

Relation of Cotton Growth and Yield to Minimum Leaf Water Potential¹

D. W. Grimes and H. Yamada²

ABSTRACT

Field studies were conducted over a 3 year period in the San Joaquin Valley of California to define the associations between minimum or mid-day leaf water potential (ψ_l) and cotton (*Gossypium hirsutum* L.) growth parameters, mainstem elongation and fiber growth, and to evaluate the suitability of using minimum ψ_l as an index for irrigation scheduling. Locations on two soils, differing widely in water retention and transmission properties, were maintained for two of the test years.

Mainstem elongation (E_L) was greatest after stress was alleviated by irrigation. E_L (cm/day) was reduced linearly as minimum ψ_l (bars) declined; the function $E_L = 5.08 + 0.200\psi_l$ was derived from available observations. Mainstem elongation essentially stopped when minimum ψ_l dropped to -24 bars. Fiber growth (elongation and weight increase) proceeded unchecked until ψ_l reached -27 to -28 bars, when the growth rate decreased markedly, indicating that fiber growth is probably a preferred sink at high stress levels.

Minimum ψ_l declined linearly with time following irrigation. High yields were obtained when minimum ψ_l was allowed to decline to about -19 bars before irrigating. Any response resulting from differential conditioning, from prior water stress, was not sufficient to detract from the usefulness of minimum ψ_l as an index for scheduling irrigation.

Additional index words: *Gossypium hirsutum* L., Pressure chamber, Irrigation scheduling, Water stress, Evapotranspiration.

COTTON (*Gossypium hirsutum* L.) irrigation scheduling varies greatly in arid and semi-arid regions, where differences in the water retention and transmission properties of soils are large. Also, soil zones restricting plant root extension may reduce the plant's ability to utilize stored soil water. For this reason, soil-based measurements do not always accurately reflect whether water available to plants is adequate. Since the plant integrates its total environment, plant-based measurements of water status appear to more accurately reflect when irrigation is needed to replace evapotranspired water.

The pressure-chamber technique is useful for measuring cotton leaf water potential (ψ_l) under field conditions (10) if measurement time is sufficiently short to avoid errors due to desiccation (17). However, cotton responds to variations in the previous water status, so no single

threshold value of ψ_l will initiate stomatal closure and the associated physiological changes. Jordan and Ritchie (12) reported that stomata of growth-chamber plants closed when ψ_l was near -16 bars, but stomatal resistance of previously stressed plants in the field indicate that stomata were fully open when ψ_l was near -30 bars. Jordan et al. (11) observed stomatal closure first on older leaves, which progressed to younger leaves as water stress increased, independent of radiation differences. Stomata on the upper epidermis were more sensitive to lowering ψ_l 's than were those on the lower epidermis. A possible explanation is that the osmotic potential of guard cells of the lower leaf surface was adjusted because of periods of water stress, but that of cells of the upper surface was not (1).

As emphasized by Hsiao et al. (8), cell growth is probably the most sensitive of the many plant processes influenced by water stress with positive turgor serving as the physical force for enlargement. Field-grown cotton and sorghum (*Sorghum bicolor* L. Moench) are good examples of important crops that exhibit an adaptive mechanism in response to periods of water stress (2,3,4,8). Possible mechanisms for the conditioning effect that provides positive turgor pressure for continued growth include solute accumulation or osmoregulation, small cells (more cell walls per unit volume), and greater cell-wall elasticity. Cutler et al. (3) concluded that an accumulation of sugars and malate and a high cell-wall elasticity in cotton contribute to turgor maintenance. Hsiao et al. (9), who compiled detailed leaf-moisture-release curves, show that solute accumulation alone is the primary mechanism in cotton.

Generally, cotton responds favorably to periods of water stress between irrigations sufficient to slow vegetative growth (13,15). Grimes et al. (6) show increases in plant height more nearly proportional to available water than was lint yield, which was reduced sharply when water supply was excessive. A preponderance of information available in the literature on measurements of cotton plant water status (potential) in the field relates to changes in stomatal sensitivity to water stress or in a growth parameter such as leaf expansion. This work was undertaken, in the field, to study vegetative (mainstem elongation) and fiber (elongation and weight increase) growth as a function of minimum (midday) leaf water potential and to assess the effectiveness of ψ_l , a direct measure of plant water status, as a means for scheduling irrigation.

