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Stem Diameter Variations in Cotton under Field Conditions[1]

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ABSTRACT

Stem diameter variations are a potentially useful indirect measure of the water status of the cotton (*Gossypium hirsutum* L.) plant under field conditions. The object of this study was to determine the information content in the stem diameter variations and the effects of irrigation and rainfall on these variations. The diameter was measured on a continuous basis for extended time periods for three seasons using linear variable differential transformers. The results indicate that the maximum differential diameter is closely correlated with the shape of the diameter-time curve. The maximum and minimum diameters occur at −5.76 ± 0.29 h and +2.93 ± 0.41 h relative to solar noon. The diameter varied from 10 to 25% of its maximum contractile value during an extended measurement period. A temporary positive expansion followed rainfall and a long term positive expansion followed irrigation.

Additional index words: **Daytime variation, Irrigation response, Rainfall response, *Gossypium hirsutum* L.**

THE stem diameter of cotton (*Gossypium hirsutum*, L. 'Deltapine 61') plants follow a rhythmic pattern of variation as the plant is subjected to normal environmental stimuli such as radiation, wind, and temperature. This variation has been the subject of a number of previous laboratory studies (3, 4, 9, 10, 12). In only one study were measurements taken over an entire water status cycle and that study involved a single test plant (5). There have been no studies in which the cotton stem diameter was examined under normal rainfall or irrigation in the field.

The object of this study was to use a large number of plants under normal field conditions over an extended time period to determine:

a) the essential information content in the daily stem diameter variation and

b) the quantitative variation of the diameter when the plants are subjected to a distinct shift in soil water content due to irrigation or rainfall.

With regard to the first objective, stem diameter daytime variation includes several quantitative features which may be useful in gaining insight into the water status of the plant. For example, the magnitude of the daytime variation or possibly the overall variation during the 24 h interval may be significant. The time at which maximum or minimum occur may also contain information. In other words, maximum values, shape of the curve, and timing are all features of the stem diameter change which may or may not contain salient information.

The second objective is closely related to the first. The stem diameter of the plant must be examined during a contrast in soil water content. This contrast was achieved by examining the stem diameter before and after a heavy irrigation and after rainfall.

Preliminary Observations

The technique was initially employed with manual data acquisition during the 1979 season at the Prince Road Site (described in detail below) and a 256 ha commercial cotton field in the Avra Valley near Tuc-

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son, Ariz. Twelve sensors on four plants were used at Prince Road and six sensors on six plants were monitored in the Avra Valley. Two preliminary conclusions were reached in 1979: the maximum differential diameter was much greater on the main trunk near the ground than on smaller side branches further up the trunk; the variation of stem diameter on the trunk was in phase with the variation in side stems, i.e., the minimum diameter at both locations would be reached at the same time in the afternoon.

MATERIALS AND METHODS

An experimental field site, 65 m by 17 m, was employed with 17 rows running in the north-south direction on 1 m centers. The soil type was a Comora sandy loam [coarse-loamy, mixed (calcareous), thermic Typic Torrifluvents]. Preparation and seeding of the field was by conventional tractor operations. Seeds were planted on Julian day 106 (16 April) in preirrigated soil. Seedlings were manually thinned to 20 cm. On day 223 plant height was 96.5 ± 15 cm. The average stem diameter of the 12 plants on day 210, at 5 to 8 cm from ground level, was 14.4 ± 0.14 mm.

