

IRRIGATION, WATER USE, AND WATER RELATIONS

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Irrigation has been an increasingly popular production practice in the USA to insure the yield potential of the peanut crop against other high cost production inputs of fungicides, insecticides, herbicides, etc. A 1978 survey in Georgia indicated that 45% of the allotted peanut acreage was under irrigation with new installations increasing steadily (Henning et al., 1979). This trend will continue as long as peanut producers in the USA have allotted acreage or poundage with a price support system. In the absence of price supports, the economics of peanut irrigation would need to be re-evaluated and irrigation probably would be reduced, in view of the peanut plant's relative tolerance to drought conditions.

The need for irrigation is considerable in the dryland areas of southwestern USA, yet many of these very areas are experiencing problems of availability and cost of water due to declining water tables and increased pumping costs. Peanut yields in dryland areas of southwestern USA are considerably less than in southeastern USA (Table 1). However, this table averages both dryland and irrigated yields, whereas a separate comparison in Texas in 1979 showed average yields of 1350 and 2800 kg ha⁻¹ for dryland versus irrigated production, respectively (1979 Texas Field Crop Statistics).

Table 1. Peanut yield in states of the USA producing more than 20,000 hectares of peanuts. Yields were averaged over 1977, 1978, and 1979. Adapted from Agricultural Statistics (1980).

State	Pod Yield kg/ha ⁻¹
Texas	1678
Oklahoma	2328
North Carolina	2907
Alabama	3051
Virginia	3156
Florida	3643
Georgia	3507

Irrigation is increasing in the humid southeast because of the high value of the crop and the desire to stabilize and insure production against rainfall-deficient periods even though total seasonal rainfall may be adequate. There may, for example, be no response to irrigation in years when rainfall is well distributed, but very sizeable increases in approximately 1 out of 3 years when distri-

bution is poor. An 8-year study at Marianna, Florida (Hewitt et al., 1980), showed an average yield increase of 535 kg ha⁻¹ in response to irrigating when soil water potential declined to -0.6 bars. The 8-year average increase by itself would indicate that irrigating peanuts was marginal economically. However, yield increases in 2 dry years exceeded 1600 kg ha⁻¹ and appeared to justify the cost of an irrigation system as insurance against poor yields and adverse cash flow in drought years. To develop probabilities of irrigation benefits at specific locations, one would need to determine a number of yield response (to water) simulations versus water holding characteristics of the soil and rainfall distributions for a number of years. Economic considerations should be included in the analysis.

In this chapter we will first address the various aspects of water relations on peanut plant physiology, growth, and development. Secondly, we will address yield response to water use, and discuss the climatic, soil, plant, and cultural factors which affect evapotranspiration by a peanut crop. Thirdly, we will discuss irrigation practices and strategies relative to soil water holding characteristics, environment, and cultural practices in the arid southwest and the humid southeast.

EFFECT OF WATER DEFICIT ON CROP PROCESSES

Root Growth and Water Uptake

During seedling development, root growth predominates and can reach 10 to 16 cm in 5.5 days and 30 cm by 11.5 days (Yarbrough, 1949). By this time, taproots and lateral roots are well developed, but only 4 leaves of the main axis have developed while 2 cotyledonary branches have begun initiation.

There are few reports on the seasonal progression of peanut root growth. McCloud (1974) observed that peanut root weight in the top 15 cm of soil was 37% of total crop dry weight at 21 days but was 1.5% at harvest. Because of the thick taproot, the majority of the root weight is in the top 15 cm of soil; Lenka and Misra (1973) reported this to be 77%. While fibrous roots below 15 cm may constitute a low fraction of root weight, they are important for water uptake because root length is more important for water uptake than root weight. Disregarding the taproot, the ratio of root length to root weight was found to be similar irrespective of soil depth (0-150 cm) or distance from the row (Robertson et al., 1979). Robertson et al. (1980) reported that 39% of the total rooting length was in the top 15 cm of soil and 55% in the top 30 cm. Robertson et al. (1980) measured rooting length density for Florunner peanut as high as 2.0 cm cm⁻³ in the top 15 cm, decreasing to 0.2 cm cm⁻³ at 150 cm depth in a Lake fine sand (Figure 1).

Figure 2 shows the increase in rooting depth throughout the life cycle of Florunner peanut in a deep Lake fine sand based on the presumption that water extraction indicates root presence. The points were derived under several treatments from which rainfall was excluded to allow water extraction estimates from tensiometer data without complications of water percolation. Apparent rooting depth progression was quite comparable from 1 year to the next even in different fields and progressed at a rate between 2.2 to 2.8 cm per day. There was an apparent lag until 30 days, possibly associated with seedling establishment and/or root penetration of a plowpan between 30 to 45 cm depth. Using

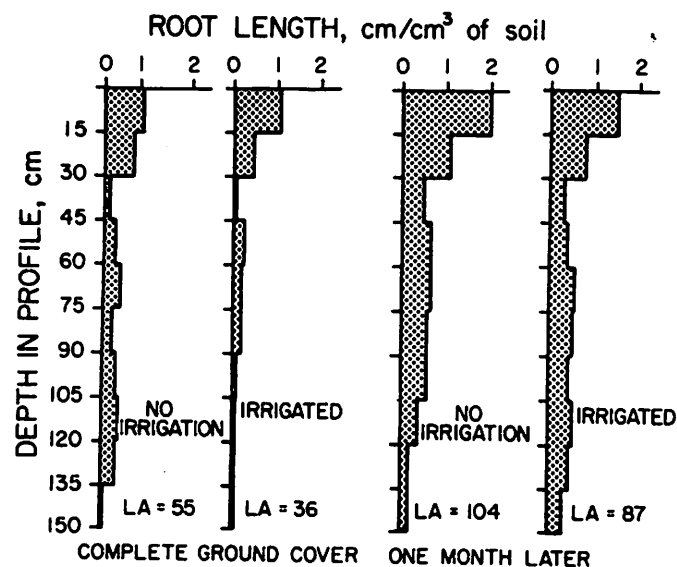


Fig. 1. Rooting length density of 65 and 95-day old Florunner peanut versus soil depth in Lake fine sand at Gainesville, Florida, in 1978. Reprinted from Robertson et al. (1980). LA represents the total accumulated root length (cm) below 1 cm² of land area.

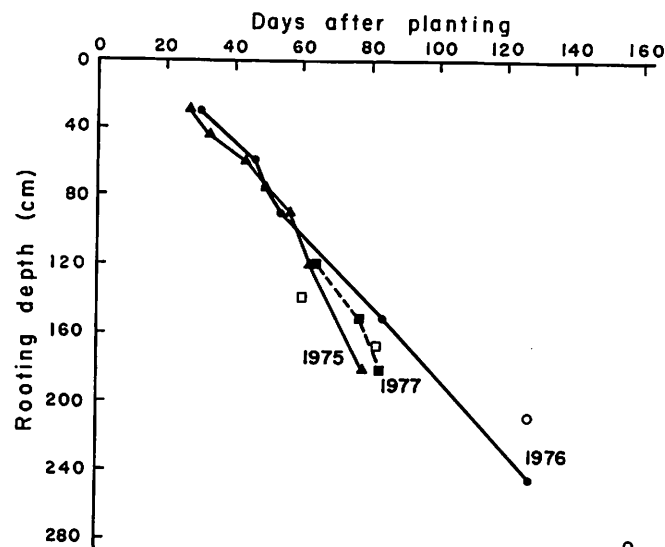


Fig. 2. Rooting depth of Florunner peanuts in a deep Lake fine sand during several seasons at Gainesville, Florida. Rooting depth was based on water extraction patterns (closed symbols) and actual rooting observations in soil cores (open symbols). Unpublished data, courtesy L. C. Hammond, W. K. Robertson, K. J. Boote, L. H. Allen, Jr., and R. J. Varnell.

soil coring techniques, the deepest rooting depth was 280 cm by the end of the season. Rooting depths to 200 cm have been observed by Hammond et al. (1978) and Robertson et al. (1980). Stern (1968) found a few roots of valencia spanish peanut reached 170 cm, but only a few reached depths greater than 130 cm in a sandy to clay loam soil. Peanuts appear to have a genetic ability for deep rooting and deep water extraction if grown in a barrier-free soil. Such a trait would postpone desiccation during extended droughts. Nevertheless, yield would probably be reduced, because the water uptake from greater depths may not be sufficient to supply all transpiration needs.

During drought-stress periods, lower roots continue to grow downward into unrestricted moist soil zones even though top growth may appear to stop (Allen et al., 1976). The net result is frequently greater rooting depth for water-stressed peanuts than irrigated peanuts (Lin et al., 1963; Lenka and Misra, 1973; Narasimham et al., 1977). Robertson et al. (1980), however, observed no difference in rooting length density (cm of root length per cm³ soil volume) at greater depths for irrigated versus non-irrigated peanuts in a dry season. They did observe greater rooting length proliferation in the top 30 cm of soil for irrigated peanuts. Taylor and Ratliff (1969) demonstrated that peanut taproots could grow into relatively dry soil (-0.19 to -12.5 bars soil water potential) so long as soil strength (penetration resistance) was low. Peanut root elongation was less severely affected by compacted soil than was cotton.

Table 2 shows water uptake by roots in various soil layers determined from soil water measurements taken during peak periods of rooting and water use for peanuts grown on clay loam under rainfree conditions in Israel (adapted from data of Mantell and Goldin, 1964). As the irrigation interval was lengthened, less water (absolute or percentage basis) was extracted from the upper 30 cm, whereas more water was extracted from the 90 to 150 cm depth. The water uptake pattern for the 10-day irrigation interval is probably closest to the situation under a humid rainfed situation. Peanuts irrigated every 10 days extracted 48% of their water from the upper 30 cm.

Table 2. Effect of irrigation frequency on water extraction from various soil layers by Virginia Bunch peanuts in Israel during July-August, 1960. Adapted from Mantell and Goldin (1964).

Soil Depth (cm)	Irrigation Frequency (water extracted, mm day)				
	40 days	30 days	21 days	14 days	10 days
0-30	1.57 (28)†	2.08 (32)	2.07 (34)	2.65 (37)	3.58 (48)
30-60	1.17 (21)	1.63 (25)	1.77 (29)	2.00 (28)	1.71 (23)
60-90	1.12 (20)	1.30 (20)	1.10 (18)	1.22 (17)	1.12 (15)
90-120	0.90 (16)	0.84 (13)	0.67 (11)	0.71 (10)	0.67 (9)
120-150	0.84 (15)	0.65 (10)	0.49 (8)	0.57 (8)	0.37 (5)
Total (all depths)	5.60	6.50	6.10	7.15	7.45

† Expressed as % of total water extracted from all depths.

Effect of Water Deficit on Vegetative Growth and Partitioning to Fruits

Vegetative Growth. Water deficit reduces dry matter production of vegetative components (Fourrier and Prevot, 1958; Ochs and Wormer, 1959; Su et al., 1964; Lenka and Misra, 1973; Stansell et al., 1976; Vivekanandan and Gunasena, 1976; Pallas et al., 1979) as well as crop growth rate (Slatyer, 1955). Soil water deficiency inhibits leaf expansion and stem elongation through its reduction of relative turgidity (Slatyer, 1955; Allen et al., 1976; Vivekanandan and Gunasena, 1976). Slatyer (1955) reported that the rate of dry matter accumulation by peanut was first reduced when relative turgidity dropped below 90%. The point of reduced growth coincided with decreased crop water use.

Most reported results pertain to samples taken at harvest or after stress points and, thus, fail to indicate season-long trends. Many studies such as that of Ochs and Wormer (1959) are pot studies. They irrigated at 25, 50, 75, or 100% soil water depletion (SWD) to resupply water in the amount of 25% of available water. The vegetative growth rate of potted plants between 31 to 75 days was maintained at maximum rates only by irrigating at 25% SWD. Irrigating at 50, 75, or 100% SWD caused progressively lower daily top growth rates.

Water deficits during several stages of growth have been shown to reduce the rate of daily leaf production (Ochs and Wormer, 1959; Billaz and Ochs, 1961; Vivekanandan and Gunasena, 1976). Vivekanandan and Gunasena (1976) grew peanuts throughout a life cycle in lysimeters controlled at -0.33, -0.55, and -0.73 bars of soil water potential. Differences in leaf area index (LAI) developed and persisted throughout the season, with each treatment achieving maximum LAI of 6.25, 4.75, and 3.81, respectively. Leaf longevity and leaf area duration were reduced by decreasing soil water potential.

Leaf and stem morphology are altered by water stress. Main axis and cotyledonary branches are shorter for water-stressed peanut plants (Lin et al., 1963; Su et al., 1964; Gorbet and Rhoads, 1975; Boote and Hammond, 1981). Soil water deficit reduces internode length more drastically than it reduces node number (Ochs and Wormer, 1959), although rate of node (plastochron) development is also reduced (Boote and Hammond, 1981). Continuous soil water deficit causes fewer and smaller leaves which have smaller and more compact cells (Il'ina, 1958; Lin et al., 1963). The xeromorphic leaf structure was retained even after adequate water was supplied, although new leaf development would apparently be normal.