¹Contribution from the Dep. of Land, Air and Water Resources, Univ. of California, Davis, CA 95616. The work was supported in part by grants from the California Planting Cotton Seed Distributors. Received 16 Mar. 1981.

²Water scientist (located at the San Joaquin Valley Agric. Res. and Ext. Ctr., 9240 So. Riverbend Ave., Parlier, CA 93648) and staff research associate, respectively.

Table 1. Amount (cm) and time (vertical dash above the water amount) of irrigation for the two soils of the study in 1976.

Soil Moisture (mm) at 100 cm Depth and Soil Water Capacity, or Infiltration for the Two Sides of the Study in 1970.											
	May		June		July		Aug.		Sept.		Total†
	20	30	10	20	30	10	20	30	10	20	
<u>Panoche clay loam</u>											
T-1 (control)			13.2		17.8		20.3				51.3
T-2 (early stress)		10.2			20.3		20.3		12.7		63.5
T-3 (late 1st)					20.3		20.3		12.7		53.3
T-4 (late 2nd)			13.2				22.9		17.8		53.9
T-5 (early 2nd)			13.2		10.2		20.3		17.8		61.5
T-6 (stress)					20.3			25.4			45.7
<u>Wasco sandy loam</u>											
T-1 (control)			7.6		8.9	8.9	8.9	8.9	8.9	8.9	69.9
T-2 (early 1st)	7.6		7.6		8.9	8.9	8.9	8.9	8.9	8.9	77.5
T-3 (late 1st)			8.9		8.9	8.9	8.9	8.9	8.9	8.9	71.7
T-4 (late 2nd)			7.6		8.9	8.9	8.9	8.9	8.9	8.9	61.0
T-5 (early 2nd)			7.6	7.6	8.9	8.9	8.9	8.9	8.9	8.9	68.6
T-6 (stress)			8.9		8.9		8.9		8.9		35.6

† Soil stored water at planting was at least 31 cm (Panoche) and 16 cm (Wasco) during all years of the study.

MATERIALS AND METHODS

A 3-year field study was conducted in the San Joaquin Valley of California on Panoche clay loam (1975 through 1977) at the University of California West Side Field Station in western Fresno County, and on Wasco sandy loam (1975–1976) at the U. S. Cotton Research Station in Kern County. The soils are members of the nonacid thermic family of Typic Torriorthents. Both soils allow deep root development and, consequently, water extraction in late season in the Wasco and Panoche soils, respectively, commonly reaches to depths of 1.5 and 2 m. Water-release characteristics of specific sites at the two locations were determined using pressure plate and membrane apparatuses. Water-retention properties of the soils are relatively uniform with depth. A minimum of 31 and 16 cm of water, through the effective rooting depth of the Panoche and Wasco soils, was available at planting in early April from preplant irrigations.

All plots received N fertilizer before planting; based on soil analysis and past nutrient response experiments no other nutrients were limiting.

Cotton, cvs. Acala SJ-4 in 1975 and Acala SJ-2 in 1976 and 1977, were planted in 1.02-m-wide rows and thinned after emergence was complete to stands averaging 47,500 plants/ha. The plots were eight rows wide at both locations and 38 and 88 m long, respectively, on the Wasco and Panoche soils.

The plots, which had little or no grade, were furrow-irrigated. Water was delivered to individual plots through gated pipe; the delivery rate was established by a time-volume procedure. Six irrigation treatments, with three replications in randomized complete blocks, were established for all locations and years of the study. Treatments T-1 through T-5 in 1975 and 1976 were designed to subject plants to different water-stress conditions during the first half of the growing season (Table 1) and to establish an optimum time for the first irrigation (7). Scheduling varied at the two locations because of contrasting water-retention properties of the soils. Treatment T-6 imposed excessive stress at both locations. In 1977, treatments T-4 through T-6

were modified to allow greater stress; T-4 was similar to T-6 of the two previous years, whereas T-5 received only one postplant irrigation and T-6 was grown solely on soil-stored water. Typically, no significant rainfall occurred during the growing season in any year; climatic conditions were near normal.

