but where crop of alfalfa (lucerne) was kept clipped short in one (A), but allowed to grow in height in other (B). Evaporation rates from (B) increased to more than double those from (A) as crop in (B) grew to 42 cm higher than in (A). Both lysimeters were surrounded by areas of alfalfa of similar heights to crops growing in them. *From Chang (1968), Figure 81. Reproduced by permission of Dr Jen-Hu Chang.*

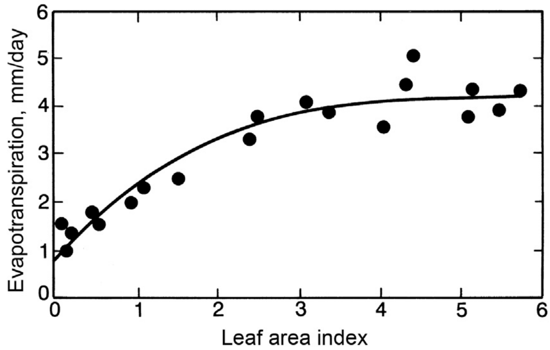

FIGURE 28.2 Relationship between leaf area index and evapotranspiration. *From Chang (1968), Figure 71, p. 130. Reproduced by permission of Dr Jen-Hu Chang.*

proportion of water lost, as transpiration increases, is closely correlated to leaf area index, with transpiration being approximately 50% of the total ET at a leaf area index of two. This proportion increases to 95% of the total ET at a leaf area index of four. [*Leaf area index* is defined as the area of leaves above a unit area of ground taking only one side of each leaf into account (Monteith, 1973, p. 52).] Figures 28.2 and 28.3 show relationships between ET and leaf area index (Chang, 1968, p. 130; Ritchie, 1972).

Fourth, let us look at the influence of the internal plant resistance to water flow. The concept of PET assumes that plants behave passively as wicks for the transport of water from the soil to the air. However, plants can close their stomata and increase the resistance to water flow. Under well-watered conditions, some plants appear to have low resistances.

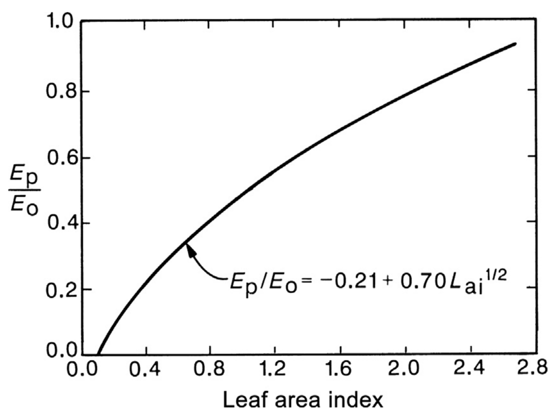

FIGURE 28.3 The plant evaporation, E_p, relative to the potential evaporation, E_o, as influenced by leaf area index, when the soil-water is not limited. *From Ritchie (1972), American Geophysical Union. Reproduced by permission of American Geophysical Union.*

Alfalfa is one of these plants. Cold weather, however, has an interesting effect on the resistance of the alfalfa crop, as shown in Figures 28.4 and 28.5 for two days, April 21 and 22, respectively. Evapotranspiraton (LE) was greatly reduced on April 22 (Figure 28.5) after a cold night. Thus, even if alfalfa is well watered, its stomata appear to close when temperatures fall (Rosenberg, 1974).

Fifth, let us look at the influence of soil-water availability. Obviously, in the case of range-land and dry-land agriculture, plants are not always well supplied with water. This can be the case in irrigated agriculture also, inadvertently or by intention. When the water supply becomes limited, it