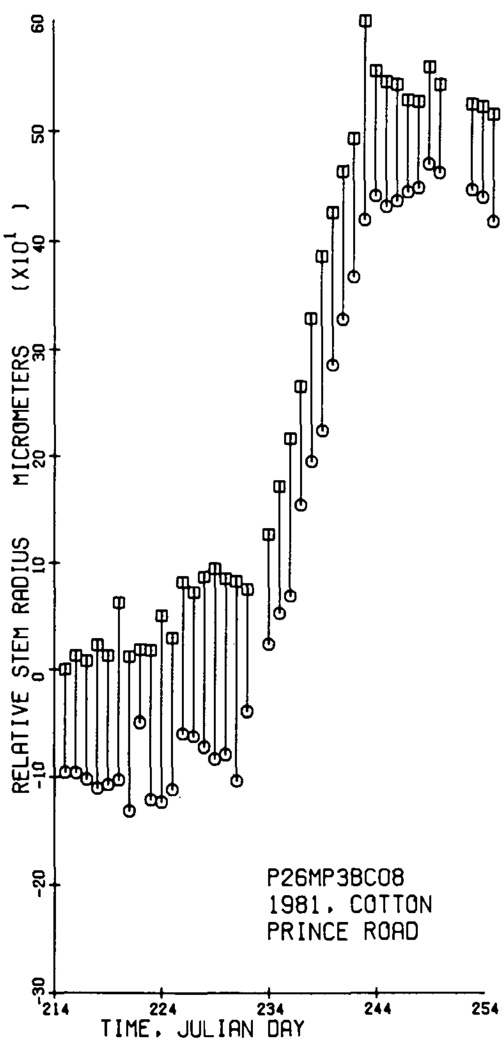

Fig. 1. Maximum (square) and minimum (circle) values of relative stem radius of plant in expanding phase. The alphanumeric code reads: plant 26, COSMAC computer channel 3B; CYBER computer channel 08. Radius value is relative to the stem radius on the morning of day 215 (14 mm).

At the onset of data acquisition the plants were in extensive flowering, but had no open bolls. There was standing water in the field from rainfall.

Twelve test plants in rows 6, 10, and 14 (four in each row) were selected which had a single main stem with the first node high enough to permit placement of the sensor housing within 5 cm of ground level and below any major side branch.

During 1981 data were taken every 15 min from day 215 (3 August) to day 255 (12 September). Resolution was 2.5 μm (2).

High and low temperature, total km of wind in 24 h, rainfall and pan evaporation were measured at an official United States Weather Bureau Station within 100 m of the field (1).

Data acquisition began at the end of a month of relatively heavy and extended rainfall. A heavy furrow irrigation (120 mm) was applied on day 232 during the middle of the test period.

The graphs were computer plotted from field data taken automatically. Conventional definitions of mean, standard deviation, linear regression and linear correlation coefficient are used.

The word "growth" as used in this paper is any permanent expansion of the stem diameter. The word "expansion" is used in an algebraic sense, and can be positive or negative.

RESULTS

Data were processed into various forms to facilitate an examination of different aspects of the daily pattern. In addition, a theoretical line was drawn between two successive maxima. This line and the curve formed by the actual data points between the two successive maxima enclosed an area which has been shown in several previous studies to vary with the degree of water stress (5, 6). In other words, the greater the water stress, the greater the daytime di-

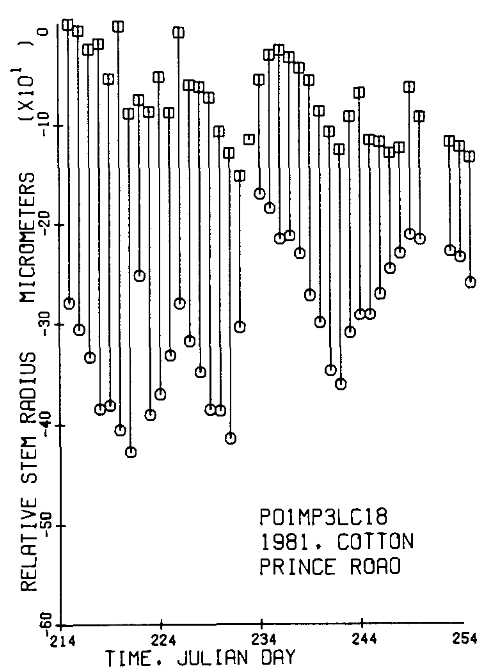

Fig. 2. Maximum (square) and minimum (circle) values of relative stem radius of a plant in a static phase. Radius value is relative to the stem radius on the morning of day 215 (16 mm).

ameter decrease below the maximum dawn diameter and the larger the area subtended. The maximum and minimum values of stem diameter were determined along with the difference between these values. The area under a line between two successive maxima and the slope of the variation between 0700 and 1200 h were also obtained on individual plants as well as the average of all 12 plants.