Leaf water potential was measured with a portable pressure chamber (PMS Instrument Co., Corvallis, OR). Minimum ψ_i 's were measured between 1200 and 1400 PST, a period of relative diurnal stability (Fig. 1). Three to five of the youngest fully expanded leaves, usually on the third or fourth node down from the terminal, were selected to represent a plot measurement. This procedure precluded sampling leaves of different physiologic age and illumination history. Leaves were excised and immediately pressurized to minimize errors due to desiccation. Before irrigations, soil water content was determined by neutron scattering at the Panoche site and gravimetrically at the Wasco location. Intensity of measurement was increased in 1977 to provide sufficient data for evapotranspiration (ET) measurements from soil water depletion.

Plant heights were measured at 3 to 5-day intervals on 10 consecutive plants in a central row of a plot. A small stake was driven flush with the ground near the base of a plant to provide a stable base for measurement to the terminal bud. Minimal ψ_i related to elongation rate was an average derived from measurements at the beginning and end of 3-day intervals; a midterm ψ_i measurement was included in 5-day intervals.

Fiber elongation and weight-increase rates were determined by the procedure of Gipson and Ray (5) on bolls tagged with the date of anthesis in early July. A sufficient number of bolls were tagged in all treatments of two replications to provide bolls for sampling at approximately 5-day intervals from anthesis to physiological maturity.

Lint production was determined by mechanically harvesting the four center rows of each plot twice from mid-October to mid-November. Three-kg samples were collected from each plot at harvest for determining lint percentage and quality characteristics.

RESULTS AND DISCUSSION

Figure 1 shows typical diurnal curves of ψ_l for contrasting soil water conditions (inset graph) and a high evaporative demand. maximum ψ_l is observed before sunrise. With stomatal opening, a rapid decline occurs that reaches a minimum at about solar noon. Relatively constant minimum values are observed for the next 2.5 to 3 hours followed by the initiation of recovery. Cotton vegetative and fiber growth were related to minimum (midday) ψ_l in this study because treatment differences were greatest when ψ_l was at a minimum, measurement time is convenient, and the values are relatively stable in this regional climate characterized by clear warm days with little day-to-day variation during the season when measurements are critical. Minimum ψ_l alone would not be expected to be suitable in regions having large fluctuations in maximum temperature and cloud cover.

An examination of mainstem growth over the season for all treatments of the study (data not shown) indicates a maximum elongation rate during the early flowering period from about 20 June to 20 July. With an increasing boll load, elongation rate was substantially reduced after this time interval. To eliminate variation associated with the phenologic stage, only mainstem elongation rates from the maximum growth period were considered. Figure 2 shows mainstem elongation (E_L) as a function of minimum ψ_l . Data from all treatments of the sites and years indicated were used to effect the greatest possible range of comparison. Growth was greatest when stress was alleviated by irrigation. A linear reduction in E_L accom-

panied declining ψ_l until little or no growth was observed at approximately -24 to -25 bars. This essentially agrees with the leaf-expansion-limiting ψ_l reported by Cutler et al. (3) for field-grown plants. Contrasting soils did not differ, and the combined relation for locations and years was $E_L = 5.08 + 0.200 \psi_l$ ($R^2 = 0.65^{**}$). The growth limiting process, cell enlargement and/or cell division, was not identified for these field studies.

Plants grown on the sandy loam soil wilted briefly in early afternoon at a ψ_l of -20 to -21 bars. Because of differing water-retention-transmission properties of the clay loam soil, plants showed no pronounced wilting even when leaf water potentials were much lower.

