CHAPTER

29

Water and Yield

In this chapter we look at water and yield and, in particular, the relationship between evaporation (or transpiration) and yield. If we could develop a reasonably simple relation (equation), we could predict the effect of water deficits on field yields, a desirable goal. To assess the relation between water and yield, Tanner and Sinclair (1983, pp. 7−11) looked at five different analyses done by the following investigators: de Wit (1958); Arkley (1963); Bierhuizen and Slatyer (1965); Stewart (1972); and Hanks (1974). Here we present only de Wit's analysis, the earliest one and basis for subsequent work. (For a biography of de Wit, see the Appendix, Section 29.7.) We consider water-use efficiency, which is defined as the "biomass production per unit cropped area for a unit of water evaporated and transpired (*ET*) from the same area" (Tanner and Sinclair, 1983; p. 2). Water-use efficiency can be based on either the evapotranspiration (*ET*), called the *ET* efficiency, or on the crop transpiration, called the *T* efficiency. The difference is important because suppression of soil evaporation and prevention of weed transpiration can improve the *ET* efficiency, but it need not improve the *T* efficiency. These two water-use efficiencies may be based on either the total dry matter production or the marketable yield, and the yield base should be given.

29.1 DE WIT'S ANALYSIS

de Wit (1958) showed that for dry, high-radiation climates, yield and transpiration were related as

$$Y/T = m/T_{max}, \tag{29.1}$$

where Y = total dry matter mass per area, T = total transpiration per area during growth to harvest, and T_{max} = mean daily free water evaporation

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for the same period. The constant m is related to the WR/pan used by Briggs and Shantz (1917) ($1/m \simeq$ WR/pan) where WR = water requirement. de Wit showed that m was governed mainly by species and, for a first approximation, it was independent of soil nutrition and water availability unless there was a serious nutrition deficiency or unless soil water was too high (e.g., due to inadequate aeration).

de Wit proposed that this relation should hold until T approaches a maximum production governed by the growing conditions. The relation in Eqn (29.1) could be simplified for humid regions because, when water was not limiting, fluctuations in intercepted radiation, although reflected in transpiration and growth, would not affect appreciably the ratio $T/T_{\max}$. de Wit found under these conditions that

$$Y/T = n, \tag{29.2}$$

where n is a constant, gave a better description than does Eqn (29.1).

The value of m in Eqn (29.1) can be approximated with Eqn (29.3) from water-use efficiency and mean daily pan evaporation (E_{pan}):

$$m = (Y/T)E_{\text{pan}}. \tag{29.3}$$

In the Great Plains of the United States, de Wit (1958) found, using data of Briggs and Shantz and a number of other sources, that m was equal to 55, 115, and 207 kg/ha/day for Grimm alfalfa, Kubanka wheat, and Red Amber sorghum, respectively (Tanner and Sinclair, 1983; pp. 8–9) [or 5.5, 11.5, and 20.7 g dry matter per kilogram water per day, respectively (Chang, 1968; p. 128)]. In the Netherlands, the value for n for beets, peas, and oats was 6.1, 3.4, and 2.6 g per kilogram water per day, respectively (Chang, 1968; p. 128). The value of m and n are more dependent on the climatic conditions than on the nutrient level of the soil and the availability of water, provided that the nutrient level is not too low and the availability of water is not too high. These values are also independent of the degrees of mutual shading, if the leaf mass is not too dense. Where these conditions are not fulfilled, the m and n values are larger (Chang, 1968; p. 128).

Table 29.1 compares the values of m derived from the experiments of Briggs and Shantz (1914) and subsequent field observations (Tanner and Sinclair, 1983; p. 8). In Table 29.1, the m's developed from the data of Briggs and Shantz (1914) and Hanks et al. (1969) do not include root dry matter, whereas an estimate of root yield was made for the other data. Also, pan evaporation was used directly with no correction to free water evaporation, as made by de Wit. [According to LeGrand and Myers (1976), readings taken of pan evaporation tell how much water evaporates from lakes, if one applies a pan coefficient of about 0.70.]