Partitioning to Fruits. Excessive rainfall or irrigation may promote vegetative growth at the expense of reproductive growth. During a dry season, Gorbet and Rhoads (1975) irrigated to maintain soil water above -0.4 bars (-40 KPa) soil water potential at 20 cm depth. Their irrigation treatment increased main stem length from 34 to 52 cm and cotyledonary branch length from 51 to 70 cm as compared to the non-irrigated control. The same authors reported yield enhancement from application of a growth retardant (succinic acid 2,2 dimethyl-hydrazide) primarily in wet years or frequently irrigated plots. Vivekanandan and Gunasena (1976) similarly observed that high soil water potentials caused a greater LAI and excessive vegetative growth, but produced no

increase in pod yield. The ratio of pods to vegetation was lowest for the most frequently watered lysimeter. An increased ratio of pods to vegetative growth under small periodic water deficits may be a natural and important mechanism of peanut adaptation to droughty conditions where rainfall or irrigations are barely sufficient and where droughty periods are short. This response may be one of the reasons that moderate degrees of drought during early vegetative growth frequently fail to reduce final yield. By contrast, the ratio of pods to vegetation is not increased by prolonged periods of drought. Pallas et al. (1979) observed that 35- or 70-day extended drought periods reduced the ratio of pods to vegetation. The ratio was lower for 70-day droughts than 35-day droughts, and was reduced more for droughts later in the Florunner peanut life cycle. One might expect yield potential and harvest index of genotypes to respond differently to inhibition of vegetative growth by early season drought since peanut genotypes have considerable variation in partitioning to vegetative and reproductive growth. Duncan et al. (1978) showed that yield improvements of recently developed peanut cultivars are associated with increased partitioning to reproductive growth.

The particular influence of water deficit on partitioning to leaves or fruit depends on the timing of water deficit relative to fruit set. Billaz and Ochs (1961) showed that the degree of partitioning to leaves during the seed growth phase (80-120 days) of spanish peanuts was inversely proportional to the number of fruits formed earlier. If pod formation was nearly complete prior to imposing water deficit, then partitioning to fruits was increased by water deficit (resupplying water only at 100% SWD) (Ochs and Wormer, 1959). However, water deficit during pod formation (50 to 80 days) reduced flowering, pod formation, and final yield more than did water deficits at any other stage. This treatment resulted in less partitioning to fruits (but more to leaves) during the subsequent seed fill period (80 to 120 days) during which the plants were irrigated (Billaz and Ochs, 1961).

Beyond altered assimilate partitioning and reduced growth rates, two researchers reported that drought can delay the onset of rapid fruit growth and thus cause later fruit maturation. Billaz (1962) observed that water deficit from planting to 67 days delayed the period of rapid fruit growth about 10 days and decreased final yield. Boote and Hammond (1981) reported that drought between 40 to 80 days after planting delayed the period of rapid fruit addition and delayed pod maturation of Florunner by 11 days. If harvest is not delayed appropriately, the result will be immature unfilled fruits. Stansell and Pallas (1979) reported that drought from 36 to 105 days after planting of Florunner reduced % sound mature kernels to only 34%.

Influence of Water Deficit on Flowering, Pegging, and Fruit Production

Flowering. The literature contains several references to the effect of soil water deficit on flowering in the peanut plant. While the published information on drought effects on flowering seems fairly consistent, there is some disagreement on the importance of this effect on final yield.

Billaz and Ochs (1961) found that water deficit (50-80 days after planting) reduced flowering and pegging and produced a greater yield reduction than

stress at any other growth period. Lenka and Misra (1973) irrigated peanut at 25, 50, and 75% depletion of available soil moisture. They found, in agreement with Lin et al. (1963), that water deficit delayed flowering by 1-2 days and reduced the total number of flowers. Irrigation at 25% depletion produced more flowers, more seeds per pod, and greater weight per pod. Reproductive efficiency of flowers was also greatest with irrigation at 25% depletion.

Il'ina (1958) reported that floral initiation was delayed 7 days and flowering inhibited where the soil was maintained at or dryer than 35% of field capacity. Flowering is most severely affected by water stress at or just before peak flowering (Fourrier and Prevot, 1958; Billaz and Ochs, 1961; Su et al., 1964).

In contrast to observations on spanish peanut (Billaz and Ochs, 1961), Pallas et al. (1979) reported that, with Florunner peanuts in southeastern USA, yield losses were more severe the later the water stress period. It seems logical that reduction in flower numbers *per se* would not greatly lower yields, because flower number may be 20-times the number of mature fruit (Smith, 1954; Su et al., 1964). The peanut plant also tends to compensate for flower reduction due to early water deficit (Lin et al., 1963; Ono et al., 1974; Boote et al., 1976) by producing a flush of flowers and fruit when the water stress is relieved (Billaz and Ochs, 1961; Pallas et al., 1979; Boote, unpublished data) or by maturing a higher percentage of the fruits (Vivekanandan and Gunasena, 1976).

The mechanism by which soil water deficit reduces flower numbers is not known with certainty, but may be similar to leaf and node reduction. The mechanism may be more than lack of photosynthate. Pallas et al. (1979) reported that diffusive resistance measurements seem to eliminate reduced photosynthesis as the cause of reduced flowering during early-season drought. While not strictly a soil water deficit effect, Bolhuis et al. (1965) reported that low humidities (which would often accompany drought) increased the occurrence of flowers with short styles probably due to reduced turgor. This abnormality lowered the rate of fertilization and was observed to vary among cultivars.

Peg and Pod Development. The subterranean fruiting habit of the peanut plant causes soil moisture content to have a dual effect on peg penetration and pod development: (1) the effect of root zone moisture on plant growth and development and transport of water and nutrients to the fruit, and (2) the effect of the moisture content of the pegging or fruit zone (from the soil surface to 4-5 cm depth) on reproductive growth. The 2 effects are not always readily separated; thus, most of the research findings discussed here refer to soil water status without reference to root or fruit zones.

In most cases, soil water deficit during pegging and pod development primarily reduces pod number while scarcely affecting weight per pod (Matlock et al., 1961; Skelton and Shear, 1971; Underwood et al., 1971; Lenka and Misra, 1973; Ono et al., 1974; Boote et al., 1976; Vivekanandan and Gunasena, 1976; Pallas et al., 1979). The transition from pegs to pods has been identified by Underwood et al. (1971) and Ono et al. (1974) as a factor in reducing pod numbers.

Soil surface moisture content is critical to peg entrance into the soil. Cox (1962), Underwood et al. (1971), and Boote et al. (1976) observed that pegs frequently failed to penetrate effectively into air-dry soil, thus preventing fruit

growth. Boote et al. (1976) reported that, within 4 days of inducing drought in the field, the soil surface became too dry for peg entrance until water was applied. Skelton and Shear (1971) reported that adequate root zone moisture will keep pegs alive until pegging zone moisture content is sufficient to allow penetration and initiation of pod development. Once in the soil, adequate moisture and darkness are needed for pod development (Zamski and Ziv, 1976). Underwood et al. (1971) found that if pegs penetrated to 1-1.5 cm depth, some pod development occurred, but that development was slower near the surface. By introducing pegs to adequate depths in soil with various water contents, they found that the plant could offset fruit zone soil water potentials down to -15 bars, but not those of air-dry soil. Ono et al. (1974) specifically observed that adequate pegging zone moisture was critical for peg development into pods and that adequate soil moisture in the root zone could not compensate for the requirement for pegging zone moisture for the first 30 days of peg development. After 30 days of adequate pegging zone moisture, the fruit could continue normal growth in dry soil if roots had adequate moisture. Schenk (1961) observed that by this fruit age, the pod was usually expanded, with a rigid shell. Stern (1968) proposed that seed growth could continue after full pod expansion with root-supplied water even if surface moisture was inadequate. Failure of pegs to penetrate and develop pods in a dry pegging zone may also result from high soil temperature (Ono et al., 1974), greater strength of dry soil (Underwood et al., 1971), lack of turgor if roots are also in dry soil (Allen et al., 1976; Bhagsari et al., 1976; Boote et al., 1976), and lack of calcium (Ca) uptake by developing fruit caused by low soil moisture (Skelton and Shear, 1971).

For water-stressed plants, Bhagsari et al. (1976) found that leaves and immature fruit had similar water potentials. This documents a xylem connection between plant and fruit even if water is not normally transpired by the subterranean fruit. Nevertheless, the similarity of water potentials shows that the subterranean fruiting habit does not confer any special water conserving feature on fruits developing in dry soils. Boote et al. (1976) reported that low soil moisture caused sucrose to accumulate in the partially expanded immature peanut fruit, apparently because the plant water potential was too low for normal expansion, growth, and synthetic activities in the developing fruit. This was an early stress treatment before any significant numbers of fruits were set.

As mentioned previously, the peanut plant can partially compensate for an early drought period by initiating a flush of reproductive growth when moisture becomes adequate, but this may require delaying harvest until later fruits mature (Boote et al., 1976; Vivekanandan and Gunasena, 1976; Boote and Hammond, 1981). If harvest is not delayed, the weight per pod and quality may be lower because the late fruits lacked time to fill. This differs from a late season water deficit which may also cause lower weight per pod by reducing the photosynthate available to fill the pod. Either example explains the lower weight per pod frequently reported to be caused by water deficit (Underwood et al., 1971; Lenka and Misra, 1973). By contrast, Matlock et al. (1961) found that pod size and the pressure to crack the shell decreased with greater irrigation of spanish type peanuts in Oklahoma.

Effect of Drought on Calcium Uptake by Developing Fruits

Effective uptake of calcium from the fruiting zone is enhanced by adequate soil water (Table 3). A lack of water in the fruiting zone was reported by Skelton and Shear (1971) to cause more unfilled pods (pops), fewer double-loculed pods, and lower Ca concentration in the hull and seed. Gillier (1969) and Cox et al. (1976) observed that peanuts grown under drought conditions often had lower Ca levels in seeds and hulls. The typical symptoms of Ca deficiency such as "concealed damage" and "hollow heart" were more prevalent following droughts during the pod initiation and formation period (Gillier, 1969). The term "concealed damage" includes poor embryo or plumule development. Peanuts showing these symptoms had lower Ca levels in seeds and hulls than those lacking Ca deficiency symptoms.

Table 3. Effect of soil water in the fruiting zone on peanut fruit formation and the calcium concentration of the hull and seed. Adapted from Skelton and Shear (1971).

Treatment †	No. gynophores per plant	No. dead gynophores per plant	Gynophores developing into fruits (%)	Ca concentration (ppm)	
				Hull	Seed
Water	17	2	41	627	150
None	20	9	19	43	7

† Fruiting media of all treatments contained Ca. Water, when added, was added every 2 days.

Cox et al. (1976) showed that application of CaSO_4 to the pegging zone enhanced Ca uptake by fruits and, especially in dry years, caused a significant increase in yield and grade. In wet years or irrigated fields, adequate water in the fruiting zone sufficiently increased the availability of soil Ca to the developing fruits so that yield and quality showed little response to CaSO_4 .

The Ca requirement for developing fruits is caused by the subterranean nature of peanut fruits. For most crops, Ca is passively supplied to aerial fruits via the xylem transpiration stream. Peanut fruits, being underground, do not transpire significantly and, therefore, do not receive sufficient Ca from xylem flow into the fruit (Bledsoe et al., 1949; Harris and Bledsoe, 1951; Skelton and Shear, 1971). Skelton and Shear (1971) showed that movement of ^{45}Ca from rooting media to fruits was increased greatly if fruits were lifted from the soil and allowed to transpire. If Ca is also supplied to fruits by phloem transport, the amount is apparently insufficient. Wiersum (1951) also demonstrated the lack of xylem flow to peanut fruits. Water-soluble dyes failed to flow from roots to fruits unless the fruits were exposed to a drying atmosphere. By contrast, movement of dye from fruits to nearby stem nodes suggested uptake of water by fruits. Bhagsari et al. (1976) found that water potentials of leaves and immature fruits were similar under drought stress conditions. But with a moist fruit zone, xylem water would probably flow from fruits to transpiring leaves in response to water potential gradient. Water uptake by fruits may be a major factor in Ca uptake by fruits. Bledsoe et al. (1949) and Slack and Morrill (1972) conclusively demonstrated Ca uptake by developing peanut fruits and even observed some Ca movement from fruits to the foliage. Larger-fruited vir-

ginia cultivars more frequently demonstrate Ca-related quality problems under drought stress (Stansell et al., 1976; Pallas et al., 1977; Boote, Hammond, and Bennett, unpublished data, 1980). They require higher fruiting zone Ca (Slack and Morrill, 1972) and respond more to CaSO_4 applications (Walker, 1975). The sensitivity of larger-fruited cultivars to Ca supply may in fact be related to the absorptive surface area of fruits relative to internal fruit volume. While Ca requirement should be a function of fruit volume, the ratio of fruit surface area to fruit volume declines as fruits become larger. The virginia-sized fruits require more soil Ca or more adequate soil moisture than smaller-fruited peanuts for equal Ca uptake and equal fruit quality.

Effect of Water Deficit on Quality and Germinability of Harvested Seed

While drought reduces yield primarily by reducing pod number, it also causes a decline in peanut quality at harvest (Table 4). The shelling % or % sound mature kernels (SMK) is frequently several units lower for drought stressed peanuts (Matlock et al., 1961; Su et al., 1964; Sandhu et al., 1972; Saini and Sandhu, 1973; Cheema et al., 1974; Gorbet and Rhoads, 1975; Stansell et al., 1976; Varnell et al., 1976; Vivekanandan and Gunasena, 1976; Pallas et al., 1977).

Table 4. Influence of water deficit on quality and germinability of harvested seed.

Investigators	Cultivar	Irrigation Level †	% SMK	% ELK	% OK	% Germin- ation of SMK	% Dark Plumule	Seed Ca (ppm)
Pallas et al. (1977)	Florigiant	-0.2 bar	66a*	33a	3c	93	-	-
Stansell et al. (1976)		-0.6 bar	64a	35a	4bc	89	-	-
		-2.0 bar ††	61a	32a	4bc	89	-	-
		-15 bar	55b	25b	6b	82	-	-
		overnight wilt	43b	19c	8a	68	-	-
Pallas et al. (1977)	Florunner	-0.2 bar	76a	-	3b	96	-	-
Stansell et al. (1976)		-0.6 bar	75a	-	4b	96	-	-
		-2.0 bar ††	74a	-	4b	93	-	-
		-15 bar	69b	-	6b	92	-	-
		overnight wilt	58c	-	10a	91	-	-
Cox et al. (1976)	Florigiant	-1-2 bar †††	71	-	-	86	4	498
		None	69	-	-	77	10	411
Matlock et al. (1961)	Argentine	-1 bar	63a	-	4	-	-	-
		None	51b	-	12	-	-	-

† Irrigated to maintain soil water potential (ψ_s) in upper 30 cm at or above a given ψ_s .