In 1977, the relationship between minimum ψ_l and fiber elongation and wall thickening (weight increase) was evaluated (Fig. 3). Bolls in anthesis in early July were selected with increasing water stress imposed by treatments T-5 and T-6. Since fiber elongation and weight increase were not affected by stress levels imposed by treatments T-1 through T-4, rates from these treatments were averaged to serve as a control (no stress) condition. Figure 3 (inset) shows fiber elongation nearly complete 3 weeks after anthesis with most of the wall thickening occurring after that time. The effect of declining ψ_l on fiber elongation and weight increase was determined by expressing the rate (mm or mg per day) observed for T-5 and T-6 as a ratio of the control treatments for bolls of the same age (Fig. 3). Though the data vary considerably, neither fiber elongation nor wall thickening appeared to be reduced until minimum ψ_l was lowered to about -27 to -28 bars. No fiber growth was observed at greater stress levels. Mainstem elongation rate was reduced line-

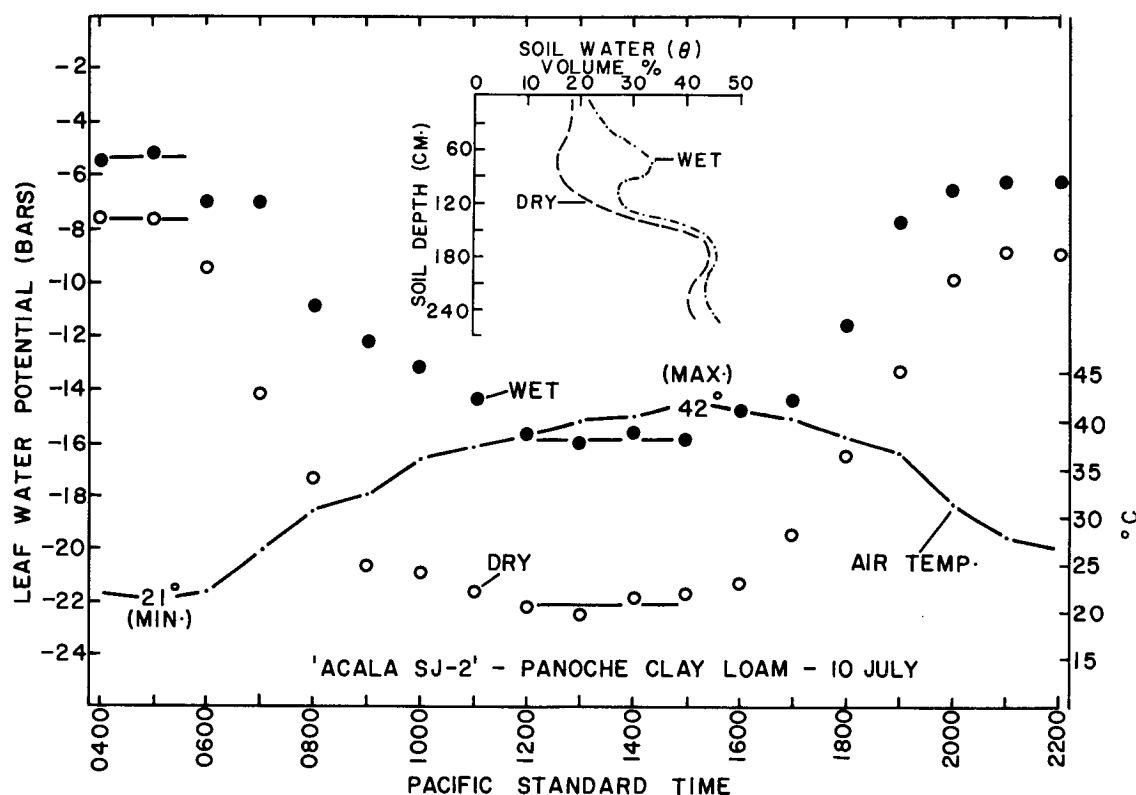


Fig. 1. Diurnal fluctuation of ψ_l for contrasting soil water conditions during high evaporative demand.