Except for the Wisconsin data, corn, sorghum, and millet give the highest values of m, followed by the grain cereals, potatoes, and then the

TABLE 29.1 Experimental Estimates of m (kg/ha/d) From Data of Briggs and Shantz (1914) and Subsequent Field Experiments

Crop	Briggs and Shantz	Subsequent Field Data	Source
Corn	213 ± 14	215 ± 20	UT, Stewart et al. (1977)
		258 ± 1	CO, Stewart et al. (1977)
		262 ± 46	AZ, Stewart et al. (1977)
		314 ± 12	CA, Stewart et al. (1977)
Grain sorghum	240 ± 10	141 ± 6	Great Plains, Hanks et al. (1969)
Millet	260 ± 35	150 ± 18	Great Plains, Hanks et al. (1969)
Wheat	158 ± 10	125 ± 15	Great Plains, Hanks et al. (1969)
Potato	160 ± 8	217 ± 24	WI, Tanner, 1976 (unpublished)
Alfalfa	90 ± 11	214 ± 26	WI, Tanner, 1977 (unpublished)
Soybean	102 ± 7	128 ± 34	KS, Teare et al. (1973)

From Tanner and Sinclair (1983). Reprinted by permission of the American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

legumes. The data for corn indicate a high level of variability in m, even though the corn crops were subjected to nearly the same experimental treatments. The high m for potato and alfalfa in Wisconsin may indicate that Eqn (29.2) rather than Eqn (29.1) is applicable to this humid region. If so, it is difficult to know whether to use Eqn (29.1) or Eqn (29.2), because gradations in humidity occur not only between locations, but also seasonally at one location. Table 29.1 also shows that there is no consistent improvement in m between the crops grown in 1912–1913 (Briggs and Shantz, 1914) and more recently, excluding the Wisconsin data for the reasons discussed above. Thus, to the extent that m is a measure of T efficiency for total biomass production, it appears that there has been no increase in T efficiency since Briggs and Shantz did their work at the beginning of the 1900s.

29.2 RELATIONSHIP BETWEEN YIELD AND TRANSPIRATION AND YIELD AND EVAPOTRANSPIRATION

Let us look at figures showing the relationship between yield and transpiration and yield and ET. Figures 29.1 and 29.2 show the relationship between yield and transpiration as determined by Arkley (1963), who used data from Briggs and Shantz (1913a). The classic work by Briggs and Shantz demonstrated a close relation between transpiration and dry matter production. That is, dry matter is decreased by water deficits. In their experiments, the linear relationship held for different varieties of oats (Figure 29.1) and barley (Figure 29.2).

For the same plant species, the efficiency of water use may vary according to the climate (Chang, 1968; p. 220). Stanhill (1960) compared measurements of pasture growth and potential ET at seven localities in

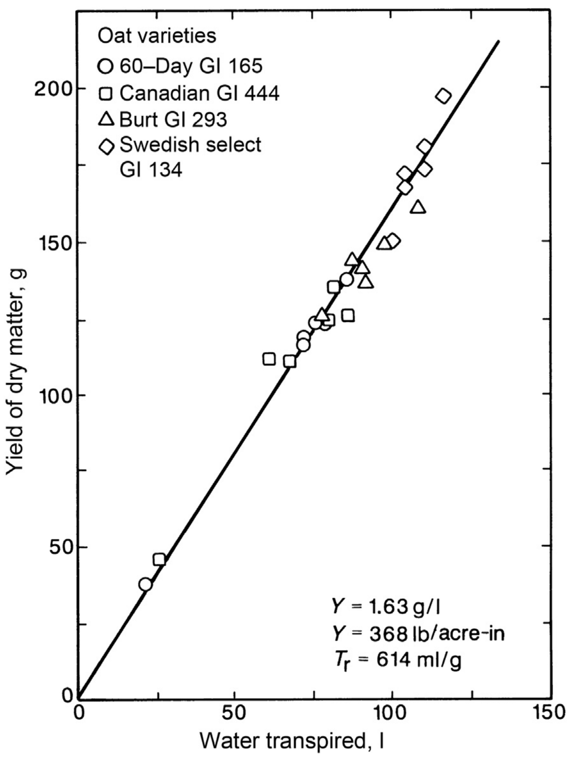

FIGURE 29.1 Relationship between yield of dry matter and amount of water transpired by oat varieties. *Data obtained by Briggs and Shantz (1913a, 1913b) and shown by Arkley (1963). From Chang (1968), Figure 69, p. 126. Reproduced by permission of Dr Jen-Hu Chang.*

different parts of the world. In Figure 29.3, the cumulative measured dry-weight yields are plotted against cumulative measured transpiration. A linear relationship exists at each site, but the slope of the line changes with latitude. In general, the growth rate per unit of water used is higher at high latitudes. This is a result of the increased respiration rate in the tropics.