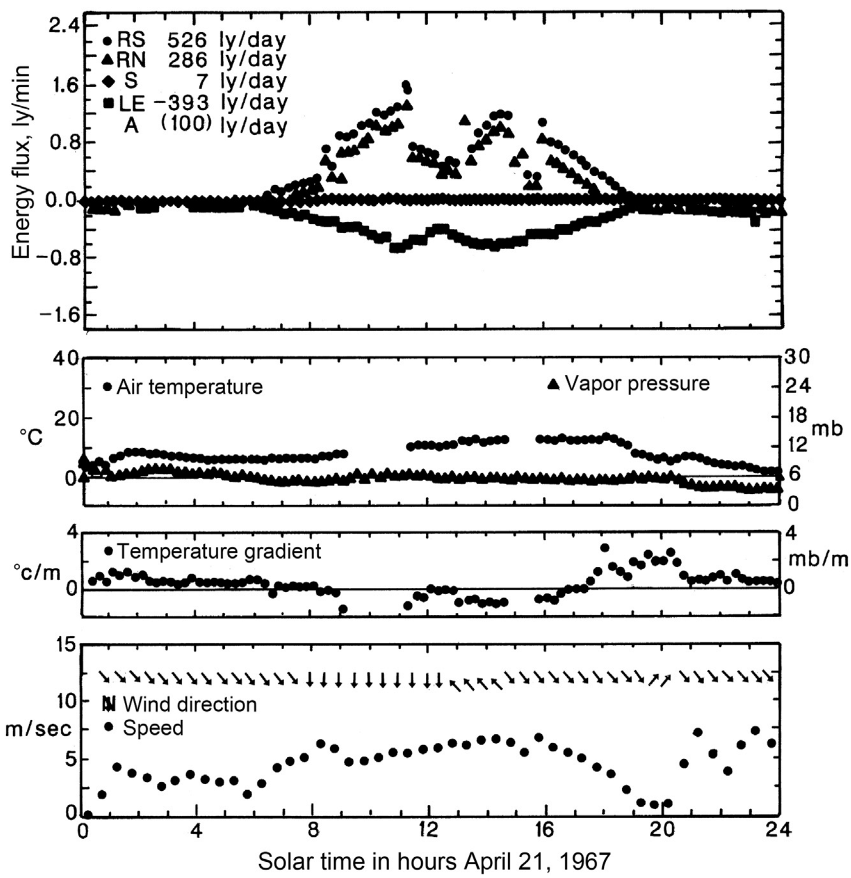

FIGURE 28.4 Energy balance with lysimetrically measured evapotranspiration from alfalfa at Mead, Nebraska, April 21, 1967. Air temperature and vapor pressure measured at 100 cm; gradients between 45 and 100 cm; wind speed at 200 cm. RS = solar radiation; RN = net radiation; S = soil heat flux; LE = evaporation; A = sensible heat flux. *From Rosenberg (1974), p. 174. This material is used by permission of John Wiley & Sons, Inc.*

is important to get the greatest yield per unit of water expended. For this reason, water is often added at critical stages of growth. Most annual crops are especially sensitive to water shortage from the time of flower initiation, during flowering, and to a lesser extent, during fruit and seed development (Salter and Goode, 1967, p. 192). We know that strategic irrigation at certain periods in the growth cycle of a crop, such an anthesis, may lead to great increases in yield.

The definition of PET states that the crop is "well supplied with water". Therefore, with decreasing soil moisture availability, ET will be reduced below the potential (Figures 28.6, 28.7, 28.8, 28.9, and 28.10).