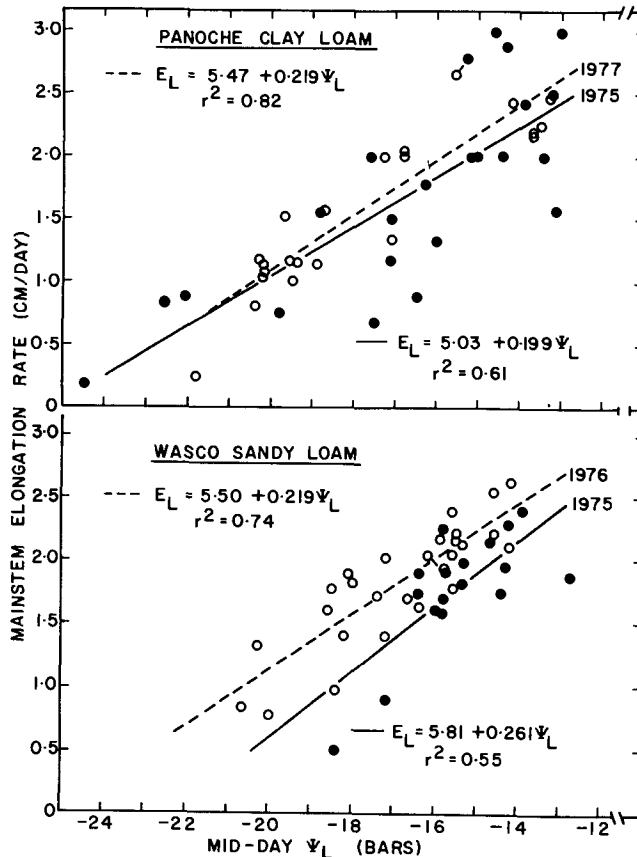


Fig. 2. Mainstem elongation rates for varied ψ_L at two locations. The combined regression over locations and years is $E_L = 5.08 + 0.200\psi_L$; $R^2 = 0.65$.

arly with ψ_L following an irrigation. This contrasting response may indicate a preferred photosynthate sink for fiber growth.

The growth responses observed in these studies appear to be consistent with canopy photosynthetic rates that can be inferred from the stomatal closure patterns reported by Jordan et al. (11) and Cutler and Rains (2). In their studies, stomatal closure was observed first in the oldest leaves and proceeded progressively to younger leaves as water stress increased.

To evaluate the potential usefulness of ψ_L as an index for scheduling irrigations, changes in ψ_L in contrasting soils over time were examined. Fluctuations above and below a strongly linear function of ψ_L on days since irrigation were relatively minor in both soils (Fig. 4) and are probably due to normal day-to-day differences in evaporative demand. The slope of the linear function declines much faster for the sandy loam, reflecting the large difference between water-retention capabilities of the soils. Leaf area index values (LAI approximately 1.0 and increasing) were essentially the same at all times of the comparison because of the more rapid early growth of the quicker-warming sandy loam soil. The linear relationship allows easy extrapolation to a time when ψ_L is critical and requires alleviation by irrigation. Following substantial root extension, optimum yields resulted when irrigations were scheduled at minimum ψ_L 's of -18 to -20 bars. Critical values are being refined with additional field studies.

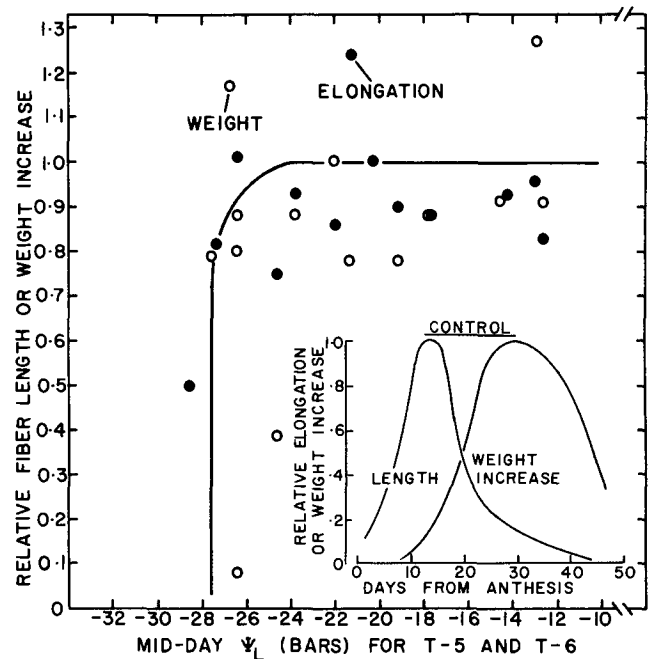


Fig. 3. Fiber elongation and weight increase as a function of ψ_L . The normal time relationship observed for fiber elongation and weight increase is shown by the inset graph.