The relationship between ET and dry matter production may or may not be linear. This is partly because the fraction of evaporation that does not contribute to plant growth varies throughout the crop life cycle. Figures 29.4–29.6 show the relationship between yield and ET as determined by Allison et al. (1958) and Staple and Lehane (1954). Even when dry matter production does increase linearly with ET, the regression line seldom passes through the zero point. In other words, ET in the field might be appreciable when the yield is still zero (Chang, 1968; pp. 211–212). Allison et al. (1958) analyzed the yields of a number of crops grown in a lysimeter near Columbia, South Carolina, for a

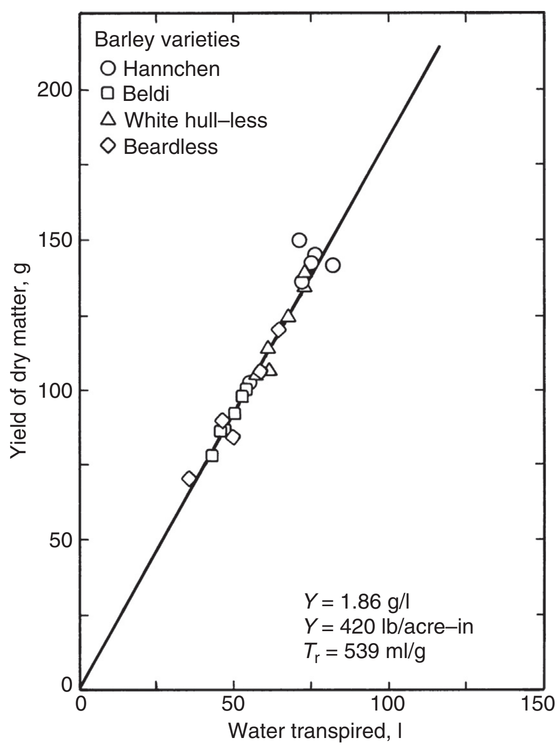

FIGURE 29.2 Relationship between yield of dry matter and amount of water transpired by barley varieties. *Data obtained by Briggs and Shantz (1913a, 19193b) and shown by Arkley (1963). From Chang (1968), Figure 70, p. 127. Reproduced by permission of Dr Jen-Hu Chang.*

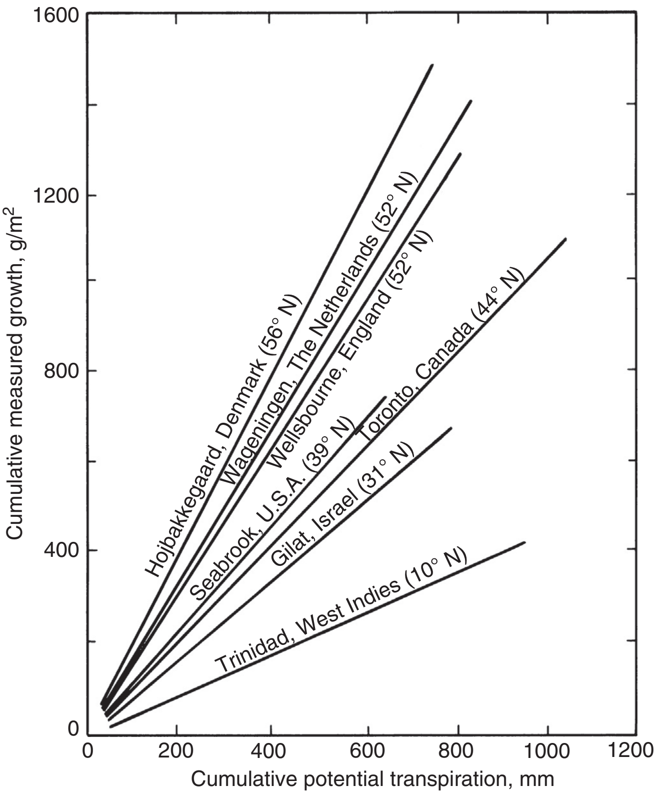

FIGURE 29.3 Measurements of potential evapotranspiration and dry matter production from pastures. *Data of Stanhill (1960). From Chang (1968), Figure 114, p. 222. Reproduced by permission of Dr Jen-Hu Chang.*

period of more than 5 years. Their data indicated that the first 18 in (46 cm) of evapotranspired water was required to produce only enough for plant survival (Figure 29.4). The increase in dry matter was almost linear with increasing amounts of water used from 18 to 22 inches (46–56 cm). Staple and Lehane (1954) studied the use of water by spring wheat grown in tanks and in the open field in Swift Current, Canada. They reported that 4.9 in (12 cm) of water for tanks and 5.64 in (14 cm) for the field were necessary to establish the plants (Figures 29.5 and 29.6). Beyond this, the yield in the tanks increased nearly linearly. But in the field the yield increased curvilinearly. In either case, the maximum production potential was not realized because of the shortage of water.