†† Irrigated at -0.2 bars until 30 days after first bloom (60 days); then, from 60 days to harvest, irrigated whenever ψ_s declined to -2.0 bars.

††† Averaged over + or - CaSO_4 applications.

* Column means within a cultivar followed by the same letter are not significantly different at the 0.05 probability level according to Duncan's New Multiple Range Test.

Water deficit frequently decreases the weight per seed (Gorbet and Rhoads, 1975; Varnell et al., 1976; Cheema et al., 1977; Pallas et al., 1977; Pallas et al., 1979) and % of extra large kernels (ELK) (Gorbet and Rhoads, 1975; Stan-

sell et al., 1976) while increasing the % of other kernels (OK) (damaged or shriveled) (Matlock et al., 1961; Stansell et al., 1976; Pallas et al., 1979). Irrigation had no consistent significant effects on oil or protein concentrations of the seed (Matlock et al., 1961; Narasimham et al., 1977).

In addition to reduced market quality, soil water deficit may reduce the germinability of seed peanuts to be used for the next year's planting (Cox et al., 1976; Pallas et al., 1977; Pallas et al., 1979). Pallas et al. (1977) observed significantly lower germination of Florigiant, Florunner, and Tifspan seed when the seed-producing plants encountered water stress sufficient to cause wilting without overnight recovery (Table 4). Drought-reduced germinability was a greater problem for the larger-seeded Florigiant than for Florunner or Tifspan. Florigiant seed germination was also reduced for treatments irrigated only when the soil water potential of the 0-30 cm zone reached -15 bars. Cox et al. (1976) demonstrated that drought-depressed germination of Florigiant seed was associated with insufficient seed Ca level. Seed germination was reduced 17% for every 100 ppm Ca below the critical seed level of 420 ppm Ca. In the absence of CaSO_4 application, irrigation of the seed-producing crop increased next season's seed germination from 64 to 80% while increasing seed Ca and reducing dark plumule (symptom of Ca deficiency). CaSO_4 application alone increased germination from 64 to 90%. Ca application was more effective than irrigation in increasing % sound mature kernels, seed germination, and seed Ca.

Leaf Gas Exchange and Water Stress

Photosynthesis and Diffusive Resistance. Research on the effect of water stress on photosynthesis in peanuts has been limited. Bhagsari et al. (1976) found that by the end of a 5- to 6-day stress period in the greenhouse, net photosynthesis (P_n) of potted Florunner peanut plants averaged 17% of the controls (6.4 compared with 37.7 $\text{mg CO}_2 \text{ dm}^{-2} \text{ hr}^{-1}$). This was at the end of a severe stress period, from which the plants did not recover turgor overnight. Relative leaf water content (RWC) was reduced from 90% to an average of 34% by the stress treatment. Decline in transpiration rates paralleled the decrease in P_n (Figure 3). The main effect of soil water deficit on P_n was exerted through stomatal closure, as shown by simultaneous measurements of transpiration and diffusive resistance (DR). Pallas and Samish (1974) and Pallas et al. (1974) reported parallel diurnal trends in P_n and transpiration which were apparently due to stomatal changes. Diurnal patterns of stomatal opening in peanut leaves were observed by Vivekanandan and Gunasena (1976). Diffusive or diffusion resistance (DR) is a measure of resistance of the leaf stomata to water vapor loss. Higher DR indicates closure of stomata which, in turn, slows water vapor loss and reduces carbon dioxide uptake. Bhagsari et al. (1976) found that DR increased with increased water stress, with DR beginning to increase when RWC decreased below 80%.

The maximum daytime DR under water stress was only half the nighttime value, indicating that the stomata were probably partially open even under the severe daytime water stress. In another study, stomatal closure did not begin until two-thirds of the available soil water was depleted (Wormer and Ochs, 1959).

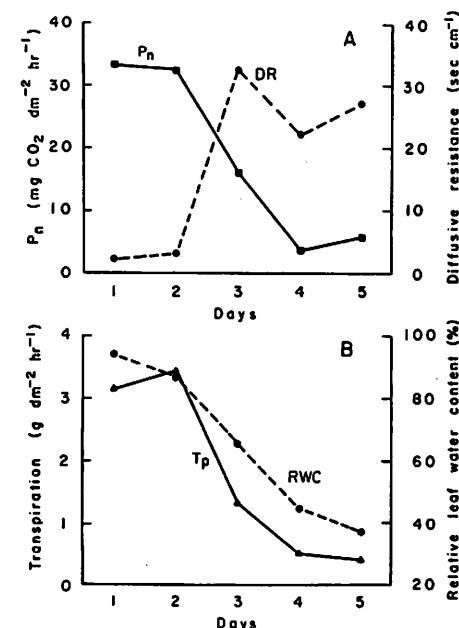


Fig. 3. Daily changes in net photosynthesis (P_n), leaf diffusive resistance (DR), transpiration (T_p), and relative leaf water content (RWC) of potted Florunner peanut plants during a drying cycle. Measurements were made at 200 nano Einsteins $\text{sec}^{-1} \text{ cm}^{-2}$ of photosynthetic photon flux density. Redrawn from Bhagsari et al. (1976).

Reduced P_n in peanuts due to water stress (Bhagsari et al., 1976) is apparently due to stomatal closure, as was reported in soybean (Boyer, 1970) and in barley (Huffaker et al., 1970). The response of P_n to water stress in peanuts was similar to that observed for soybeans and reported for cotton (Bhagsari et al., 1976). While the relationship of P_n and DR to RWC for peanut was similar to that of other crops such as soybean (Bhagsari et al., 1976), Iyama and Murata (1961) suggested that peanuts maintained leaf water content against a soil water deficit better than did soybeans or small grains. They reported that P_n of peanut first declined when soil water was depleted to 32% of field capacity compared to P_n declines for soybean and small grains at 41-45% of field capacity.

Bhagsari et al. (1976) noted that, although reduced, P_n was still appreciable in the stressed plants. The stress attained in these potted plants in the greenhouse was almost certainly greater than would normally be experienced in the field, because of limited soil volume, the higher evaporative demand, and the orientation of test leaves. Even at the greatest stresses, the test leaves were held flat and perpendicular to direct-beam radiation. Normally, the leaflets would have folded, cutting exposed evaporative surface and holding the leaf laminae parallel to direct-beam radiation. This suggests that considerable P_n is probably occurring in the field even during moderate water stress.

Chen and Chang (1974) found no difference in P_n at water regimes of 40% to 80% field capacity, except a slight reduction in P_n at 40% field capacity at a late reproductive growth stage. Tsuno (1975) studied the effect of evaporative

demand on Pn in peanuts by varying leaf temperature and relative humidity under $0.8 \text{ cal cm}^{-2} \text{ min}^{-1}$ solar radiation flux. In relatively young peanuts, Pn rates were insensitive to short-term leaf temperatures as high as 38°C , but Pn was reduced in older plants due to leaf water deficit and high stomatal resistance. In young plants, Pn was not affected when transpiration was reduced by high humidity (about 90%). Thirty-six days later, however, reducing transpiration by increasing relative humidity increased Pn. Tsuno (1975) concluded that Pn was limited in older peanut plants by the ability of the root system to supply water to the leaves. The ratio of root weight to leaf area was less in the older plants. This study compared responses of peanuts, soybeans, sweet potato, and rice. Most responses were similar in all the crops which indicates that Pn characteristics probably do not give peanuts special drought resistance, in agreement with Bhagsari et al. (1976).

Atmospheric vapor pressure deficit (VPD) was shown by Black and Squire (1979) to have a strong influence on stomatal resistance of irrigated peanuts. Under low VPD, DR was routinely as low as 0.33 to 0.5 sec cm^{-1} . Under the same irradiance (600 W m^{-2}), DR increased to 1 sec cm^{-1} as VPD increased from 10 to 30 millibars. Stomatal sensitivity to changes in VPD was greatly reduced or absent in unirrigated plants in which DR was already high. Manipulation of transpiring surface by covering some leaves of unirrigated plants decreased DR of remaining leaves and partially restored stomatal sensitivity to VPD. These results support the hypothesis that effective transpiring surface times rate is dependent on ability of roots to supply water.

The DR values reported by Black and Squire (1979) are much lower than those reported by Allen et al. (1976), Bhagsari et al. (1976), and Pallas et al. (1977) who used a non-steady state version porometer. The difference is likely due to type porometer. Black and Squire (1979) used an automatic diffusion porometer (Delta-T Devices, Mark II). Similarly low DR's for peanuts have been measured using the Li-Cor 1600 Steady State Autoporometer (Bennett, Boote, and Hammond, unpublished data, 1981). Relative treatment effects on DR are reliable from old and new style porometers but absolute comparison should not be made.

Diffusive Resistance under Field Environments. Under field conditions with deep-rooted peanuts, drought stress develops more slowly, causing a more gradual increase in DR (Allen et al., 1976; Pallas et al., 1977). Allen et al. (1976) measured DR of peanut leaves under increasing water stress conditions over a 21-day period in the field. By the 7th day of the drying cycle, there was a slight increase in DR, indicating that stomatal closure was beginning (Figure 4). Ten days into the drying cycle, DR was significantly higher in the stressed plants. This was most pronounced just prior to sunset with an average DR of 8 sec cm^{-1} in stressed plants and 4 sec cm^{-1} in the control plants.

On the 17th day of induced drought (July 7 on Figure 4), Allen et al. (1976) found an interesting pattern of stomatal response to drought by the peanut plant. By this time, water stress was fairly severe, with most available water depleted from the upper 120 cm of soil. Early in the day, DR was only slightly higher in the stressed plants than in the control plants. By 1300 hours (Eastern Standard Time), DR of the stressed plants rose to 10 sec cm^{-1} and the leaflets had folded. Intervention by cloud cover, however, caused the DR to recover to about 2 sec cm^{-1} within 1 hour, again only slightly higher than the control values. Irradiance rose again at 1400 EST, causing DR in the stressed leaves to

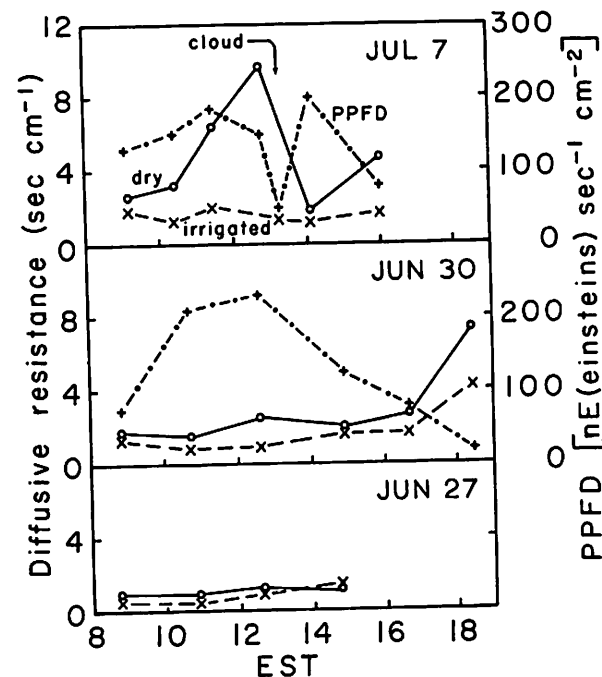


Fig. 4. Stomatal diffusive resistance for induced-drought (O) and irrigated (X) Florunner peanuts on the 7th (June 27), 10th (June 30), and 18th (July 7) day of a drying cycle at Gainesville, FL. in 1975. Average photosynthetic photon flux density (PPFD) (+) was measured during periods when stomatal diffusive resistance was measured. Reprinted from Allen et al. (1976).

begin rising slowly, reaching about 4 sec cm^{-1} by 1600 EST.

On the final day of the induced drought period, leaf water potential (Ψ_L) in the stressed plants had reached the extremely low value of -8.3 bars (-8.3 MPa) under high evaporative demand conditions. Even under these extreme soil water deficit conditions, Ψ_L rose rapidly to -8.5 bars by sunset under cloudy, humid conditions. For comparison, the control leaves were at -13.3 bars near midday and -4.9 bars at sunset. Two days following the end of the drought, Ψ_L in the stressed plants was -4.3 bars at the end of a cloudy day, with -3.9 bars for the controls.

Allen et al. (1976) concluded that drastic stomatal closure occurred in peanuts only when most soil water was depleted. At that time, the plants reduced further water loss by folding their leaflets, which reduces exposed evaporative surface area and places leaf laminae parallel to direct-beam radiation.

Pallas et al. (1979) measured mid-day DR in Florunner peanuts subjected to drought at 36-70, 36-105, 71-105, 106-145, and 71-145 days of age. The early 35-day drought had little effect on DR. The early 70-day drought increased DR 5-fold over controls. Mid-season 35-day stress increased DR 12-fold on the lower leaf surface and 5-fold on the upper surface. After irrigation, DR for these treatments returned to that of the controls. The late 40-day stress did not affect DR, but the 75-day mid-to-late stress doubled DR by harvest. Pallas et al. (1979) reported that peanuts, like soybeans, may recover stomatal function more quickly following relief of water stress than has been reported

for some species. This agrees with the rapid recovery of DR and water potential with a lowering of evaporative demand observed by Allen et al. (1976). This ability to rapidly recover stomatal function with relief of water stress may be an important adaptive response of peanut plants to drought.