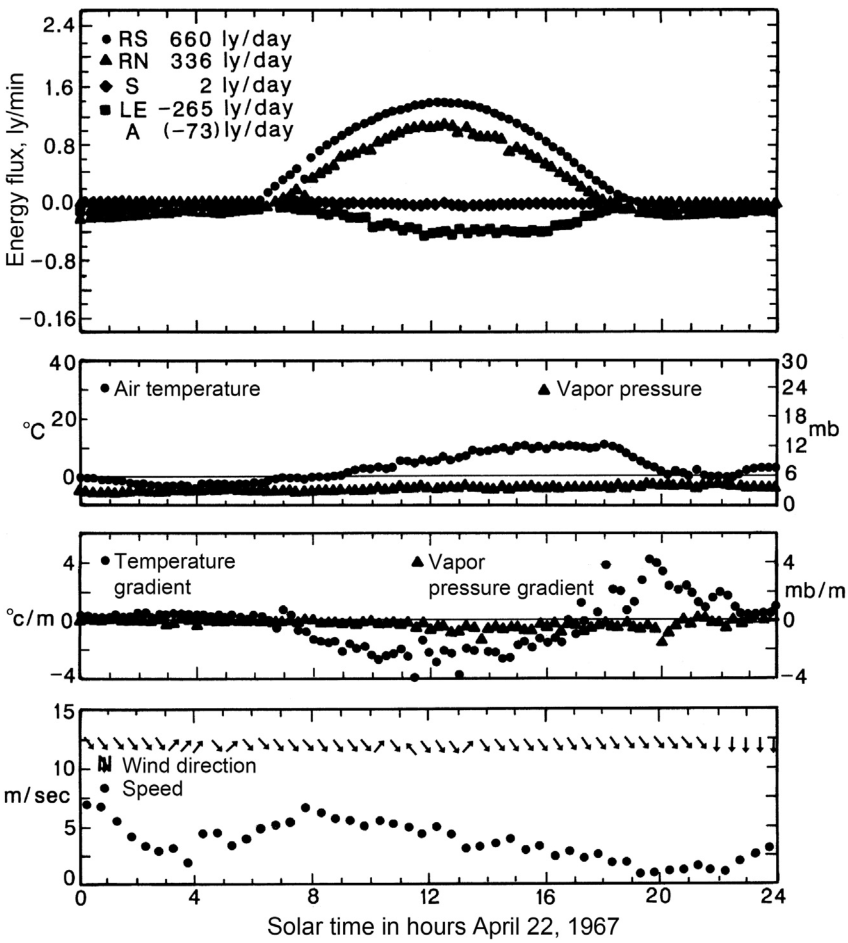

FIGURE 28.5 Same as Figure 28.4 except for April 22, 1967. *From Rosenberg (1974), p. 175. This material is used by permission of John Wiley & Sons, Inc.*

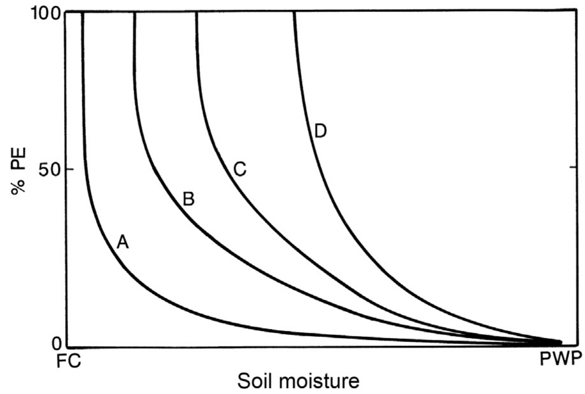

FIGURE 28.6 Adjustment of potential evapotranspiration for soil dryness and rooting depth of crops. Curves A to D correspond to increases in rooting depth of crop. FC = field capacity; PWP = permanent wilting point. *From Chang (1968), Figure 79, p. 139. Reproduced by permission of Dr Jen-Hu Chang.*

van Bavel (1967) suggested that the transpiration rate in alfalfa begins to diminish after a soil-water potential of about −4 bars is reached and cites other works in which this breaking point has ranged from −0.2 to −10 bars for corn and cotton, respectively. Ritchie (1972) said that the evaporation from the soil surface is a two-stage process. The first stage is the constant-rate stage in which the evaporation is limited only by the supply of energy to the surface of the soil. The second stage is the falling-rate stage in which water movement to the evaporating sites near the surface is controlled by the hydraulic properties of the soil.

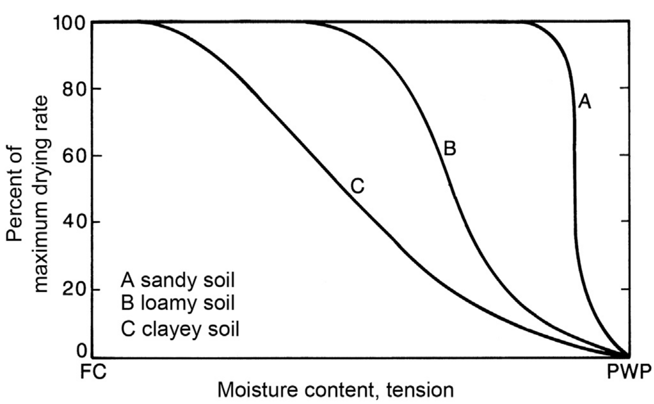

FIGURE 28.7 Drying rate of three types of soil. FC = field capacity; PWP = permanent wilting point. *From Chang (1968), Figure 78, p. 13. Reproduced by permission of Dr Jen-Hu Chang.*