Before concluding this section on the relationship between water and yield, let us briefly look at the situation of an individual leaf. Up to

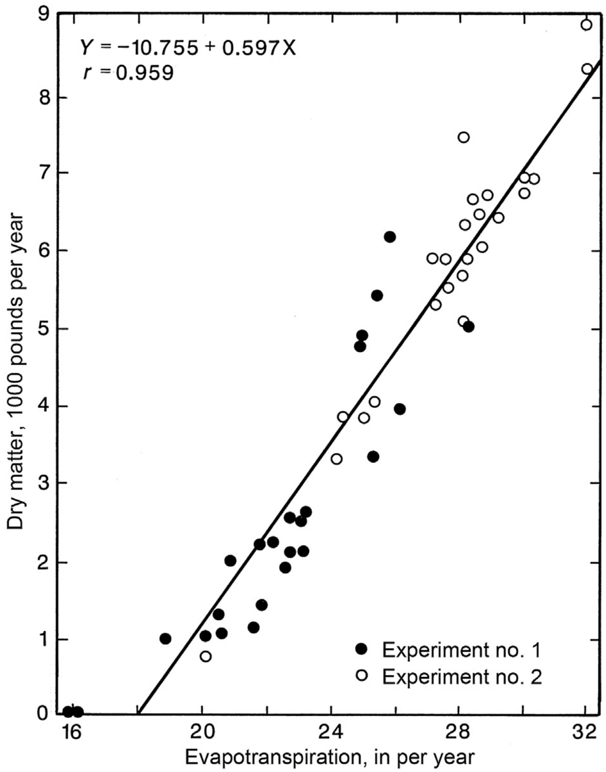

FIGURE 29.4 Relationship between crop yields and water use. *Data of Allison et al. (1958). From Chang (1968), Figure 105, p. 212. Reproduced by permission of Dr Jen-Hu Chang.*

now, we have been considering groups of leaves as they might exist under field conditions. For a single leaf, the net assimilation, or net photosynthesis, increases with light intensity to the saturation point and then levels off. The transpiration rate will, however, increase linearly with radiation to a much higher intensity. Thus, the ratio between transpiration and photosynthesis will vary according to the radiation intensity in a manner postulated by de Wit (1958) (Figure 29.7). This same relationship was later quantitatively presented by Bierhuizen (1959) (Figure 29.8). The high ratio occurring at extremely low radiation intensity is because transpiration has some value, whereas photosynthesis first has to compensate for the respiration. This high ratio is of little significance because of the low rates of both processes. The lowest ratio is reached at a radiation intensity of 0.1—0.2 langleys per minute. Such low radiation intensities are observed only in the early morning and late afternoon. As the radiation intensity increases, beyond 0.2 langleys per minute, the ratio of transpiration to photosynthesis for a

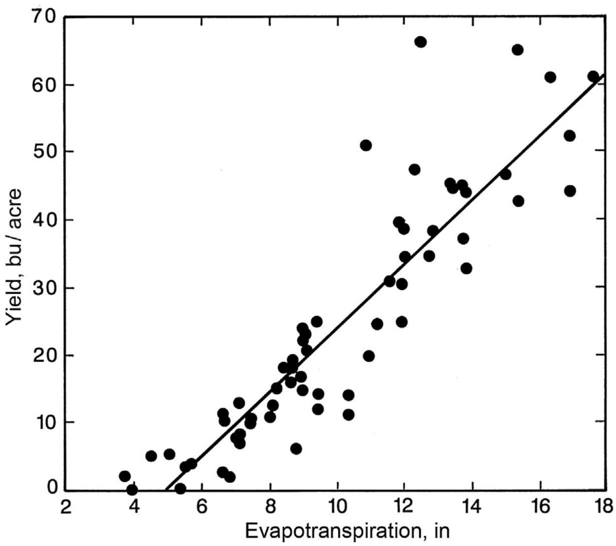

FIGURE 29.5 Relationship between wheat yield and evapotranspiration in tanks, 1922–1952. *Data from Staple and Lehane (1954). From Chang (1968), Figure 106, p. 213. Reproduced by permission of Dr Jen-Hu Chang.*

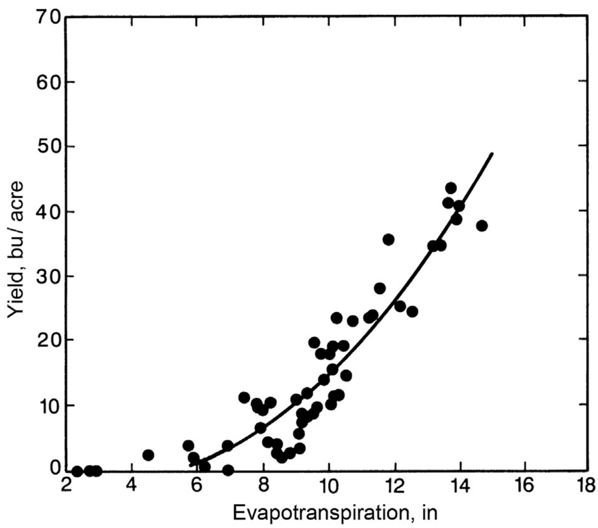

FIGURE 29.6 Relationship between wheat yield and evapotranspiration on field plots. *Data from Staple and Lehane (1954). From Chang (1968), Figure 107, p. 213. Reproduced by permission of Dr Jen-Hu Chang.*