Reddy (1969) reported that water stress reduced chlorophyll concentration of peanut leaves. This might reduce P_n , since chlorophyll absorbs light energy and aids in its transformation into chemical energy in the photosynthetic process. Concentrations of both chlorophyll a and chlorophyll b were reduced by water stress. Chlorophyll a/b ratio was not altered. Reduction in chlorophyll was greater in distal than in proximal leaflets.

Leaf Display

During periods of water deficit and high radiant energy load, peanut leaflets have been observed to fold from their more normal horizontal or sun-tracking positions to an orientation nearly parallel to the incident radiation (Il'ina, 1958; Allen et al., 1976; Bhagsari et al., 1976). The vertical folding together of the compound leaflets minimizes leaflet interception of direct-beam radiation. This minimizes leaf temperature and water vapor gradient at a time when stomata are nearly closed and the leaf least able to lose heat by transpirational cooling. This response may be considered an adaptation to drought avoidance because it permits a reduction in leaf heat load and evapotranspiration. Il'ina (1958) reported a layer of transparent aquiferous cells (also called motor cells) on the lower side of the leaf and along the leaf vein. A decrease in water volume of these aquiferous cells during water stress was suggested to be the physical mechanism causing the vertical folding of the peanut leaflets. Leaflet folding may be related to the inhibition of active ion transfer mechanisms between these cell types. Direct evidence concerning peanuts is lacking; however, ion transfer mechanisms in pulvinar regions of petiolules have been associated with leaflet movement in other plants (Satter and Galston, 1971; Satter, 1980). *Albizia julibrissin*, a species which undergoes nighttime leaflet folding (nyctinasty) similar to peanut, unfolds its leaflets in the light in response to active K^+ from the ventral cell membranes (Satter and Galston, 1971). Active K^+ transport appears to be essential for both leaflet unfolding and for stomatal opening. Abscisic acid, which accumulates during drought stress (Beardsell and Cohen, 1975), induces stomatal closure by inhibiting active K^+ transport into the guard cells, thereby resulting in less guard cell turgor and less stomatal opening (Mansfield and Jones, 1971; Horton and Moran, 1972). Abscisic acid appears to increase membrane permeability to water and to decrease membrane selectivity (active transport) toward certain ions (Glinka, 1980). During water stress, accumulation of abscisic acid would inhibit active K^+ transport, thereby reducing both stomatal opening and the degree of leaflet unfolding.

Plant Water Potential Measurements

Leaf water potential of frequently irrigated peanuts has not been found to be less than -12 or -13 bars (-1.2 or -1.3 MPa) (Allen et al., 1976; Pallas et al., 1977, 1979). By contrast, water-stressed peanut plants had leaf water potentials of -30 to -45 bars (Bhagsari et al., 1976; Pallas et al., 1977, 1979). Bhag-

sari et al. (1976) also observed that water potential of pods was similar to that of leaves on stressed and non-stressed peanuts; thus peanut fruit, in spite of being underground, are exposed to similar degrees of water stress. These reported values were obtained with *in situ* leaf thermocouple hygrometers in the dew point mode (Allen et al., 1976; Bhagsari et al., 1976; Pallas et al., 1977, 1979). Pallas and Michel (1978) demonstrated the reliability and technique for using *in situ* leaf thermocouple hygrometers. By contrast, Allen et al. (1976) and Pallas et al. (1979) experienced difficulty in measuring peanut water potential with the pressure bomb technique. With the pressure bomb technique, phloem sap exuded at low pressures and made it nearly impossible to visually observe xylem sap expression. Gautreau (1978), used the tedious Chardakov densimetric dye technique and reported leaf water potentials of near -12 and -17 bars at mid-day for 80 to 90 day-old peanuts grown under high and low water treatments, respectively, during the dry season in Senegal. Water potential was more negative on drought-stressed plots, decreased throughout the morning hours, and decreased during the crop life cycle.

Thermocouple psychrometry was used by Bennett et al. (1981) to evaluate the relationship of leaf turgor potential (Ψ_p) to leaf water potential (Ψ_L), leaf osmotic potential (Ψ_π), and leaf relative water content (RWC). Leaves from irrigated Florunner plants were sampled at 0800 hours, hydrated on deionized water for 2 hours, and then allowed to desiccate for varying time periods during which Ψ_L , Ψ_π , Ψ_p , and RWC were determined. Turgor potential (Ψ_p) was calculated from Ψ_L minus Ψ_π . Zero Ψ_p was achieved at Ψ_L of -12.5 bars (Figure 5A). The relationship of Ψ_p to RWC indicated that Ψ_p was +12 bars at 100% RWC and decreased linearly to zero Ψ_p at RWC of 86% (Figure 5B).

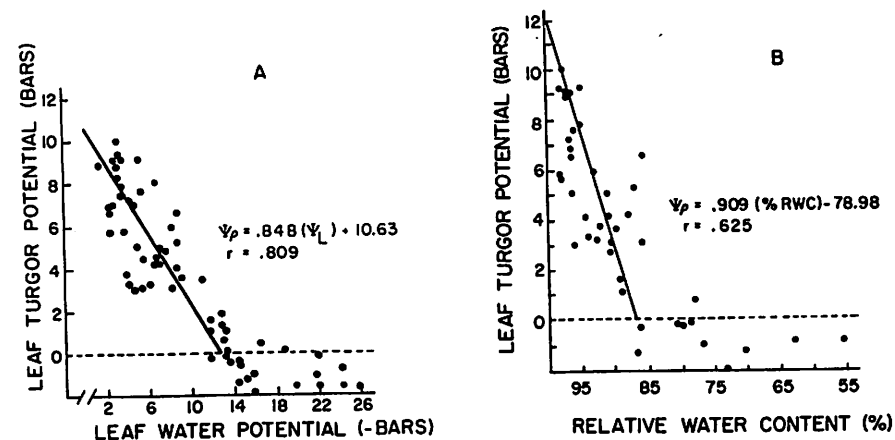


Fig. 5. The relationship of: A. Leaf turgor potential to leaf water potential, and B. Leaf turgor potential to relative leaf water content, for well-watered Florunner peanut leaves. Reprinted from Bennett et al. (1981).

The Ψ_π at 100% RWC was -11.4 bars. These relationships are characteristic of those reported for leaves from irrigated plants of other species. Under field drought conditions causing apparent zero Ψ_p (leaf wilting), Bennett et al. (1981) observed considerably lower Ψ_π (-15.3 bars) indicative of osmotic adaptation beyond a solute concentration effect.

Response of N₂-Fixation to Water Deficit

The influence of water stress on N₂-fixation by peanut is largely unknown. Lenka and Misra (1973) reported fewer nodules per plant (240 versus 553) for peanuts irrigated at 75% soil water depletion (SWD) compared to 25% SWD. By contrast, Shimshi et al. (1967) found no effect of irrigation frequency on nodulation events. Peanut nodulation in response to inoculation on *Rhizobium*-free soil was not inhibited by repeated drying of the top 5-10 cm of soil between 2 or 3 week irrigation applications. Although more frequent irrigation tended to give somewhat better early nodulation, the nodule number, nodule weight, and pod yields at the end of the season were similar for 7, 14, or 21 day irrigation frequencies on a deep loess soil. Irrigation in the moderate climate of Ontario also caused no effect on nodule number or nodule weight per plant, although N₂ (C₂H₂ reduction) fixation and yield of spanish peanuts was increased (Reddy, 1978; Reddy and Tanner, 1980). Irrigation also increased the fraction of total plant N coming from N₂-fixation, partly because more N fertilizer was leached from the soil. In spite of limited data on peanut, there is no reason to suspect that N₂-fixation in peanut responds any differently to soil water deficit than other grain legumes (Sprent, 1976).

Genotypic Variation in Drought Tolerance

Drought-tolerant peanut cultivars are needed in semi-arid regions. Investigators at the Research Institute for Oils and Oilseeds in West Africa have attempted to define physiological differences associated with drought resistance in known varieties and set up tests to screen germplasm and hybrid progeny for drought tolerance. Tests to screen germplasm included: 1) germination at high osmotic concentrations, 2) relative rate of early growth, and 3) heat resistance of young plants. Progenies were further screened by comparisons of relative transpiration rate and water potential of leaflets (Gautreau, 1978).

Early (90 day) and late (120 day) varieties have been developed for West Africa which have drought tolerance and yield better than other cultivars in dry years; however, they have equal yield in normal years (Bockelee-Morvan et al., 1974; Gillier, 1978). They reported that a cultivar, C-55-437, produced yields of 1920, 1275, and 485 kg ha⁻¹ with only 296, 242, and 156 mm of rainfall, respectively, in Senegal and Nigeria. In zones normally receiving 400 to 750 mm of rainfall, a 120-day cultivar, C-59-127, gave higher yields in wet seasons, yet had good yields in drier years.

Gautreau (1978) separated his collection of peanut cultivars into 3 groups having low, intermediate, and high leaf water potentials which corresponded inversely to yield levels. The low yielding cultivars had higher water potentials and the higher yielding, drought-tolerant cultivars had lower, more negative, water potentials. Theoretically, a more negative water potential should allow drought-tolerant cultivars to have a steeper water potential gradient to drive root uptake of water. This would be a drought tolerance or drought withstanding trait. As reviewed by Elston and Bunting (1978), other varieties lacking this trait may also be adapted to dry areas because of low LAI, short season (avoidance or escape), or because of indeterminacy and recovery mechanisms.

Accumulation of free proline in leaves is a response associated with drought stress. Mehkri et al. (1977) surveyed 10 peanut cultivars for free proline ac-

cumulation in leaves and found that under stress conditions the drought-tolerant cultivar, C-55-437, accumulated more proline and fixed more ¹⁴CO₂ than the other cultivars. Proline accumulation was not correlated to relative water content.

Sensitivity of Peanut to Drought at Various Growth and Development Phases

To effectively irrigate peanuts, one must consider the current stage of growth and development of the peanut crop. For example, water extraction is affected by rooting extension, and crop evapotranspiration (E_c) is influenced by canopy cover and LAI. Moreover, pegging and fruiting have particular requirements for adequate moisture in the fruiting zone.

To facilitate discussion of water deficit relative to crop growth and development, Figure 6 shows dry matter accumulation and distribution for Florunner peanut (McGraw, 1977) in conjunction with visually identifiable phenological stages proposed by Boote (1982). The proposed vegetative and reproductive stages are similar to those developed for soybeans by Fehr et al. (1971). The phenological events appear in order and are affected by temperature, soil water deficit, and genotype. The shorter season spanish-valencia cultivars differ primarily by having shorter intervals between stages and a more compressed period of dry matter accumulation and distribution.

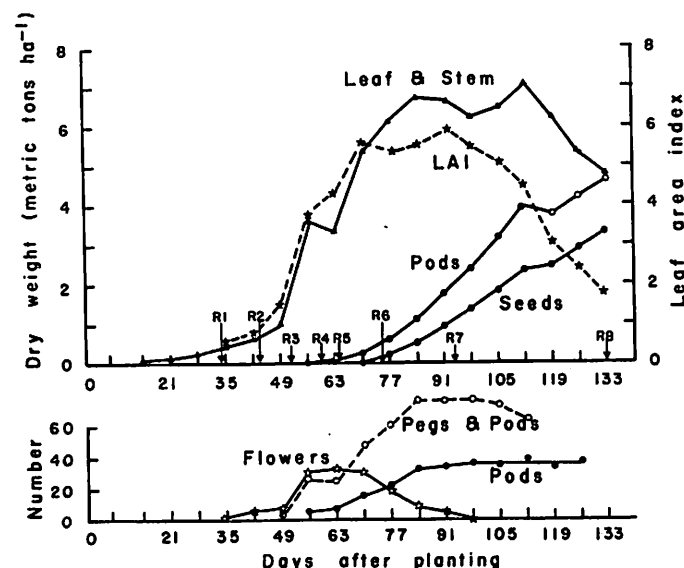


Fig. 6. Dry matter distribution and reproductive development of Florunner peanut relative to reproductive growth stages during the 1976 season at Gainesville, FL. Adapted from dry matter distribution of McGraw (1977) and growth stages of Boote (1982). Reproductive stages are R1 (beginning bloom), R2 (beginning peg), R3 (beginning pod), R4 (full pod), R5 (beginning seed), R6 (full seed), R7 (beginning maturity), and R8 (harvest maturity).

During Vegetative Growth. One can hypothetically evaluate the effect of water deficit at different periods in the Florunner peanut life cycle. For example, water deficit during the first 7 weeks should primarily reduce only vegetative growth, since few flowers and pegs are present (Figure 6). Since vegetative growth of peanuts is frequently excessive in wet years (Gorbet and Rhoads, 1975; Vivekanandan and Gunasena, 1976), we would expect minor effects on final yield if moderate water deficit was relieved by 50 days after planting. Several researchers (Il'ina, 1958; Su et al., 1964; Stansell et al., 1976; Reddi and Reddy, 1977; Pallas et al., 1979) have observed that water deficit only during vegetative growth has minimal effects on peanut growth and yield. Likewise, less frequent irrigation and irrigating at greater SWD has its least detrimental effects if applied prior to pegging and pod formation (Subramanian et al., 1975; Reddi and Reddy, 1977). Moderate stresses are less damaging during vegetative growth, and the ground cover and LAI are incomplete. Thus, less water is consumed for evapotranspiration, and irrigation amounts and frequency can be reduced during this phase. Moreover, early vegetative growth may continue by using up much of the stored soil water as root extension increases.