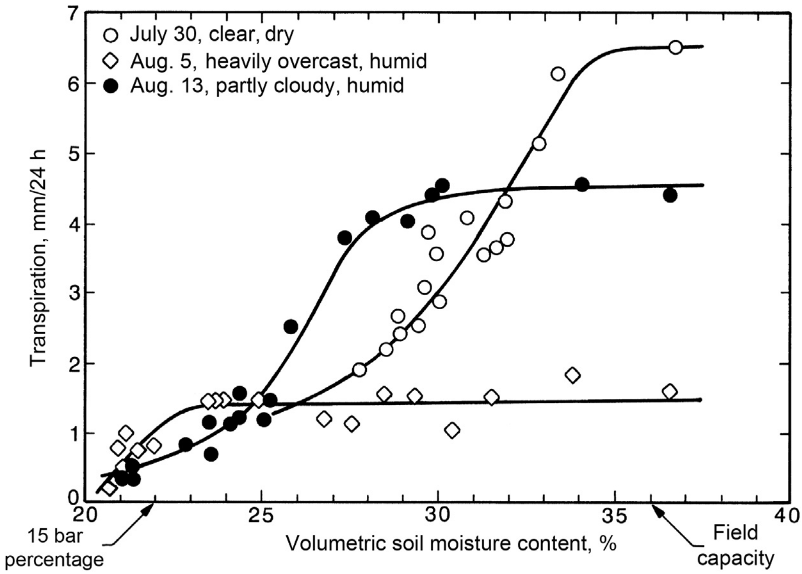

FIGURE 28.8 Actual transpiration rate as a function of soil moisture content. *From Chang (1968), Figure 75, p. 136. Reproduced by permission of Dr Jen-Hu Chang.*

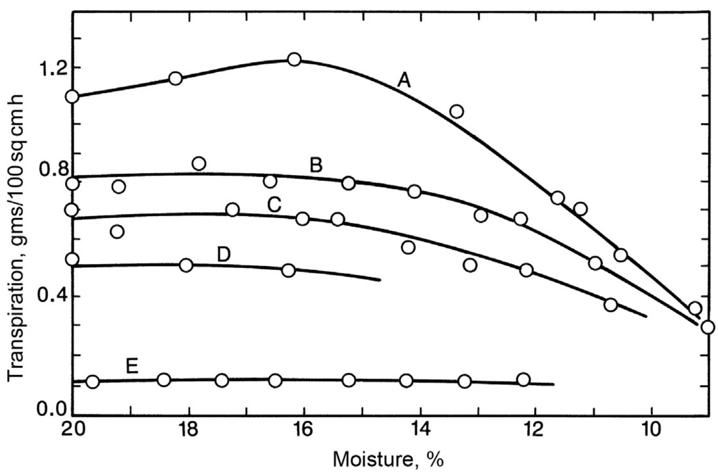

FIGURE 28.9 The transpiration of kidney beans in grams 100 cm^2/h versus the moisture percentage of the soil at various light intensities at a temperature of 20 °C and a relative humidity of 40%. A: light intensity 4.5×10^4 erg/cm^2/s; B: 2.4; C: 1.4; D: 0.66; E: results from Veihmeyer and Hendrickson (undated). *Data from Bierhuizen (1958), Chang (1968), Figure 74, p. 135. Reproduced by permission of Dr Jen-Hu Chang.*