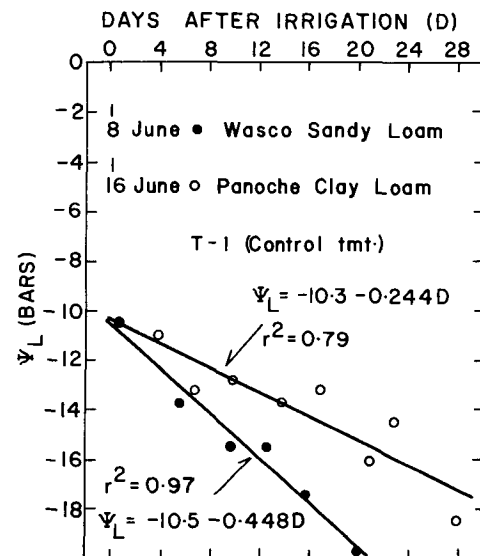


Fig. 4. Declining ψ_L over time since irrigation for contrasting soils.

A series of regressions, similar to that of Fig. 4, are given in Table 2 for treatments at both locations stressed differently during the first half of the growing season. This was done to detect possible differences in this relation due to conditioning effects of the treatments. Treatments T-1 and T-3 of the Wasco site and T-3 of the Panoche site were irrigated once before the comparison period, whereas all other treatments were irrigated twice. A visual examination of the regression coefficients reveals no major differences due to treatment at either location. The similarity of regression-line slopes for the two soils is

Table 2. Regression of minimum ψ_l on the number of days (D) since irrigation for two contrasting soils.

Treatment	Period	$\psi_l = a_0 + a_1 D$				
		a_0	a_1	r^2	s_1	t_1
PANOCHE CLAY LOAM						
T-1 (control)	15 July- 7 Aug.	- 11.13	-0.4416	0.94	0.0636	- 6.94**
T-2 (early 1st)	10 July- 7 Aug.	- 8.484	-0.4959	0.93	0.0666	- 7.45**
T-3 (late 1st)	17 July-29 July	- 8.615	-0.5308	0.93	0.1037	- 5.12*
WASCO SANDY LOAM						
T-1 (control)	8 June-29 June	- 10.39	-0.4598	0.96	0.0443	-10.38**
T-2 (early 1st)	10 June-29 June	- 10.83	-0.5776	0.92	0.0996	- 5.80**
T-3 (late 1st)	16 June-29 June	- 12.90	-0.4146	0.93	0.0816	- 5.08*

*,** Significant at the 0.05, and 0.01 probability levels, respectively.

Table 3. Lint yield and quality for contrasting irrigation treatments and soils.

Treatment										
1975 & 1976	1977	1975	1976	1977	1975	1976	1977	1975	1976	1977
		— yield—kg lint per ha —			— 2.5% span length—cm —			— micronaire—curvilinear scale —		
Panoche clay loam										
T-1 (control)		1849 c*	1600 c	1852 c	2.87 a	2.95 abc	2.97 c	4.21 ab	4.02 ab	4.48 b
T-2 (early 1st)		1844 c	1463 b	1816 c	2.84 a	2.97 abc	3.00 c	4.19 ab	4.00 ab	4.10 a
T-3 (late 1st)		1564 a	1336 a	1744 c	2.90 a	3.02 c	3.02 c	4.17 a	4.10 b	4.32 b
T-4 (late 2nd)	(stress)	1697 b	1631 c	1712 c	2.84 a	2.90 a	2.95 bc	4.39 c	4.33 c	4.40 b
T-5 (early 2nd)	(dry; 1-irrig.)	1779 bc	1596 c	1056 b	2.82 a	2.92 ab	2.90 b	4.25 abc	3.90 a	4.04 a
T-6 (stress)	(no post-plant irrig.)	1724 b	1547 bc	571 a	2.87 a	3.00 bc	2.69 a	4.33 bc	4.10 b	4.31 b
Wasco sandy loam										
T-1 (control)		1531 b	1608 b		2.79 a	2.97 a		4.02 a	4.10 a	
T-2 (early 1st)		1495 b	1585 b		2.72 a	3.00 a		4.06 a	4.00 a	
T-3 (late 1st)		1581 b	1692 b		2.82 a	2.97 a		4.13 a	3.65 a	
T-4 (late 2nd)		1508 b	1505 b		2.82 a	2.97 a		4.18 a	4.30 a	
T-5 (early 2nd)		1529 b	1612 b		2.84 a	3.00 a		4.12 a	4.30 a	
T-6 (stress)		943 a	692 a		2.79 a	2.90 a		3.95 a	3.80 a	