During Pod Formation and Addition. The period of pod formation and pod addition is probably the period when peanut plants are most sensitive to water deficit; therefore, irrigation is more essential at this time (Sandhu et al., 1972; Subramanian et al., 1975; Reddi and Reddy, 1977). Phenologically, this period starts when the peg tips first begin to swell (R3-beginning pod) and ends when a full fruit load has been established and vegetative growth begins to slow down (Figure 6). For Florunner, this period continues from about 50 to 90 days after emergence. In Spanish peanuts, pod formation starts sooner and ends about 10 to 15 days earlier. Differences in varietal development may account for some of the discrepancies reported for the periods most sensitive to water deficit. For a Spanish cultivar, Su et al. (1964) reported that 50-69 days was the most critical 20-day period for water deficit, closely followed by the 30-49 day period. Billaz and Ochs (1961) indicated greatest drought susceptibility at 50-80 days of age, followed by 30 to 50 days and 80 to 120 days of age. Su and Lu (1963) reported drought sensitivity of short season peanuts in the following descending order of severity: 30 to 60 days, 0 to 30 days, 60 to 90 days, and 90 to 120 days after planting. Thus, the most drought sensitive period for short season peanut is between 30 and 80 days, although the review by Klepper (1973) indicated 30 to 60 days. On the other hand, the peak sensitivity to soil water deficit for the long season cultivar Florigiant was given as 87-94 days after planting (Cox et al., 1976), although Martin and Cox (1977) subsequently identified 50 to 80 days as the critical period for Florigiant. Stansell and Pallas (1979) reported that drought from 71 to 105 days of age was more damaging to seed yield of Florunner than drought at 36-70 days or at 106-140 days. The apparent differences in periods sensitive to drought for short- and long-season cultivars is caused partly by different maturities (absolute days to a stage) and partly by additional vegetative growth, pegging capacity, and longer seed filling periods of the later maturing cultivars (which reduce the impact of early droughts).

The greater drought sensitivity of the pod formation and addition phase is partly related to the fact that the crop reaches its peak water use and evapotranspiration during this time. Additionally, this is the period in which a fruit

load is set. Soil water deficit may reduce fruit addition in 1 of several ways. First, low soil moisture in the fruiting zone reduces peg penetration and fruit formation (Cox, 1962; Underwood et al., 1971; Ono et al., 1974; Boote et al., 1976). This may be related to water requirement for adequate Ca uptake by developing fruits (Gillier, 1969; Skelton and Shear, 1971; Cox et al., 1976). Second, if both soil and plant water potentials are low, plant turgor pressure may be reduced to the point that peg elongation, fruit expansion and fruit addition are inhibited and sucrose accumulates (Bhagsari et al., 1976; Boote et al., 1976). Third, water deficit reduces photosynthesis (Bhagsari et al., 1976), thereby limiting the number of fruit added and decreasing final yield. On the basis of shading studies, An (1978) found the period from 65 to 86 days to be most sensitive to reduction of photosynthate supply in term of yield reduction of Florunner peanut. Drought-induced reductions in photosynthesis would likely have the same effect on fruit addition. If water deficit is relieved after 86 days, late pods may be added, but this would cause fruit of different maturity at harvest.

During Seed Growth and Maturation. After a full fruit load is set (about 90 days for Florunner), water deficit reduces yield primarily by causing smaller and younger fruits to terminate growth and possibly by reducing growth rate of older fruit. Prolonged water deficit during seed growth and maturation (90 days to maturity) can reduce yield of peanuts almost as drastically as stress during the pod addition phase (Pallas et al., 1979). Increased numbers of shriveled and aborted seeds reduces quality and yield.

Water deficits during the latter part of the seed fill period are somewhat less critical because pods have been formed and water use and evapotranspiration have declined somewhat. Excessive and too frequent irrigation or rainfall during later phases of fruit growth might reduce yield, especially on heavier soils or those with restricted drainage. Decreased yields, probably associated with weakened peg attachments and a subsequent loss of detached pods, were related to more frequent irrigations on a clay soil (Mantell and Goldin, 1964) and to frequent irrigations applied to maintain a high soil water potential (-0.2 to -0.4 bars) in loamy sand soils (Gorbet and Rhoads, 1975; Stansell et al., 1976).

EVAPOTRANSPIRATION AND WATER USE BY PEANUT CANOPIES

Defining Evapotranspiration, Crop Water Use, Water Use Efficiency, and Water Application

Evaporation and transpiration are the primary mechanisms of consumptive water loss during crop production. Evaporation of water is a response to applied energy. In agricultural terms, evaporation is water which is vaporized and dispersed into the atmosphere without passing through the plant. Transpiration, on the other hand, is the process by which water is vaporized from within the living plant. The combination of the 2 processes is commonly described as a single term evapotranspiration (E_t). Potential evapotranspiration (E_p) is the rate of water loss from a freely-evaporating surface (often estimated from pan evaporation). Actual evapotranspiration (E_a) can be less where water is not available or resistances such as stomatal control reduce water loss.

Crop water use must be carefully defined to prevent confusion with seasonal water applied. Seasonal water application includes all water received (irrigation plus rainfall) whether lost to crop water use, to runoff, to percolation, or left stored in the profile. The most appropriate figure for water regulating agencies is the total seasonal water application because irrigators sometimes receive unpredictable rainfall, which is frequently unused by a crop because it is lost to runoff or percolation. Crop water use or evapotranspiration is equal to water used from irrigation water, effective rainfall, and soil profile water. Soil water content measurements can be used to show initial and ending soil water storage and to determine whether rainfall additions are stored in the profile or moved beyond the rooting zone. Such deep soil losses must be excluded from E_t estimates. Water use efficiency (WUE) is defined as pod yield per ha per cm of water used for evapotranspiration. It indicates whether irrigation or cultural practices were successful in conserving water, but it does not define the point of greatest economic yield. Highest WUE will frequently occur on relatively dry treatments having less than the highest economic yields.

Experimentally Estimating E_t from Soil Water Balance

Evapotranspiration can be defined by the net loss in soil water during a period of interest. Soil water can be measured at the start of the period and at the end, with evapotranspiration loss determined by difference. The neutron-scattering technique is well adapted to this procedure and excellent instruments are commercially available. Of course, this water difference method does not account for evapotranspiration where dew on the plants is the water source. Measurement of water loss using weighing lysimeters will account for such sources, and weighing techniques are probably regarded as definitive on evapotranspiration. Weighing lysimeters capable of accounting for losses over periods of a few minutes length and which have large root volumes are very expensive. Neutron scattering meters are manageable in many research programs, but the researcher must be careful to include all the soil profile which contributes water to evapotranspiration. If measurements to such depths (no less than 1.2 m) are not feasible, then a means for estimating flux density of water across some arbitrary lower bound must be made. Even at 1.2 m depth, such flux can account for as much as 20% of the net water change in the profile in high rainfall periods of the growing season. If soil water conductivity information is available, such flux densities can be determined from the Darcy law and measurements of water potential across the boundary (Hillel, 1980).

In general, if information is needed on evapotranspiration as related to causal effects, the researcher can use energy budget or direct vapor exchange techniques to estimate evapotranspiration. If one must merely characterize the water loss itself, the more direct soil moisture changes, as outlined above, are used.

Seasonal Trends in Evapotranspiration and Water Use

The seasonal trend of daily water use and evapotranspiration of peanuts was measured under controlled lysimetric conditions by Kassam et al. (1975), Stansell et al. (1976), and Vivekanandan and Gunasena (1976). In each of

these experiments, rainfall and ground water were excluded. Water applications for peanut growth were carefully controlled to prevent or allow measurement of percolation. Daily water use (evapotranspiration) was calculated from soil water profiles and irrigation water.

Figure 7 illustrates seasonal evapotranspiration data for peanut cultivars, Florigiant, Florunner, and Tifspan, as determined by Stansell et al. (1976). Daily water use was low during early vegetative growth, but increased as the leaf canopy developed and closed. The maximum daily water use rate ranged from 0.5 to 0.6 cm day⁻¹ with similar results being obtained by each of the above three research groups. Under very high evaporative demand conditions in Israel, daily water use of Improved Virginia Bunch averaged 0.69 cm day⁻¹ during 53 to 83 days after planting (Mantell and Goldin, 1964). Stansell et al. (1976) observed that maximum water use rates occurred at 70, 80, and 95 days after planting for Tifspan, Florunner, and Florigiant cultivars, respectively. The delays in the peak daily water use are consistent with varietal differences in maturity. The period of maximum E_t for spanish peanuts was reported at 67 to 77 days after planting by Kassam et al. (1975), and at 55 to 80 days by Vivekanandan and Gunasena (1976). Goldberg et al. (1967) observed peak evapotranspiration to potential evapotranspiration ratios (E_t/E_p) for Virginia Bunch peanuts at 70 to 110 days after planting — a period of complete ground cover. Kassam et al. (1975) observed that peak E_t occurred shortly before peak LAI was achieved. After full foliage development and ground cover, daily E_t for all varieties gradually declined from the maximum until the plants reached maturity. This may be due in part both to plant senescence and to seasonal decrease in potential E_t .

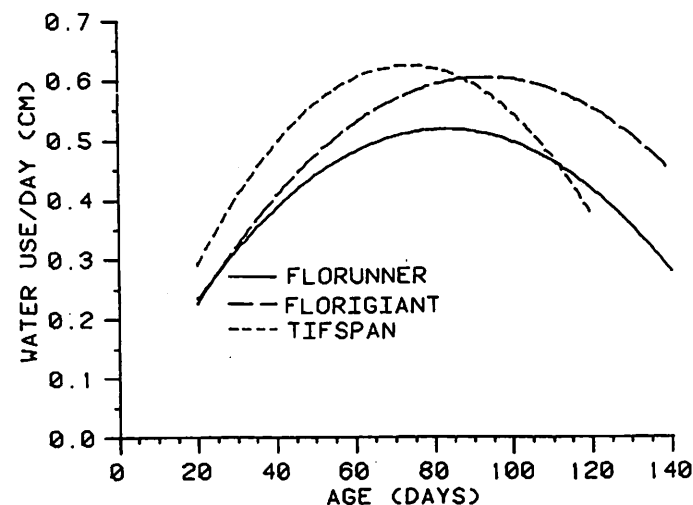


Fig. 7. Water use by peanuts as a function of age when grown under optimum soil water conditions. Reprinted from Stansell et al. (1976).

Yield Response to Water Use

Between 50 to 60 cm of water, if reasonably well distributed, will provide satisfactory peanut production (Mantell and Goldin, 1964; Gorbet and Rhoads, 1975; Stansell et al., 1976; Pallas et al., 1977; Hammond et al., 1978). What constitutes reasonable distribution can vary widely. In Israel, on fine textured sandy clay and clay loam soils, Mantell and Goldin (1964) obtained high yields (5800 kg ha^{-1}) on plots irrigated at 30-day intervals. On a fine sand, irrigation every 7 days may not be sufficient during a prolonged rain-free period.

The importance of distribution is seen in the data of Matlock et al. (1961). They reported irrigated yields in the 1957 growing season which had 46 cm of rainfall. All irrigations were 7.5 cm. The month of July was virtually without rain. One treatment received irrigation on July 21 and another on July 31. August rainfall was 7.5 cm and each treatment received 1 irrigation in August. The treatment irrigated on July 21 yielded 2690 kg ha^{-1} and the other treatment was significantly different at 1810 kg ha^{-1} .

Data from many sources were used to derive 2 figures representing yield response to crop water use and water supply, respectively. The first was taken from results measured under carefully controlled lysimetric conditions (Figure 8) and represents water use. The second (Figure 9) was for short season cultivars under variable field conditions, some of which may have suffered periods of excess rainfall and apparent percolation. The latter represents response to water use and/or water supply. The highest yield of short season or full season peanuts occurred when seasonal water use was 60 cm or more. The yield response was gradual between 40 to 60 cm, but yield rapidly dropped to zero as water use declined from 40 to 10 cm. In the linear range of yield response to water use (up to 50 cm), yield increased 93 kg ha^{-1} for each additional cm of water evapotranspired (Figure 8). Similarly, in crop seasons receiving less than 50 cm rain-

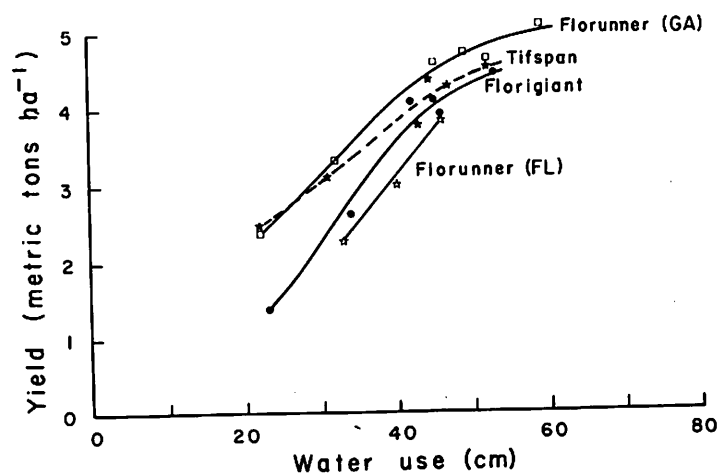


Fig. 8. Peanut yield response to water use in controlled experiments. Data for Florunner (□), Tifspan (★), and Florigiant (●) at Tifton, GA from Stansell et al. (1976) and Pallas et al. (1977). Data for Florunner (☆) at Gainesville, FL from Hammond et al. (1978).