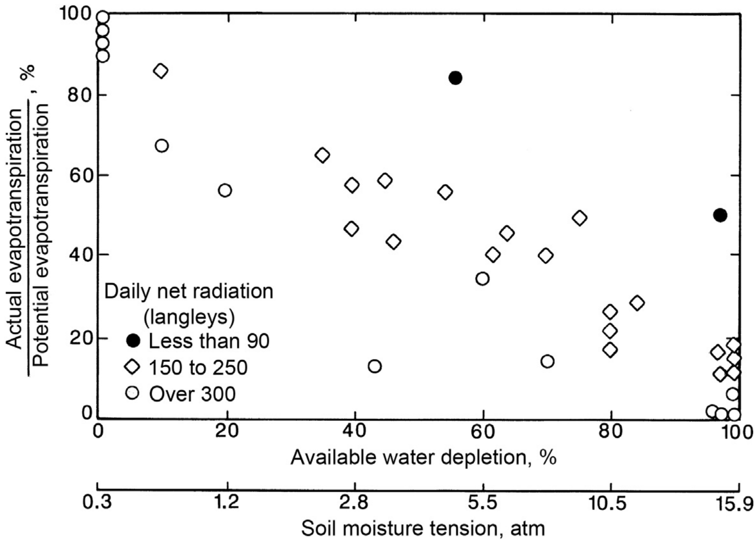

FIGURE 28.10 Relative daily actual evapotranspiration rate from short grass as function of moisture depletion from the root zone and soil moisture tension averaged over the total root depth. *From Chang (1968), Figure 76, p. 137. Reproduced by permission of Dr Jen-Hu Chang.*

These studies relating soil-water to ET show that the potential rate of ET cannot prevail unless the soil is kept well supplied with water.

Sixth, let us look at the relation of free water evaporation and plant water use (Rosenberg, 1974, p. 176). The condition that PET cannot exceed free water evaporation under the same weather conditions probably applies well in humid regions. For example, the amount of water used by rye and fescue grass is about 80% of that evaporated from open water in evaporation pans, except when winds are strong and the air is hot and dry. Then the ratio drops, apparently because hot and dry conditions cause an increase in stomatal resistance.

However, in the Great Plains of the United States and in yet more arid regions, well-watered crops that exert little canopy resistance and that are tall or aerodynamically rough can consume more energy and transpire more water than is evaporated from free water surfaces. If the free water surfaces are extensive and the crop areas are not, the differences may be pronounced. A case in point occurred during the period of strong regional advection of sensible heat into eastern Nebraska during May, 1967 (Rosenberg, 1974, p. 177). Evaporation from evaporation pans with land exposures and with lake exposures showed lower daily evaporation than was measured with precision weighing lysimeters in an irrigated alfalfa field (Table 28.1). The data in Table 28.1, and other data, show that free water evaporation need not always show the upper limit or the PET in

TABLE 28.1 Lysimetrically Measured Alfalfa Evapotranspiration (ET) Compared with Pan Evaporation in Nebraska

Location	May 17–22, 1967 (5 days Total) Alfalfa about 25 cm Tall (mm)
Alfalfa in lysimeters at Mead, Nebraska	51.91
Alfalfa ET due to advection	19.10
Land exposure pans	45.66
Lake exposure pans	36.08

Data extracted from Rosenberg, 1974, p. 177.

subhumid and arid regions as it does, apparently, in humid regions (Rosenberg, 1974, p. 178).

28.3 ADVECTION

In the preceding paragraph, we used the term *advection*. Advection is defined as the exchange of energy, moisture, or momentum as a result of horizontal heterogeneity (Chang, 1968, p. 140). If an area upwind of an irrigated field is hot and dry, then sensible (measurable) heat will be transferred to the irrigated field and its ET rate will be increased. However, if the advected air is colder than the vegetation, then the ET rate will be relatively low. Advection is a serious problem in arid and semiarid climates.

Advected energy involves the *clothesline effect* (Chang, 1968, p. 140). When warm air blows through a small plot with little or no guard area, a severe horizontal heat transfer occurs. The clothesline effect represents either the experimental bias because of the small size of the field or the border conditions unrepresentative of the large field as a whole. The clothesline effect cannot be tolerated in agronomic or climatological investigations. Where advection is important, plant growth may be improved by having larger irrigated fields to minimize the clothesline effect.

Advected energy also involves an *oasis effect* (Chang, 1968, p. 140). Inside a large field, the vertical energy transfer from the air above to the crop is called the oasis effect. The oasis effect must be reckoned with as a climatic characteristic, because it affects the ET rates many kilometers into an irrigated field (unlike the clothesline effect).