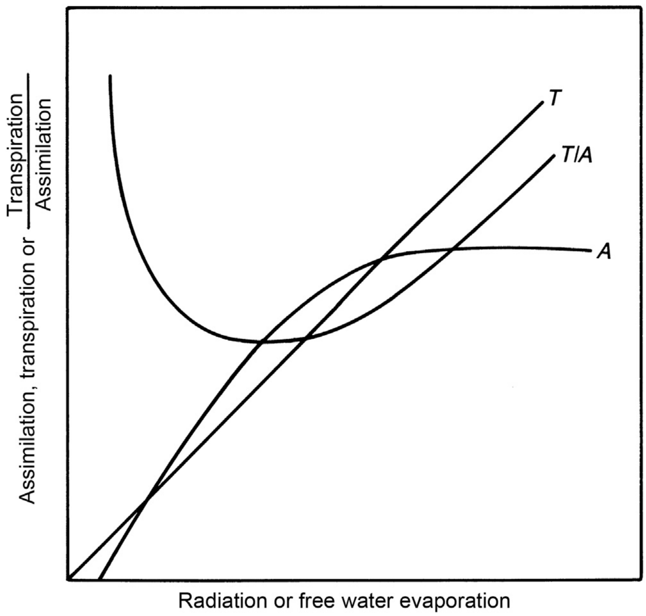

FIGURE 29.7 Relationship between net assimilation (A), transpiration (T), and the transpiration to assimilation ratio (T/A) for leaves of plants as a function of the radiation or free water evaporation. *Figure from de Wit (1958). From Chang (1968), Figure 67, p. 124. Reproduced by permission of Dr Jen-Hu Chang.*

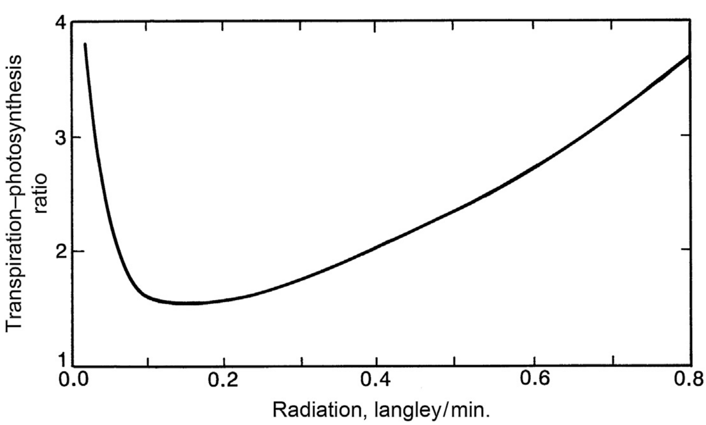

FIGURE 29.8 Relationship between radiation and the transpiration–photosynthesis ratio. *Figure from Bierhuizen (1959). From Chang (1968), Figure 68, p. 124. Reproduced by permission of Dr Jen-Hu Chang.*

single leaf increases nearly linearly. Thus, for a single leaf, the efficiency of water use in the production of dry matter will be lower in areas of high radiation, such as in the arid tropics.

29.3 WATER AND MARKETABLE YIELD

In many instances, the reductions of yields of grain and other marketable parts of crops are roughly in proportion to the decreases in transpiration induced by water deficits (Tanner and Sinclair, 1983; p. 18). However, often there are stages of development, such as pollination, at which marketable yield may be extraordinarily affected. Figure 29.9 shows a generalized relation between yield and adequacy of water at different stages of growth. The curve was developed for sugar cane in Hawaii, but can be applied, in general, to other crops (Chang, 1968; pp. 214–215). Table 29.2 summarizes moisture-sensitive periods for selected crops during which a water deficit depresses the economic yield much more than at other periods (Chang, 1968; p. 216). Varieties (cultivars) may also respond differently under drought conditions. A drought-resistant variety may follow the upper broken curve in Figure 29.9, whereas a variety less resistant to drought may follow the lower broken curve.