* Means in the same column not followed by the same letter differ at a 0.05 probability level with Duncan's Multiple Range Test.

accounted for by the different time intervals with greater leaf area and potential ET existing for the Panoche. From 15 July to 7 August LAI's increased from 3.0 to near 5.0. A statistical test (14) of regression-line slopes revealed no significant difference within a soil location. Statistical differences in elevation were detected, but they were not consistent with trends expected from differential conditioning, and their magnitude within a location was relatively small. Diffusion porometer measurements, on the same cultivars similarly preconditioned in another experiment at these locations, showed some stomatal closure (resistance of 15 sec cm^{-1}) at -28 bars, and that was only at the Wasco site.

These observations indicate that differential conditioning did not exist at a level that would detract from the usefulness of employing minimum ψ_l as an index for irrigation scheduling. Significant conditioning is evidently imposed by the climate and soil water status that resulted in optimum productivity (Table 3). Excluding the minimum ψ_l achieved before the 1st irrigation of the season (7), the average minimum ψ_l was -18.9 bars just before irrigation for the three top-yielding treatments at the Panoche site and treatment T-1 through T-5 of the Wasco soil location. Thomas et al. (16) observed considerable conditioning of field-grown plants experiencing

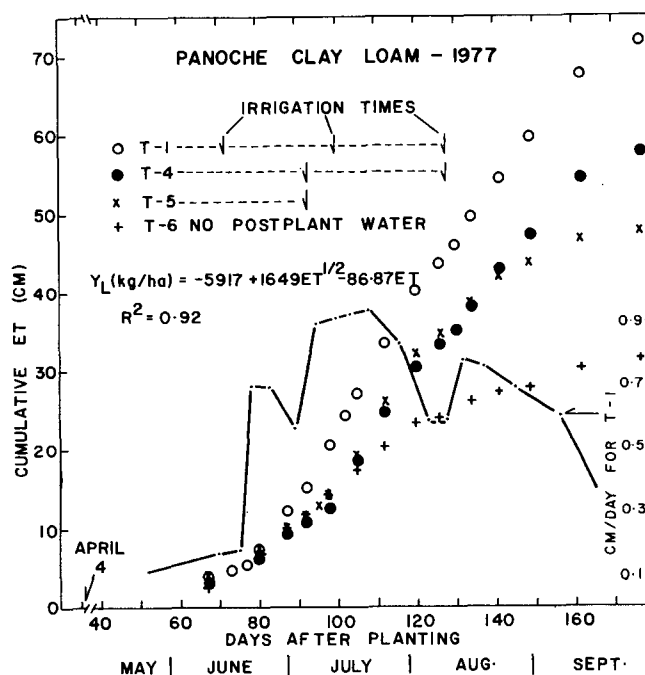


Fig. 5. ET of four contrasting irrigation treatments in 1977. Lint yield (kg/ha), as a square-root function of ET, is presented for this range of conditions.

stress levels of this magnitude. While the decline in ψ_i associated with a drying cycle between irrigations was linear at both locations, recovery lagged occasionally (up to 6 days) following the last irrigation of the season at the Panoche site.

In agreement with the trend illustrated in Fig. 3, fiber length was not substantially affected until water stress was great enough to lower lint productivity to about 600 to 700 kg/ha (Table 3). Micronaire (a measure of fiber fineness) was generally lower for treatments that delayed maturity. However, the high degree of stress at intervals throughout the season for T-6 on the Wasco soil caused a trend for lower micronaire even though maturity was not delayed.

Water stress imposed by treatments T-4, T-5, and T-6 in 1977 resulted in gradational reduction in evapotranspiration when compared with the T-1 control (Fig. 5). The daily ET rates of the low-stress control are typical for the region. Lower ET rates in early July and early August are associated with below-normal daily maximum temperatures: 31 C on 3 July and an average 33 C from 4 to 9 August. The functional relation between lint yield (Y_L - kg/ha) and total season ET (cm) for these treatments was $Y_L = -5917 + 1649 ET^{1/2} - 86.87 ET$ ($R^2 = 0.92^{**}$).