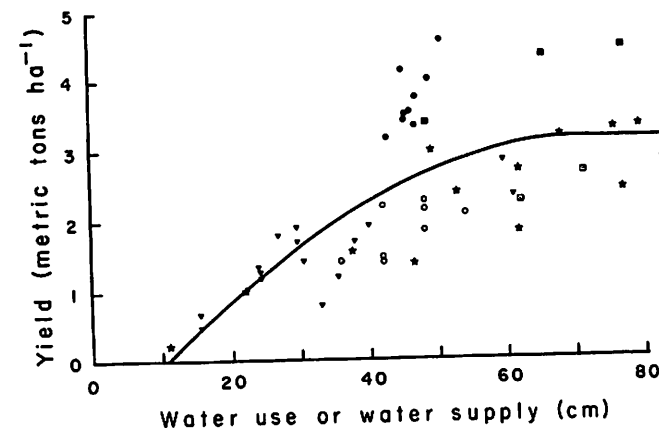


Fig. 9. Yield response of short season peanuts to water use or water supply (rainfall plus irrigation) in a variety of field experiments. Data from Matlock et al., 1961 (★), Subramanian et al., 1975 (○), Narasimham et al., 1977 (■), Reddi and Reddy, 1977 (●), Lenka and Misra, 1973 (□), and Bockelee-Morvan et al., 1974 (▼).

fall plus irrigation, yield response was 76 kg ha^{-1} for each additional cm of rainfall or irrigation (Figure 9). Sixty cm appears to be the minimum water supply required for optimum yield if seasonal distribution is good. If distribution is poor, even more water must be supplied. Up to 50% of the yield variability in Figure 9 was attributable to factors other than water use. A future approach to irrigation scheduling may take a crop modeling approach to include factors such as crop sensitivity stages, leaf area, diseases, insects, nematodes, rooting depth, and soil water holding characteristics plus driving parameters of real time weather data: rainfall, humidity, temperature, wind, and solar radiation.

CHARACTERIZING EVAPOTRANSPIRATION

Energy Balance Considerations

Evaporation and transpiration are processes which occur in response to applied energy. The energy for evapotranspiration initially comes directly from the sun as that portion of solar radiation which is converted to heat when absorbed by plant or soil surfaces. An energy input of 586 calories (2452 J) at 20°C is required to vaporize 1 cm^3 of water. Heat for vaporization can come from the soil, the plant, or the air (Israelson and Hansen, 1962), although the air more frequently absorbs excess heat from plants, and the wind transports this heat away from the crop canopy. When the air is warmer than the plant canopy, heat is absorbed by the canopy and E_t will be increased, especially if the air masses are dry and windy. The mechanisms involved in the conversion of this energy and the wind effect to cause E_t are complex but are discussed in several texts (for example, Jensen, 1973; Rosenberg, 1974; Campbell, 1977).

The partitioning of energy in a peanut field in the southwestern USA is illustrated by data of Stone et al. (1976) and McCauley et al. (1978). Figure 10 shows input solar energy (R_s), net radiation (R_n), and evaporative energy flux (LE) throughout an arid day for peanuts grown in 30 cm and 90 cm rows oriented in north-south or in east-west directions. For some portions of the day, the LE curve was above the R_n curve. In these cases, all the net radiation was going to evapotranspiration and some heat energy was extracted from the air and used for E_t . Note that the LE curves were generally below the R_n curves in the late afternoon. This indicated sensible heat was exchanged to air. This is characteristic of dry regions. As Lemon (1963) indicates, in humid regions where advected sensible heat plays only a minor role in dense crops, evaporation appears to be largely controlled by radiant energy supply. Thus, curves in the fashion of Figure 10 for southeastern USA peanut area would be expected to show the LE curve close to the R_n curve throughout the day. There, little of the net radiant energy becomes sensible heat.

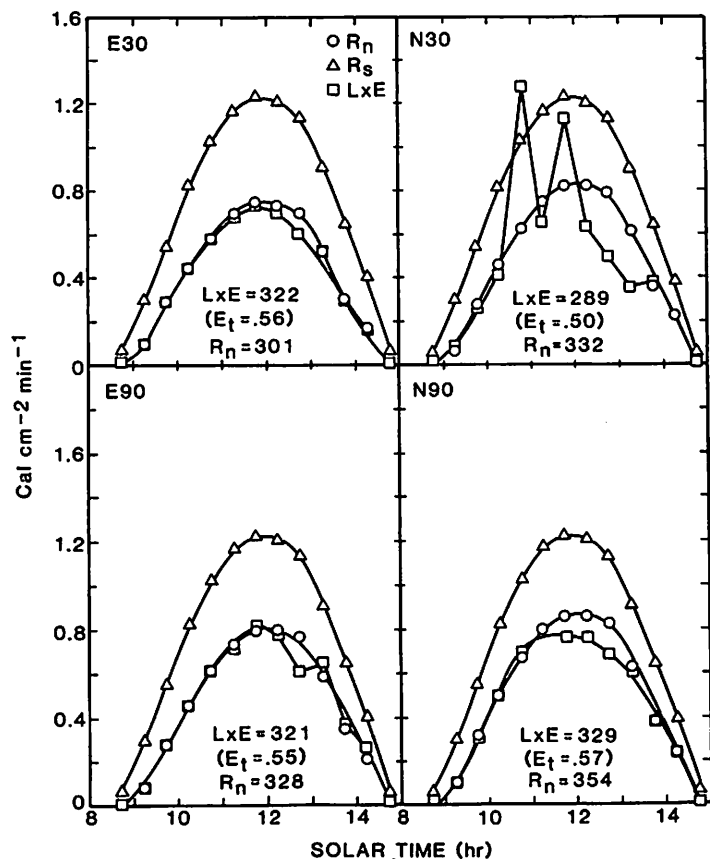


Fig. 10. Solar radiation (R_s), net radiation (R_n), and evaporative energy flux (LE = LxE) throughout an arid day for Comet spanish peanut grown in two row spacings (30 versus 90 cm) in two row directions (E-W and N-S). Total R_n and LE (Cal cm⁻²) and total evapotranspiration (cm) for the day is listed on each graph. Unpublished data, courtesy J. F. Stone, G. N. McCauley, E. W. ChinChoy, and H. E. Reeves.

An Integrated Approach to Characterizing Evapotranspiration

Characterizing evapotranspiration of a crop involves more than the meteorological inputs. While environmental factors of radiation, temperature, humidity, and windspeed interact to cause an evaporative demand, the evaporative demand is not always met or supplied. Crop E_t can be as high as the environmental demand or considerably less depending on wetness of the soil surfaces, the degree of soil covered by foliage, and the availability of soil water in the root zone. One approach to integrating all these diverse factors into a more unified concept of crop evapotranspiration is to develop crop-water economy models such as those described by Jensen et al. (1971), Jensen (1973), and Jensen and Wright (1978). The model of Ritchie (1974, 1976) is a good example. These water economy models use common meteorological information, most require information on soil characteristics and rooting depth, and some even require leaf area index and other hard-to-measure parameters of the crop. They all attempt to predict or account for E_t losses at all times. Such modeling approaches are not yet perfected and many have built-in compromises which restrict their usefulness to particular crops, environments, and locations. Nevertheless, the potential for using these approaches to schedule crop irrigation appears promising. Now, we will examine the individual effects of climate, plant, cultural, and soil factors on evapotranspiration.

Climatic Factors Affecting Evapotranspiration

Solar Radiation. Solar radiation is the ultimate source of energy for all plant processes, including evapotranspiration. It supplies energy which warms the air, soil and plant, thus providing heat for vaporization. As seen earlier in Figure 10, the net radiation (R_n) largely determines the E_t rate and net radiation is largely determined by solar radiation (R_s). R_n is closely related to R_s and can often be estimated by $R_n = (1 - \alpha)R_s - R_b$ where α = reflectivity for solar radiation of the crop canopy and exposed soil and R_b is the outgoing thermal radiation (Jensen, 1973).

There are only a few studies on the direct effect or relationship of solar radiation to evapotranspiration by peanut plants. Lysimetric water balance studies by Stansell et al. (1976) show greater daily evapotranspiration in mid-summer when solar radiation is high. This is confounded with growth phase and seasonal temperature. Short term (0.5 minute) measurements of water vapor flux from peanut canopies showed close relationships to incident photosynthetic photon flux density (Boote, Bennett, and Hammond, unpublished data, 1981). Integrating these instantaneous E_t rates over the course of a day resulted in daily E_t very comparable to that reported by Stansell et al. (1976).

Rapid changes in solar radiation absorbed by the leaves can cause rapid changes in transpiration. Stansell et al. (1973) recorded the response of a cotton plant to direct radiation following brief cloud cover. Radiation intensity increased from 0.4 cal cm⁻² min⁻¹ to 1.0 cal cm⁻² min⁻¹ within 2 minutes. Leaf water potential decreased from -10 bars to about -14 bars within 2 minutes and to -18 bars in 6 minutes. A decrease in stem diameter was recorded within 6

minutes. This implies a very rapid increase in transpiration in response to the increased radiation.

Temperature and Relative Humidity. Evapotranspiration is enhanced by high temperature and low relative humidities; and ironically, it tends to moderate both. Temperature indicates the level of energy stored in air, soil, water, and plants. The product of temperature of a body and its heat capacity represents heat energy and this heat represents some of the energy available for evapotranspiration. The energy lost to long-wave radiation can be about 15 to 20% of incoming R_s and is proportional to the 4th power of the absolute temperature (Jensen, 1973). The remaining energy is dissipated to sensible heat (or to latent heat of vaporization). If leaf temperature is greater than air temperature, sensible heat is transferred to the air, cooling the leaf. If the vapor pressure is higher in the substomatal cavities than in the air and if the stomates are open, water vapor moves into the air, carrying latent heat of evaporation and thus cooling the leaf. Obviously, this process cannot be sustained without continual input of energy. If the vapor pressure of the air is greater than that in the leaf, there will be little or no evapotranspiration. In addition to meteorological factors, a leaf under drought stress will likely have lower water potential and lower vapor pressure than a turgid leaf. Hypothetically, the lower vapor pressure difference between leaf to air would reduce evapotranspiration. However, at 25 C and 50% relative humidity, the gradient would drop an insignificant 2% for a 10 bar decline in Ψ_L (Milthorpe, 1961).

The temperature and humidity of the air, in conjunction with radiant energy supply, can be considered to define the evaporative demand. Lower evaporative demand in late season was shown to reduce evapotranspiration rates (Stansell et al., 1976) and to reduce plant water stress (less negative water potential) even at similar low soil water potentials (Pallas et al., 1979). Increased evaporative demand on peanut canopies does not necessarily mean reduced photosynthesis and growth of peanut canopies, provided root uptake of water is adequate. Tsuno (1975) increased evaporative demand (by varying temperature and humidity) and observed no effect on leaf photosynthesis during early growth but found reductions during a later growth phase.

The degree to which evaporative demand (E_o) is met by actual evapotranspiration (E_t) can be represented by ratios of E_t/E_o . The seasonal ratio of E_t/E_o during full ground cover was estimated at about 0.8 to 0.9 under arid conditions in India and Israel (Mantell and Goldin, 1964; Goldberg et al., 1967; Cheema et al., 1974), but higher (about 1.0) during a rainy, humid period in Samaru (Kassam et al., 1975). The failure of E_t to meet E_o in arid regions results because there is a lower availability of free soil surface moisture (a function of rainfall and irrigation frequency) and free leaf surface moisture (dew) to evaporate. The ratio of E_t/E_o during the season is increased by more frequent irrigations (Mantell and Goldin, 1964; Goldberg et al., 1967; Cheema et al., 1974; Cheema et al., 1977). When irrigation was supplied to replace 0.9 rather than 0.6 of the cumulative pan evaporation between irrigations, the ratio E_t/E_o increased from 0.73 to 0.92 (Goldberg et al., 1967). Thus, increased soil moisture supply increases the E_t/E_o ratio; however, these increases were not always associated with increased yield. Apparently, some of the additional water may be evaporated from the soil or transpired without increasing the rate of dry matter production by the crop.

Wind (Air Turbulence). If water vapor escaping to the atmosphere is removed from the evaporating surface, continuous evaporation can occur and is then energy limited. Air turbulence in and above the crop canopy is the primary transport mechanism for vapor removal. If vapor is continuously removed, evapotranspiration may continue for several hours after sunset with energy coming from sensible heat stored in the air, crop or soil. Conversely, under calm conditions evapotranspiration ceases after sunset as net radiation becomes negative. The wind factor in supplying advected sensible heat energy for evaporation takes on importance in arid regions and in the southwest USA peanut area. Wind effects can be seen in the curves of Figure 10. When LE is above R_n , wind is transferring heat from the air to the crop canopy. The opposite is true when LE is below R_n .

Ground Cover and Plant Effects on Evapotranspiration

With full ground cover, different crop species freely transpire water and at nearly equal rates when soil water is available. Different values in the literature are primarily a function of environmental evaporative demand and length of season rather than crop species. Plants certainly exert an influence on transpiration by stomatal activity and leaf orientation, but any reduction in transpiration is usually accompanied by decreases in photosynthetic rate. In our opinion, genotypic differences in evapotranspiration among peanut cultivars are probably caused by differences in root extension for water and differences in ground cover.

Daily and seasonal evapotranspiration is greatly influenced by % ground cover and leaf area development. In the absence of plant ground cover, average evaporation from the soil surface was reported to be 30 to 40% of pan evaporation (Goldberg et al., 1967; Kassam et al., 1975). Soil surface water content was not defined in these reports. Goldberg et al. (1967) and Kassam et al. (1975) observed that the E_t/E_o ratio increased linearly from 0.3 to near 1.0 as the peanut ground cover increased from 0 to 100% and as LAI increased during peanut growth. After establishment of full ground cover, the E_t/E_o ratio remained fairly stable under adequate soil water supply until the leaf area began to decline. Declining E_t during later stages is related to loss of leaf area and declining physiological activity of conductive tissues and stomata.