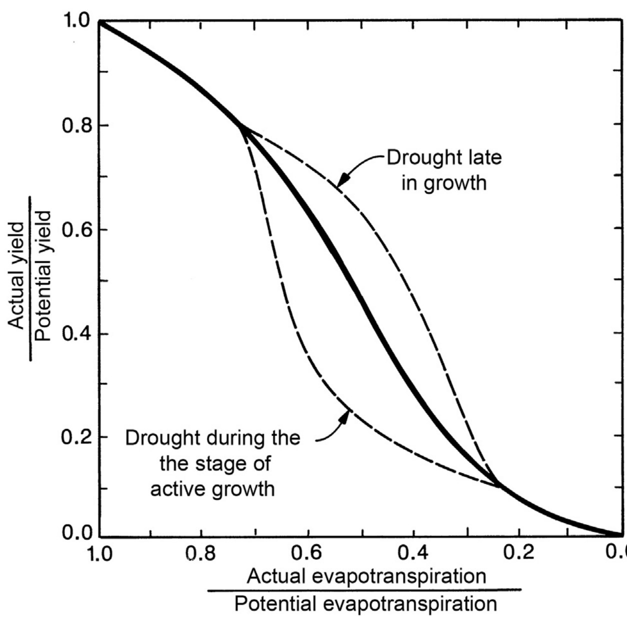

FIGURE 29.9 Generalized relationship between yield and adequacy of water application. *From Chang (1968), Figure 108, p. 214. Reproduced by permission of Dr Jen-Hu Chang.*

TABLE 29.2 Moisture-Sensitive Stages (from Chang, 1968, p. 216)

Crop	Critical Stage
Cauliflower	No critical moisture-sensitive stage; frequent irrigation required from planting to harvest
Lettuce	Just before harvest when the ground cover is complete
Cabbage	During head formation and enlargement
Broccoli	During head formation and enlargement
Radishes and onions	During the period of root or bulb formation
Snap beans	During flowering and pod development
Peas	At the start of flowering and when the pods are swelling
Turnips	From the time when the size of the edible root increases rapidly until harvest
Potatoes	After the formation of tubers
Potatoes (White Rose)	From stolonization to the beginning of tuberization
Soybeans	Period of major vegetative growth and blooming
Oats	Commencement of ear emergence
Wheat	During heading and filling
Barley	Effects of water stress on grain yield and protein content shown to be greater at the early boot stage than at the soft dough stage, and shown to be greater at the soft dough stage than at the onset of tillering or ripening stages
Corn	Period of silking and ear growth
Cotton	At the beginning of flowering
Apricots	Period of floral bud development
Cherries and peaches	Period of rapid growth prior to maturity
Olives	Later stages of fruit maturity

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29.4 WATER AND QUALITY

We need to note also that water deficits may be necessary to increase the quality of a crop. So far, we have been concerned only with the relationship between water and dry matter (or marketable yield) production. The quality of an agricultural product, however, is not necessarily related to the yield. In analyzing the relationship between water and crop quality, one must differentiate between natural rainfall and controlled irrigation water. Rainfall usually is accompanied by high cloudiness and low radiation, but the application of irrigation water is not complicated by a change of unfavorable weather conditions.

The effects of irrigation on crop quality are summarized in Table 29.3 from Chang (1968, pp. 223–224). In general, adequate irrigation throughout periods of active vegetative growth results in an improvement in crop quality. However, during the ripening period, moderate moisture stress often has been found to be desirable, especially in the case of certain compounds such as rubber, sugar, and tobacco. For example, the rubber content of guayule is increased by a slight moisture stress. The withdrawal of irrigation water several weeks before harvest is a common practice in sugar cane culture. Late water stress also has been found to increase the sucrose concentration of sugar beets. The aroma of Turkish tobacco is improved by water stress late in the crop cycle. The flavor and taste of most fruits also can be enhanced by the same means (Chang, 1968; p. 224).

29.5 CROP WATER-USE EFFICIENCY

Here are a few final comments on crop water-use efficiency (Tanner and Sinclair, 1983; pp. 18–21). Experimentally, we need to do three things: (1) be able to distinguish transpiration (T) from evaporation (E) in studies of ET; (2) be able to make estimates of vapor pressure deficit (VPD) because data on yield and transpiration are normalized by using VPD to account for differences in years and locations; and (3) improve our understanding of dry matter partitioning into roots, shoots, and marketable yield.