For conventional irrigation methods, the drying cycles of irrigation schedules associated with optimum production were sufficient to condition field-grown cotton plants in a semi-arid climate. This resulted in a uniformity of response such that the linear decline in minimum leaf water potential was demonstrated to be a reliable indicator of plant water state useful for irrigation scheduling in regions free of wide day-to-day variations in cloud cover and temperature.

Reduction in vegetative mainstem elongation was linearly related to declining ψ_i ; elongation essentially stopped at minimum ψ_i 's of -24 bars. Fiber-elongation and weight-increase rates were not affected until a very rapid decline was observed at about -28 bars; indicating that fiber growth may be a preferred sink at high-stress levels.

REFERENCES

1. Brown, K. W., W. R. Jordan, and J. C. Thomas. 1976. Water stress induced alterations of the stomatal response to decreases in leaf water potential. *Physiol. Plant.* 37:1-5.
2. Cutler, J. M., and D. W. Rains. 1977. Effects of irrigation history on responses of cotton to subsequent water stress. *Crop Sci.* 17:329-335.
3. ----, ----, and R. S. Loomis. 1977. Role of changes in solute concentration in maintaining favorable water balance in field-grown cotton. *Agron. J.* 69:773-779.
4. Fereres, E., E. Acevedo, D. W. Henderson, and T. C. Hsiao. 1978. Seasonal changes in water potential and turgor maintenance in sorghum and maize under water stress. *Physiol. Plant.* 44:261-267.
5. Gipson, J. R., and L. L. Ray. 1969. Fiber elongation rates in five varieties of cotton (*Gossypium hirsutum* L.) as influenced by night temperature. *Crop Sci.* 9:339-341.
6. Grimes, D. W., W. L. Dickens, and W. D. Anderson. 1969. Functions for cotton (*Gossypium hirsutum* L.) production from irrigation and nitrogen fertilization variables: II. Yield components and quality characteristics. *Agron. J.* 61:773-776.
7. ----, ----, and H. Yamada. 1978. Early-season water management for cotton. *Agron. J.* 70:1009-1012.
8. Hsiao, T. C., E. Acevedo, E. Fereres, and D. W. Henderson. 1976. Stress metabolism. *Phil. Trans. R. Soc. Lond. B.* 273:479-500.
9. ----, E. C. Oliveira, Jr., and W. M. Hall. 1978. Adaptation of cotton leaves to water stress. *Plant Physiol.* 61(5):80.
10. Jordan, W. R. 1970. Growth of cotton seedlings in relation to maximum daily plant-water potential. *Agron. J.* 62:699-701.
11. ----, K. W. Brown, and J. C. Thomas. 1975. Leaf age as a determinant in stomatal control of water loss from cotton during water stress. *Plant Physiol.* 56:595-599.
12. ----, and J. T. Ritchie. 1971. Influence of soil water stress on evaporation, root absorption, and internal water status of cotton. *Plant Physiol.* 48:783-788.
13. Longenecker, D. E., and L. J. Erie. 1968. Irrigation water management. p. 321-345. *In* F. C. Elliot, M. Hoover, and W. K. Porter, Jr., (ed.), *Advances in production and utilization of quality cotton: Principles and practices*. Iowa State Univ. Press, Ames.
14. Snedecor, G. W. 1956. *Statistical methods*. Iowa State College Press, Ames.
15. Stockton, J. R., L. D. Doneen, and V. T. Walhood. 1961. Boll shedding and growth of the cotton plant in relation to irrigation frequency. *Agron. J.* 53:272-275.
16. Thomas, J. C., K. W. Brown, and W. R. Jordan. 1976. Stomatal response to leaf water potential as affected by preconditioning water stress in the field. *Agron. J.* 68:706-708.
17. Wenkert, W., E. R. Lemon, and T. R. Sinclair. 1978. Changes in water potential during pressure bomb measurement. *Agron. J.* 70:353-355.