28.4 EXAMPLE CALCULATION TO DETERMINE POTENTIAL EVAPOTRANSPIRATION

Let us now follow an easy method developed by Kanemasu (1977) that we can use to estimate PET. Farmers who irrigate need to know how much moisture is being used by their crops. By estimating PET, they can tell the amount of water lost by plants. As we have said, PET is evaporation from a wet surface. It is limited by the energy that the surface can absorb. The more energy it absorbs, the higher the evaporation is. So evaporation is much higher on a sunny day than on a cloudy day, and PET depends primarily on the energy from the sun. Various methods of estimating PET require data on solar radiation, temperature, humidity, and wind speed. [We will not discuss the various methods used to measure ET, but the interested reader is referred to the following publications for a discussion of methods: Rose (1966, pp. 78–87); Slatyer (1967, pp. 56–64); Tanner (1967); Rosenberg (1974, pp. 159–205); Kanemasu et al. (1979); and Allen et al. (1998), who use the term "reference evapotranspiration" instead of potential evapotranspiration. Reference evapotranspiration is more specifically defined than PET. It is in reference to a particular surface, which has a grass crop with an assumed height of 0.12 m, a fixed surface resistance of 70 s/m, and an albedo of 0.23. The reference surface closely resembles an extensive surface of a green, well-watered grass of uniform height, actively growing, and completely shading the ground. The fixed surface resistance of 70 s/m implies a moderately dry soil surface resulting from about a weekly irrigation frequency (Allen et al., 1998). Pereira et al. (1997) also define PET and reference evapotranspiration.] To estimate PET, Kanemasu (1977) chose the Priestley–Taylor method, because it requires relatively easy-to-obtain information (solar radiation and average temperature).

Figures 28.11 and 28.12 show the relationship between the daily solar radiation and daily PET at various mean temperatures. In Kansas, solar radiation on a clear summer day would typically be about 650 cal/cm^2/day; on a cloudy day, it would be about 450 cal/cm^2/day; and, on an overcast day, it would be about 150 cal/cm^2/day.

Example calculation: Suppose that one wanted to know the PET for corn in Kansas. The solar radiation is 600 cal/cm^2/day; maximum temperature is 30 °C (86 °F); and minimum temperature is 25 °C (77 °F). One would calculate the average temperature as $(30 + 25)/2 = 27.5$ °C (81.5 °F). One then looks at Figure 28.11 (for wheat and corn) and selects the appropriate point between the 30 and 20 °C lines. The PET value is about 0.24 inch of water per day (0.61 cm/day). If maximum and minimum temperatures are not available, one can use the noon temperature.

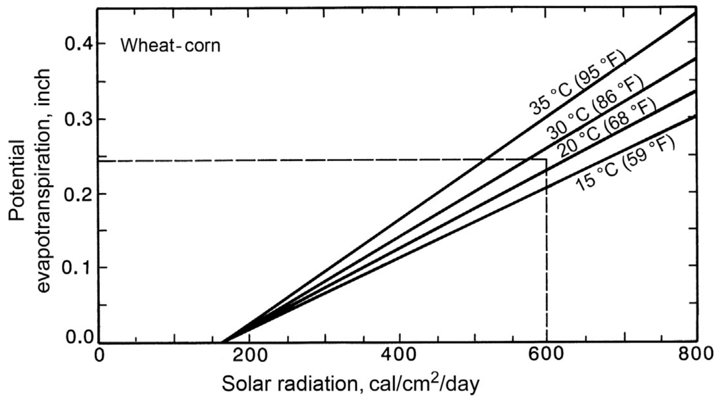

FIGURE 28.11 Potential evapotranspiration for winter wheat and corn as a function of solar radiation and mean temperature. 1 inch = 2.54 cm. *From Kanemasu (1977). Reproduced by permission of the Publications Coordinator, Department of Communications, College of Agriculture, Kansas State University.*

Under a full crop cover and when water is not limiting (plants are not severely stressed), actual ET and PET are approximately equal (Kanemasu, 1977). Therefore, under normal cropping conditions, ET would equal PET for an extended period during the summer, for example, from pretasseling to blister stages in corn. Under situations of little crop cover (e.g., poor stand development, early and late in the growing season), actual ET can be less than PET. Then, evaporation from the soil surface is important.