When increased water-use efficiency is found as a result of improved management, the increases result from increased transpiration as a fraction of the ET. ET efficiency is increased, although T efficiency is changed little, if any (Tanner and Sinclair, 1983; p. 20). Conditions such as low fertility, water stress, plant disease, or insects that lower the leaf area so that the canopy is no longer closed will increase soil evaporation and thereby lower Y/ET. Factors such as poor growing temperatures and extreme infertility can lower both Y/T and Y/ET. Nevertheless, a decrease

TABLE 29.3 Effect of Irrigation on Crop Quality

Crop	Effect
Pasture	Irrigation increased the protein and decreased the fat contents of the herbage but had little effect on the crude fiber and ash content.
Vegetables	Maintaining a low moisture stress during the whole growth period generally resulted in the highest yield and quality.
Snap beans	Irrigation decreased the percentage of pods that were badly crooked or severely malformed. Fibrous content of beans was generally reduced.
Sweet corn	Irrigation increased the number of marketable ears per plant, the average weight per ear and the gross yield of unhusked ears, and the percentage of usable corn cut from these ears for canning or freezing.
Soybeans	Irrigated soybeans had slightly lower oil content and slightly higher protein content.
Barley	Irrigation increased the yield of grain and improved malting quality, mainly by increasing extract.
Potatoes	Irrigation that gave good increase in yield of potatoes very seldom reduced the specific gravity and was more likely to increase it.
Tobacco	Irrigated tobacco had lower nicotine and protein, but higher carbohydrate content.
Fruits	Canned peaches that were tough and leathery in texture, pears that remained green and hard a week or more after the ripening season, prunes that were sunburned, and walnuts with partly filled shells were some of the results of a relatively long time without readily available moisture.
Olives	The higher yield obtained by irrigation was due to an increase in fruit size, rather than in the number of fruits. Irrigated groves had a higher oil content than unirrigated ones.

For references for the results, see Chang (1968, pp. 223–224). Table reproduced with the permission of Dr J.-H. Chang.

in leaf area index has to be severe before substantial changes in Y/T will be observed. Changes in ET efficiency occur more readily than changes in T efficiency.

Changing plant architecture is not likely to change T efficiency significantly in canopies achieving a leaf area index of about three. However, canopy structure and population can modify the loss due to evaporation relative to the loss due to transpiration, and, therefore, can affect ET efficiency more than T efficiency. Crop breeding can change rates of maturation to take advantage of seasonal water availability and perhaps change rooting habits to increase soil water supply or change the timing of withdrawal. Such changes may aid in the efficient use of water and ET efficiency without changing the T efficiency.

The crop can be managed (e.g., population and fertility) to increase or decrease leaf area index, thus changing the partitioning of E and T and ET efficiency. Preventing evaporation from the soil and transpiration from weeds also modifies the partitioning of E and T. However, there is a limit to the improvement in water-use efficiency that such manipulations can provide. The ET efficiency can only approach the T efficiency as the upper limit.

To summarize, it appears that there are two ways to modify the T efficiency based on total dry matter of crops (Tanner and Sinclair, 1983; p. 20). First, crops can be grown in humid climates where the VPD is small and advection is minimal. However, in these regions, sunlight is usually less and total yields may be smaller. Second, the partitioning of total dry matter can be changed to create more marketable products. This would increase the T efficiency of the marketable yield. This option means changing the chemistry of the plant. The changes would have to be large, and, consequently, are unlikely. Therefore, changing the T efficiency of the marketable yield seems improbable. Tanner and Sinclair (1983, p. 25) conclude that transpiration efficiency is a relatively difficult to manipulate variable. Transpiration efficiencies of different crops have changed little since Briggs and Shantz did their work at the beginning of the 1900s. Even though the likelihood of large improvements in T efficiency is small, crop water-use efficiency can be improved, as was noted in the preceding section (e.g., changing rooting habits, increasing leaf area index, minimizing soil evaporation, and preventing transpiration from weeds).

29.6 WATER-USE EFFICIENCY UNDER ELEVATED CARBON DIOXIDE

As noted by Tanner and Sinclair (1983), it is difficult to increase crop water-use efficiency unless there is a basic change in the chemistry of the plants. One way would be to change photosynthetic systems. Crops with the C_4 type of photosynthesis have a higher water-use efficiency than crops with the C_3 type of photosynthesis. This is due to two facts. First, under the same environmental conditions, C_4 plants keep their stomata more closed than C_3 plants, thereby losing less water than C_3 plants. Second, due to their efficient cycling of carbon dioxide in the plant, C_4 plants are more productive than C_3 plants. [For further discussion, see the following chapters in Kirkham (2011): Chapter 8 on stomatal conductance; Chapter 11 on water-use efficiency, and Chapter 12 on C_3 and C_4 plants.] Therefore, both biomass and water use are different in C_4 plants, and each contributes to increased water-use efficiency of C_4 plants compared to C_3 plants. But changing C_3 plants into C_4 plants has not been successful. C_3−C_4 intermediates do not show the whole spectrum of components of the C_4 pathway and have shown little or no advantages in terms of productivity (Kirkham, 2011; p. 112).