Ritchie (1974, 1976) has proposed a method of describing ground cover effects on E_t . His method reflects information gathered on several crop species over a large portion of the southern USA. He considers evaporation from soil separately from transpiration. Input information includes net radiant energy and leaf area index. A term is included to correct for advective effects and is locally calibrated.

Diseases may affect E_t . Subramanyam et al. (1978) showed that rust infection of peanut leaves was coincident with increased water vapor loss in proportion to the number of pustules rupturing the leaf epidermis. Stomatal pores were also opened more widely. In spite of disease effects on conductance, one must realize that E_t is energy-dependent and energy-limited.

Effect of Soil Water Deficit on Evapotranspiration

Evapotranspiration of peanuts, and other crops, is reduced by soil water deficits. Wormer and Ochs (1959) found that the transpiration rate of peanuts remained nearly constant as soil moisture was reduced until two-thirds of the available soil water had been depleted. Transpiration then decreased gradually to the wilting point, but was still about 66% of maximum at this level. Vivekanandan and Gunasena (1976) reported maximum daily E_t values of 0.61, 0.48, and 0.38 cm day⁻¹ for peanuts grown in wet, intermediate, and dry soil water potentials (-0.33, -0.55, and -0.73 bars), respectively. Mantell and Goldin (1964) observed that seasonal consumptive water use was higher for plots receiving the most frequent irrigation (Table 2), although errors from deep percolation cannot be excluded in their data. Daily E_t was reported as 0.56, 0.65, 0.61, 0.72, and 0.75 cm day⁻¹ for peanuts irrigated to field capacity at 40, 30, 21, 14, and 10 day intervals, respectively. Stansell et al. (1976) reported that seasonal water use by 3 peanut varieties was approximately 10 cm less for plants watered at -0.6 bar than for those watered at -0.2 bar.

Ritchie (1974, 1976) has included allowance for soil water deficit in his method for predicting E_t of vegetated areas. He used the concept of extractable water which is defined as available water in the root zone. Since the root zone varies through the growing season, extractable water is not the same as profile available water. Again, evaporation from soil is considered separately from transpiration. This permits greater sensitivity at low LAI conditions. The method includes allowance for 2-stage evaporation from soil. Ritchie found E_t/E_o to exhibit consistency for several crops and locations. He found the ratio to stay constant if extractable water was above 25% and found the ratio to decrease linearly between 25% and 0%. This observation was included in his method for predicting E_t .

The diurnal pattern of transpiration and evapotranspiration for non-stressed peanuts is a normal-shaped curve influenced by diurnal evaporative demand and radiant energy load (Slatyer, 1955; Stone et al., 1976; McCauley et al., 1978) (Figure 10). With increasing soil water deficit, the daily transpiration curve was reduced and became progressively skewed to a peak earlier in the morning (Slatyer, 1955). This observation of greater transpiration in early morning hours is consistent with nighttime recovery of relative turgidity to allow stomatal opening during early morning hours even during soil water deficit periods (Allen et al., 1976).

Effect of Cultural Practices on Evapotranspiration

Certain cultural conditions such as row spacing, row direction, planting density, and fertility levels have small but important effects on E_t . Studies in the southwestern USA peanut area by Stone et al. (1976), ChinChoy et al. (1977), and McCauley et al. (1978) compared E_t of spanish peanuts in 30 versus 90 cm rows in 2 row directions. They reported that peanuts grown in the 30 cm north-south rows tended to show lower E_t during periods of high evaporative demand than any of the other 3 combinations of row spacing and direction. During some of the periods studied, the narrow, north-south rows showed one-third the E_t of the highest E_t treatment for that period. Factors related to the low E_t in the narrow north-south rows were: wind-generated tur-

bulence in the canopy, warming of the soil by the mid-day radiant energy, and earlier closure of stomata by the peanut plants. Abdul-Jabbar (1978) reported a tendency of the stomata to close earlier in the day for plants in narrow north-south rows when evaporative demand was high.

Not only did narrow rows have lower E_t , but their pod yield was nearly 20% higher (ChinChoy et al., 1977). The net result was a sizeable increase in water use efficiency (yield per cm of water). Davidson et al. (1973) reported substantial yield response to narrow row spacing for both irrigated and non-irrigated spanish peanuts. Bhan and Misra (1970) observed slightly lower E_t and greater percolation losses for peanuts in 60 cm rows as compared to 30 or 45 cm rows. Applications of N and P tended to increase E_t and water use efficiency.

INFLUENCE OF SOIL CHARACTERISTICS ON WATER AVAILABILITY AND IRRIGATION PRACTICES

To effectively irrigate peanuts, one must obtain a few basic soil and plant characteristics. Basically these include the infiltration rate, the maximum available water the soil can store, curves relating soil water content to soil water potential, and an estimate of the effective rooting depth of the crop at several growth stages.

Infiltration data is a requisite for designing and operating an irrigation system. Water supplied at a rate faster than it can be infiltrated into the soil will run off the field, with subsequent erosion and loss of plant nutrients. Israelson and Hansen (1962) listed the following infiltration ranges for several soils (cm hr⁻¹): sands, 2.5-25; sandy loams, 1.3-7.5; loams, 0.75-2; clay loams, 0.25-1.5; silty clays, 0.02-0.5; and clays, 0.13-1.0. Obviously, the heavier loam and clay soils will require slower water application rates than sandy soils.

Although sandy soils can be irrigated at high application intensities, there are drawbacks. The amounts of plant-available-water storable by a soil profile varies inversely as the infiltration rate. Typical ranges for total available water (cm cm⁻¹) that can be held by several soils are: sands, 0.07-0.1; sandy loams, 0.09-0.15; loams, 0.14-0.19; clay loams, 0.17-0.22; silty clays, 0.18-0.23; and clays, 0.20-0.25 (Israelson and Hansen, 1962). Thus in a 25 cm depth of a clay soil, more than 6 cm of available water can be stored, but in a 25 cm depth of sand only 2.5 cm can be stored.

From an irrigation viewpoint, the soil is a reservoir for water storage and disbursement to the crop. The amount which a soil can store in a unit increment of the profile depends upon its structure and texture. The amount which the plant can utilize between irrigations depends upon the ability of peanut roots to proliferate into the soil. If physical or chemical barriers restrict root growth to a shallow zone, the water storage volume available to the plant will also be restricted to the rooting zone. In soils which permit free root growth, the water storage reservoir may be considered to be 100-200 cm deep (Stansell et al., 1976; Hammond et al., 1978). This, of course, is the desirable situation. The deep rooting observed by these researchers may permit less frequent irrigations of larger amounts and may provide some drought protection in an emergency, although the water at greater depths is not as readily extracted as water at shallow depths and will not support optimum yields.

Although water retention curves, as in Figure 11, are not commonly available for individual farmer fields, this type of data is basic to irrigation planning and practice. Research has developed irrigation criteria for peanuts based on irrigation when the soil water potential is in the range of -0.25 to -0.5 bars (Gorbet and Rhoads, 1975; Stansell et al., 1976; Hammond et al., 1978). These water potentials are applicable over a wide range of soil types, but actual irrigation amounts must be computed from curves such as those in Figure 11. Such curves have been used in the preparation of irrigation guides which are convenient and easy to use (Anon., 1970).

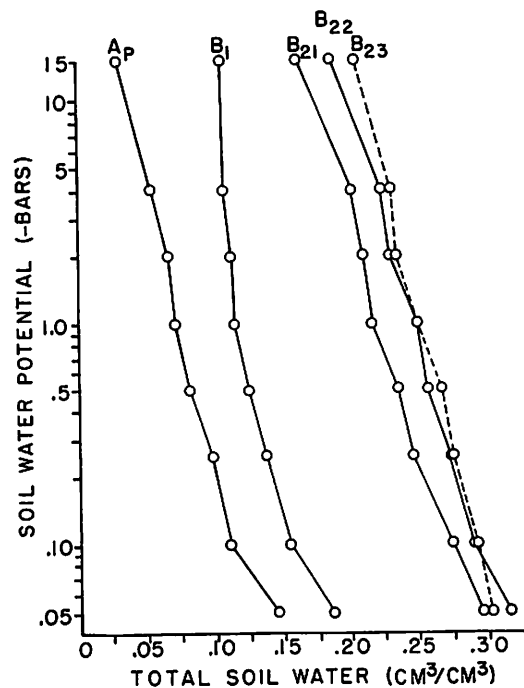


Fig. 11. Water retention curves for various soil horizons (Ap, B₁, B₂₁, B₂₂, and B₂₃) of a Tifton loamy sand. Reprinted from Stansell et al. (1976).

Normally, a loamy sand soil allows rapid infiltration as well as rapid drainage by percolation whenever water application exceeds the soil water holding capacity. This rapid drainage limits, to a short time period, the value of excessive rainfall or irrigation water to the crop. Davidson et al. (1969) studied a Cobb loamy sand which is characterized by a layer of sandy clay loam at 50 cm depth (Figure 12). This layer of finer textured material in the soil was shown to temporarily impede water flow through the soil as infiltrating water approached it from above. Therefore, a greater amount of water was stored in the profile. The presence of this water-impeding layer in the root zone of an otherwise sandy soil caused 50% less water to percolate through the profile after 1 to 3 days and resulted in a greater amount of water held in the root zone available to the peanut plants. This lessens the probability of losses due to deep percola-

tion and simplifies the water management process. Such a layer has been a boon to some peanut farmers in some southwestern USA peanut growing areas.

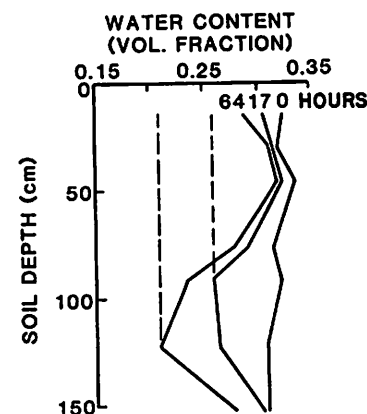


Fig. 12. Water content of Cobb loamy sand after equilibrating with ponded water, curve 0. Drainage curves for 17 and 64 hr are shown. Layer of sandy clay loam is centered at 50 cm depth. Vertical lines estimate the water contents for drainage ignoring the presence of the layer. Adapted from Davidson et al. (1969).

IRRIGATION STRATEGY

The goal of irrigation is to supply the crop rooting zone with sufficient water at appropriate times in order to prevent a soil water deficit which, in turn, causes crop stress. There are 2 major approaches to accomplish this goal. One is to measure soil water status and schedule irrigation at a soil water potential above which we know the crop will not be stressed. This approach could ignore E_t or crop water use and requires less precise information on rainfall and irrigation amounts or soil water holding capacity. The second approach is to estimate crop water use (E_t) from calibrated data or as a fraction of cumulative pan evaporation and irrigate to re-supply water lost by E_t . Soil water potential measurements are not required for this approach, but estimates of effective rooting zone, soil water holding capacity, rainfall, irrigation amounts, and daily crop E_t are needed to gauge when the available soil water will deplete enough to cause crop stress and fail to supply evapotranspirational demand.

In practice, the 2 approaches are sometimes combined. The bookkeeping and evapotranspiration approach can be corrected by periodic observation of soil water potentials, which indicates whether water supply was insufficient or that over-irrigation was causing water to percolate out of the profile. Secondly, both approaches need estimates of soil water holding capacity and effective rooting depth to calculate the amount of water to apply without causing deep percolation. In order to evaluate ways of irrigation scheduling, we will first discuss yield responses obtained from irrigations based on 3 approaches: 1) irrigations based on measured soil water potential (Ψ_s) or soil water depletion (SWD); 2) irrigations based on published evapotranspiration values or upon cumulative pan evaporation; and 3) irrigations in arid zones based on frequency (this is similar to irrigation based on calibrated evapotranspiration).

Soil Water Potential

One approach is to irrigate when soil water potential (Ψ_s) reaches a defined value at the 15 to 30 cm soil depth (Matlock et al., 1961; Hiler and Clark, 1971; Gorbet and Rhoads, 1975; Stansell et al., 1976; Hammond et al., 1978). Theoretically, this system is best because the soil water sensors employed for this technique estimate the soil water potential in the zone of greatest rooting density, and thereby can minimize stresses of low potential (high soil water tension) on the plant growth processes. Secondly, the use of soil water sensors eliminates the need to record rainfall, pan evaporation, etc. One of the problems with irrigation scheduling by soil water potential is that soils have different soil water retention curves. At -0.3 bars Ψ_s , most of the available water may be depleted from a sandy soil; yet considerable available water will remain in a clay loam. These considerations affect the trade-off between irrigation scheduling and making optimum use of soil water reserves. The solution here is that irrigation should probably be scheduled at a Ψ_s worked out for the given soil type and the crop.

Gorbet and Rhoads (1975) and Stansell et al. (1976) used Ψ_s to schedule irrigation of Florunner and Florigiant peanuts (Table 5). Gorbet and Rhoads (1975) observed that yield response to irrigation at -0.6 bars was as good as irrigating at -0.3 or -0.4 bars on a sandy loam soil (Table 5). Yield was only

Table 5. Peanut yield, water use, and water-use efficiency in response to irrigating at different soil water potentials (Ψ_s).