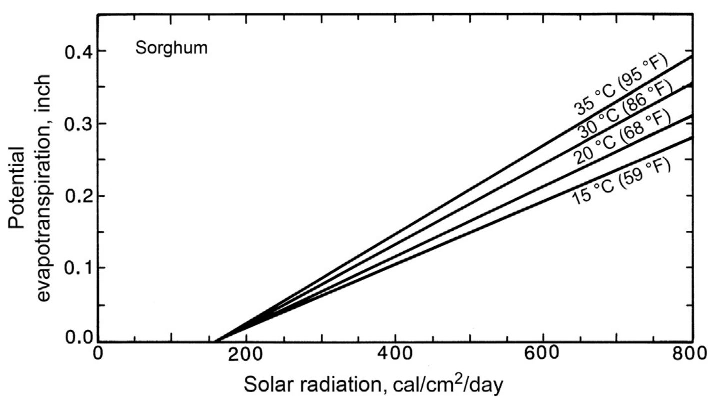

FIGURE 28.12 Potential evapotranspiration for sorghum as a function of solar radiation and mean temperature. 1 inch = 2.54 cm. *From Kanemasu (1977). Reproduced by permission of the Publications Coordinator, Department of Communications, College of Agriculture, Kansas State University.*

Although the procedure outlined by Kanemasu (1977) gives only an approximation of daily PET, it allows quick estimates of daily water loss from several crops during a major portion of their growing season when irrigation is often necessary to avoid stress. To maintain the root zone at optimum soil-water content, ET losses must be matched by rain or irrigation. In Kansas, for example, a 2 inch (5 cm) irrigation on corn can be used up in eight hot days (8×0.25 inches = 2 inches). Thus, it is important to estimate the amount of water lost by ET, to know when to irrigate.

28.5 APPENDIX: BIOGRAPHY OF HOWARD PENMAN

Howard Latimer Penman (1909–1984), an English agricultural physicist, was born in 1909 at Dunston-on-Tyne in County Durham. He was raised in modest circumstances and was the son of a master carpenter employed by a shipbuilding company in Tyneside, a coastal area in northeast England (Ratcliffe, 1994). Because of his outstanding ability and interest in science, he qualified for a first-class honors degree in physics at Armstrong College, then part of Durham University (which is now called the University of Newcastle on Tyne), where he did his earliest research (van Bavel, 1985). Later, he was awarded an M.S, in physics for research concerning the absorption of sound by porous bodies. For his PhD research, done at Durham University, he studied the temperature dependence of the dispersion of sound in gases (Ratcliffe, 1994). In 1937, he took a position in the Physics Department of the Rothamsted Experimental Station, where he remained until his retirement in 1974, with a three-year interruption during the war to work with the Admiralty (van Bavel, 1985). His work during the war was with the Mine Design Department, and he measured the output of sound from ships and submarines to aid in the development of acoustic mines. He had distinguished physicists working with him during the war, including Francis H.C. Crick, who won the Nobel Prize in 1962. In 1944, he returned to Rothamsted, where he published his classic paper "Natural evaporation from open water, bare soil and grass" (1948). He was head of the physics department at Rothamsted Experimental Station from 1954 to 1974 and was president of the Royal Meteorological Society from 1961 to 1963 (Royal Meteorological Society, 1985). The Royal Meteorological Society awarded him the Darton Prize in 1952 for his paper on "Evaporation over the British Isles" and in 1966 he was awarded the Hugh Robert Mill Prize for work on "The water balance of the earth's surface and its practical application to agriculture". He was elected Fellow of the Royal Society and awarded the Officer of the Order of the British Empire (OBE) in 1962. He was a founding member of the British Soil Science Society (Ratcliffe, 1994). He and his wife had no children.

Internationally known among soil scientists, agricultural meteorologists, and hydrologists for his classic work on evaporation under natural conditions, he did equally innovative research on the movement of gases and vapors in soil, and, in cooperation with R.K. Schofield, on diffusive gas exchange by plant leaves (van Bavel, 1985). This last work is less well known, but it anticipated by decades later work by others that clarified the linkage between plant transpiration and photosynthesis through the stomatal mechanism. Algorithms now used in models of crop growth and water use differ little from the original equations given by Penman and Schofield.

Penman's writings on the relation between evaporation from agricultural lands and atmospheric conditions established his wide reputation, and he had scientific contacts on every continent. He was unremittingly dedicated to the idea that physics had a significant contribution to make in agriculture (van Bavel, 1985). In public, he was a stern lecturer and acrimonious debater, but, on the personal level he was a kind, gentle, and helpful person. His interests included gardening and music. He was passionate about music and was a faithful member of choral groups in London. It was his habit to take the train after work into the city, rehearse all night, and then return around midnight to his home in Harpenden. He died on October 13, 1984, at St. Alban's City Hospital after a brief illness (van Bavel, 1985).

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