However, all plants, both C_3 and C_4, have increased productivity under elevated carbon dioxide, and all plants close their stomata when the carbon dioxide in the atmosphere is increased (Kirkham, 2011; p. 353). Therefore, as the carbon dioxide concentration in the atmosphere has increased, we are inadvertently increasing the water-use efficiency. We can calculate this increase in water-use efficiency. Let us look at the increase in water-use efficiency since 1958, when the carbon dioxide concentration in the atmosphere was first carefully measured (Kirkham, 2011; p. 1). In 1958, the carbon dioxide concentration in the atmosphere was 316 ppm. Based on data from experiments done with grain sorghum [*Sorghum bicolor* (L.) Moench] under different carbon dioxide concentrations (Kirkham, 2011; p. 234), we can calculate that in 2011, when the carbon dioxide concentration in the atmosphere was 390 ppm, it took 55 ml less water to produce a gram of sorghum grain than it did in 1958. We shall work in English units for our calculations, because producers in the United States use English units. However, our answer will be a percentage increase in water-use efficiency, which does not require knowledge of English units. We know that 1 bushel (abbreviated bu) of sorghum grain weighs 56 pounds. Let us consider the 55 ml/g: (55 ml/g) × (453.6 g/lb) × (56 lb/bu) = 1,397,088 ml/bu. Rounding and converting to liters we get 1397 l/bu. We convert this number to gallons (abbreviated gal) per bushel, as follows: (1397 l/bu) × (1 gal/3.8 lL) = 367 gal/bu. We remember this number, because we shall return to it. We know 1 acre = 43,560 ft^2. We divide this number by 12 in, and we get 3630 ft^3 of H_2O per inch per acre. (Think of this as the equivalent of 1 in of water standing on 1 acre.) We know 1 ft^3 = 7.48 gal. This is given in textbooks or we can calculate it. Therefore, 1 in H_2O/acre = 27,152.4 gal. In Kansas, grain sorghum requires 22 in of ET (Loyd R. Stone, Department of Agronomy, Kansas State University, personal communication, April 1, 2013). The water can come from irrigation or rain.

We then multiply, as follows: 22 in $\times$ 27,152.4 gal = 597,352.8 gal to raise 22 in of ET. The average yield of grain sorghum in Kansas between the years 2000 and 2011 has been 62 bu/acre, so we get 9634.7 gal/bu. We return to the number we remembered from before (367 gal/bu) and then do the following division to get our water savings: (367 gal/bu)/(9634.7 gal/bu) = 0.038 savings ratio per bushel. Due to the increase in carbon dioxide, we saved 3.8% water to raise sorghum in 2011 compared to 1958. This water savings will increase as the carbon dioxide concentration in the atmosphere increases.

29.7 APPENDIX: BIOGRAPHY OF CORNELIUS DE WIT

Cornelius ("Kees") Teunis de Wit (1924−1993), professor at the Agricultural University, Wageningen, The Netherlands, was born east of Arnhem. His introduction to agriculture was while he worked as a farm laborer during World War II (Rabbinge, 1995). His thesis at Wageningen was notable for its theoretical nature and foreshadowed his founding of the department of theoretical production. Early in his career, he worked in Burma. Later, he developed strong ties with Mali, Israel, and the United States. In the 1950s, after writing his dissertation on fertilizer placement, he wrote classic monographs on competition, on the relation between transpiration and crop yields, and on the photosynthesis of leaf canopies. He calculated the population that the earth's photosynthesis could feed. In the 1960s and 1970s, de Wit and his colleagues at Wageningen took up the dynamic simulation of crop growth, incorporating biochemistry, development from seeds to grain, the soil and atmosphere around the crop, and its pests (American Society of Agronomy, 1994). His countrymen elected him a senator in the parliament of Gelderland, and, in The Hague during the 1980s, he served on the Netherlands Scientific Council for Governmental Policy. Afflicted by diabetes, he retired in February, 1989, and was honored by ceremonies attended by scientists from many countries. Undaunted, he continued to work and advised the Consultative Group on International Agricultural Research and suggested research that should be carried out on crops in different regions.

He was a Knight of the Order of The Netherlands Lion and Foreign Associate of the National Academy of Sciences of the United States. In 1984, he was cowinner, with Don Kirkham, of the Wolf Prize in agriculture; Kirkham was recognized for theoretical work and de Wit for development of numerical models. The citation read, "for their innovative contributions to the quantitative understanding of soil water and other environmental interactions influencing crop growth and yield".

de Wit and his wife had two children. He died at age 69 years on December 8, 1993 (American Society of Agronomy, 1994).

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