Investigators	Cultivars	Irrigation at Ψ_s (bars)	Pod Yield (kg ha ⁻¹)	Water Use (cm)	Water Use Efficiency (kg ha ⁻¹ cm ⁻¹) ¹
Stansell et al. (1976) Pallas et al. (1977)	Florunner	-0.2	5080	59	86
		-0.6	4728	49	96
		-2.0†	4580	52	88
		-15.0	3341	32	104
		Overnight wilt	2375	22	108
Hammond et al. (1978)	Florunner	-0.2	3820	46	83
		-1.0	3000	40	75
		None (wilted)	2260	33	68
Gorbet & Rhoads (1975)	Florunner	-0.3	5120	-	-
		-0.6	5260	-	-
		Midday wilt	4840	-	-
		None	4690	-	-
Stansell et al. (1976) Pallas et al. (1977)	Tifspan	-0.2	4543	52	87
		-0.6	4407	44	100
		-2.0†	4309	47	92
		-15.0	3125	31	101
		Overnight wilt	2491	22	113

† Irrigated at -0.2 bars until 30 days after first bloom (60 days); then from 60 days to harvest, irrigated whenever Ψ_s declined to -2.0 bars.

slightly less if irrigation was delayed until plants showed a noticeable wilt. By contrast, in a wet year, yield was reduced by frequent irrigation to maintain Ψ_s above -0.3 bars. Over an 8-year period at Marianna, Florida, yield was increased an average of 535 kg ha⁻¹ in response to irrigating when Ψ_s at 15 cm declined to -0.6 bars (Hewitt et al., 1980). Rochester et al. (1978) in Alabama reported satisfactory yield responses for irrigation initiated when Ψ_s at 15 to 30 cm dropped to -0.2 to -0.6 bars. Stansell et al. (1976) reported harvestable yields of 4460, 5080, and 4540 kg ha⁻¹ for Florigiant, Florunner, and Tifspan, respectively, when irrigated to a depth of 60 cm when Ψ_s in the 0-30 cm zone of loamy sand reached -0.2 bars. Yields of Florunner and Tifspan were lower, but not significantly less, if irrigation was scheduled at -0.6 bars in the 0-30 cm zone or if irrigation was scheduled at -2 bars Ψ_s from 60 days after planting to harvest. Yield was significantly reduced if irrigation was delayed until Ψ_s reached -15 bars or the plants wilted to the stage of no overnight recovery (Table 5). Water use efficiency (WUE) of Florunner peanuts was lowest for the highest yielding treatments and was usually highest for the driest treatments (Stansell et al., 1976), although Hammond et al. (1978) observed highest WUE for the most frequent irrigation treatment. In a recent study by Pallas et al. (1979), WUE of Florunner peanut was reduced drastically by prolonged water deficits, although an early 35-day drought (from 36 to 70 days) gave highest WUE, but a significantly lower yield than the well-irrigated plots. Thus high WUE is a poor and variable indicator of optimum economic use of water for yield. Optimum economic yield and water use on loamy sand or sandy loam appears to result from irrigation scheduling when Ψ_s reaches -0.6 bars or when peanut plants show temporary, but noticeable wilt at mid-day. Irrigating when Ψ_s reaches -1 or -2 bars has usually allowed satisfactory peanut growth and yield especially for spanish type peanuts on a finer textured sand (Matlock et al., 1961; Stansell et al., 1976).

Soil Water Measuring Devices as an Aid to Irrigation Scheduling

Instruments such as tensiometers or electrical resistance blocks can be useful aids to help schedule irrigation, although they require proper maintenance and interpretation. Both types of instruments are reliable. Optimum irrigation depends on the interpretation of the readout from the instruments.

Tensiometers (Figure 13) are basic instruments for measuring soil water potential. They consist of a plastic tube with a water permeable ceramic cup on the bottom end and a vacuum gauge at the top. When properly installed in the soil, water in the tensiometer and the soil water forms a continuous film through the permeable tip. As water is removed from the soil by evapotranspiration or drainage, a potential gradient is formed and water leaves the tensiometer to re-establish equilibrium. This creates a vacuum within the tensiometer which is indicated by the gauge. Tensiometer gauges may be calibrated directly in millibars or centibars so the Ψ_s can be read directly. Tensiometers operate satisfactorily in the desirable soil moisture range for peanuts but will malfunction if Ψ_s is lower than about -0.75 bars. To re-establish operation, the soil must be watered to a Ψ_s above -0.75 bars, the tensiometer must be refilled with distilled water and re-sealed. Tensiometers should be installed at different depths so they will sample the rooting zone of the peanuts. Research indicates that irrigation should be started when the top soil reaches a Ψ_s of

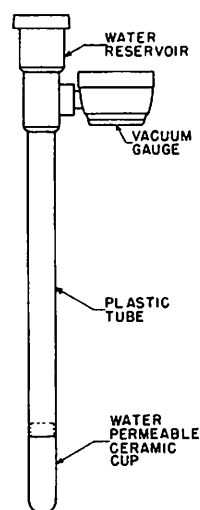


Fig. 13. Illustration of a vacuum-type tensiometer for measuring soil water potential.

-0.25 to -0.50 bars (Gorbet and Rhoads, 1975; Stansell et al., 1976; Pallas et al., 1977; Hammond et al., 1978) and that sufficient water should be added to refill the soil reservoir to a depth of 60 cm. Tensiometers installed in the sub-soil indicate whether sufficient water is being applied by irrigation. For large fields, several instrument stations located at sites representative of the soil water conditions in the field are recommended.

Electrical resistance blocks perform the same function as tensiometers, but perform best at Ψ_s below -0.25 bar. However, they give an indirect indication of soil moisture content and can be calibrated against soil water potential. In most cases, the factory calibration is adequate.

The resistance block system consists of a sensor which contains 2 stainless steel electrodes encased in a water-absorbent medium. The resistance of the sensor decreases with water content. Gypsum, or fiberglass-reinforced gypsum, is a typical material because the gypsum tends to buffer the effects of dissolved salts in the soil water. The sensor leads are attached to an instrument which applies an alternating voltage across the electrodes. A current related to the absorbed water in the sensor flows through the sensor and its magnitude is indicated by the meter.

Resistance blocks are not sensitive to Ψ_s in the 0 to -0.2 bar range, but respond well at more negative potentials. The sensors are inexpensive and essentially trouble free except for mechanical damage to the leads. The hand-held meter is a one-time-cost item and can service many resistance block sensors.

Installation recommendations are similar to those given for tensiometers. By converting meter readings to potentials through calibration curves, irrigation is scheduled as for tensiometers.

Other moisture measuring methods are available, but are not generally suitable for routine on-farm use. These include neutron moderation and gamma transmission instruments and, of course, the gravimetric dig, dry, and weigh methods.

Soil Water Deficit

A frequent irrigation management strategy is to irrigate when the soil water in a given layer (usually 0 to 30 cm) reaches a given level of soil water depletion (SWD) as summarized in Table 6. This requires an estimate of either soil water content or potential. The latter is used with curves relating soil water release versus potential. The soil water potential at a given SWD is a characteristic of the soil. Lenka and Misra (1973) and Narasimham et al. (1977) irrigated semi-erect short season varieties at 75, 50, and 25% SWD during the dry season in India. Irrigation at 25% SWD gave the highest yield, but lowest water use efficiency. Irrigation at 75% SWD gave high WUE, but significantly lower yield. Scheduling irrigation at 50% SWD was a good compromise which gave good WUE with no significant yield reduction. Pallas and Stansell (1978) similarly observed an inverse relationship between WUE and yield. Reddi and Reddy (1977) measured water use of 426 to 505 mm by varieties AH 1192 and TMV2 during a nearly rainless winter season in India (Table 6). Irrigation was scheduled at 25 or 50% SWD during 3 growth phases: (1) sowing to pegging, (2) pegging to pod formation, and (3) pod formation to harvest. Irrigation scheduling at 50% SWD was adequate from "sowing to pegging", but highest yields and WUE were obtained for those treatments irrigated at 25% SWD during "pegging to pod formation" and from "pod formation to harvest". Irrigating at 25% SWD gave the highest yield of 4680 kg ha⁻¹ and highest WUE of 92 kg ha⁻¹ cm⁻¹. Irrigating cultivars or fields with poor yield potentials did not significantly increase their yields (Saini and Sandhu, 1973; Cheema et al., 1974; Cheema et al., 1977).

Table 6. Peanut yield, water use, and water-use efficiency in response to irrigating at different soil water depletions (SWD).

Investigators	Cultivar	Irrigation at SWD (%)	Pod Yield (kg ha ⁻¹)	Water Use (cm)	Water Use Efficiency (kg ha ⁻¹ cm ⁻¹)
Lenka & Misra (1973)	AK12-24	%	kg ha ⁻¹	cm	kg ha ⁻¹ cm ⁻¹
		25	2794	83	34
		50	2653	71	37
Narasimham et al. (1977)	TMV2	75	2249	62	36
		25	4455	77	58
		50	4314	66	66
Reddi & Reddy (1978)	AH-1192	75	3396	48	70
		50/50/50†	3170	43	75
		25/50/50	3430	45	76
		50/25/50	3530	46	77
		50/50/25	3750	47	80
		25/25/50	3490	46	77
		50/25/25	4140	45	91
		25/50/25	4000	49	82
		25/25/25	4680	51	92
		once/week	3360	47	77

†Irrigated at defined SWD during three stages: up to pegging, pegging to pod formation, pod formation to harvest, respectively.

Cumulative Pan Evaporation

Another irrigation approach is to apply irrigation water sufficient to supply a given fraction of the cumulative pan evaporation (CPE) since the last irrigation. Goldberg et al. (1967) and Subramanian et al. (1975) used this method on peanuts grown on sandy soils under arid conditions in Israel and India, respectively. Goldberg et al. (1967) irrigated every 7 to 10 days at the rate of 0.60, 0.75, 0.90, and 1.05 of the CPE between irrigations. Subramanian et al. (1975) irrigated at 0.60 and 0.90 of CPE since the last irrigation, applied during 3 phases: (1) up to flowering (30 days), (2) active pegging (30 days), and (3) pod formation to maturity (45 days). Both researchers reported that irrigation at 0.9 CPE was best during full canopy development. Irrigation at 0.6 CPE was not detrimental during early growth and caused an increase in WUE if followed by irrigation at 0.9 CPE during later stages. The underlying cause for this observation is that the ratio of E_t/E_o is relatively low during early growth because of insufficient ground cover. Irrigation at 90% of CPE works well for closed canopies in arid regions because E_t/E_o under such conditions is nearly 0.90, but a different approach must be used when plants are small or in humid areas where E_t/E_o exceeds 0.90. In rainy humid areas, a similar approach could be used by adding up rainfall and subtracting CPE.

Bookkeeping of a Water Account

A bookkeeping method was suggested by Stansell (1975) in which available water holding capacity of the top 60 cm of soil is considered the total water account. Rainfall and irrigations are considered deposits to the water account and daily evapotranspiration as withdrawals from the account. Daily evapotranspiration rates (Figure 7) have been developed which account for plant age, ground cover, and canopy decline at the end of the season (Mantell and Goldin, 1964; Anon., 1970; Stansell et al., 1976). These rates can be used to estimate daily profile water depletion. After some pre-set depletion, irrigation is applied to replace water which has been used. Since previous research has shown that water withdrawals of more than 50% of available soil water decreased yield, the peanut crop is usually allowed to withdraw one-half of the total available water before irrigation is scheduled. This is a simple method for scheduling irrigation, but should be more objective and give better results than irrigating by guess or plant appearance. It is, in effect, recommending irrigation at 50% SWD, but without measuring soil water. The bookkeeping is simplified in arid, low rainfall areas by determining the rooting depth and the atmospheric demand for water and calculating water applications needed to maintain the soil-root profile above 50% available soil water. Assuming the atmospheric demand is fairly constant, irrigations can be scheduled on a simple frequency interval. Mantell and Goldin (1964), growing a virginia type cultivar under high evaporative demand conditions in Israel, obtained the highest yield and highest WUE of 69 kg ha⁻¹ cm⁻¹ with 67.5 cm of water use on a 21-day irrigation interval. Less frequent irrigation on the clay loam soil resulted in lower WUE. Water consumption was 54 to 82 cm during the 138 days from emergence to harvest. With a loamy sand in Israel, a 7-day irrigation interval was found to be optimum (Goldberg et al., 1967). While good in arid zones, inter-

val scheduling of irrigation is poorly adapted to rainfed areas.

Best Irrigation Strategy

Optimum water management appears to be scheduling irrigation to maintain less than 50% SWD in the top 30 cm during early growth and possibly irrigating at 25% SWD during pod formation and seed growth. If soil water potential (Ψ_s) is measured in the top 15 or 30 cm of soil, irrigation should be scheduled to maintain Ψ_s above -0.6 bars (on sands or sandy loam), although irrigating to maintain Ψ_s above -0.25 to -0.50 bars may be desirable during long, dry, hot periods occurring during the sensitive growth stages of pegging, pod formation, and early pod fill.

A Systems Approach

The decision to install an irrigation system involves more than just alleviating drought stress to peanuts. One should consider water supply, labor and energy conservation, water infiltration rates, multiple cropping potentials, and use of the irrigation system to manage other cultural and pest control practices. For example, irrigation allows the producer to pre-select the optimum planting date for high yield, an advantage sometimes overlooked. It also allows more effective use of pre-emergence herbicides which require rainfall or irrigation for activation. On the other hand, irrigation may intensify certain pest problems. Backman et al. (1978) found that irrigation increased *Cercospora* leafspot severity and increased damage from *Sclerotium rolfsii*.

There are exciting potentials for using irrigation systems to apply fertilizer nutrients, herbicides, and pesticides as needed for control of soil-borne insects, diseases, and nematodes. Such uses require uniform application capabilities and flexible application rates. Aspects of irrigation system design and operation are discussed by Keese et al. (1975) and by Davidson et al. (1973).

Future irrigation scheduling may involve automated soil water and rainfall measurements linked to micro-processor controlled irrigation systems. Water and energy conservation will be a major concern, leading to the development of more efficient water distribution systems and scheduling techniques.

More intensive use of the irrigated acreage is needed to fully capture the advantages of the system. Thus, producers must consider the problems and potentials of multiple cropping as a method to offset the capital costs of such systems. They will also need to address problems of increased residues from other crops and less rotation-time between peanut crops.

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