Figure 1, 2, and 3 illustrate three examples of the considerable variability from plant to plant encountered in the minimum and maximum values of stem radius from day to day. A heavy furrow irrigation (120 mm) occurred on day 232. The plants began in a relatively similar state but diverged into either an expanding, static or contracting phase as time progressed. The ordinate values of micrometers given in these curves are the relative radii with the dawn of day 215 as a starting radius value. The mean and standard deviation of the maximum daytime change in radius for all 12 sensors are shown in Fig. 4.

While the value of stem diameter has a wide variability on the 12 plants tested, the response of the plants to rainfall and irrigation showed a remarkable similarity. This is manifest by plotting the rate of expansion in Fig. 5. These values were obtained by

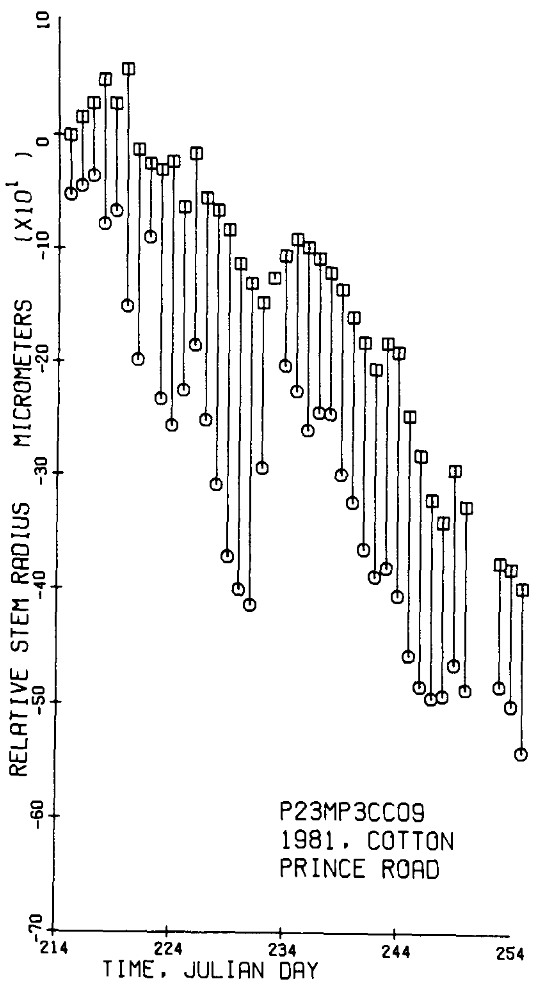

Fig. 3. Maximum (square) and minimum (circle) values of relative stem radius on a plant in a contracting phase. Radius value is relative to the stem radius on the morning of day 215 (16 mm).

algebraically subtracting the value of maximum stem diameter on day (x + 1) from the value of maximum stem diameter on day (x). With no exception all the plants exhibited brief positive expansions and growth under rainfall and irrigation stimuli. For example, on day 226, a positive expansion occurred which lasted only a single 24 h period. An example of this brief positive expansion is clearly seen in the variation of the maximum stem radius on day 226 in Fig. 1. A similar increase in the expansion rate followed every appreciable rainfall. The expansion rate due to irrigation on day 232 was sustained for 4 days following the irrigation. There was a substantial positive expansion on day 242 even though there was no rainfall. One possible explanation for this is the relatively cool night which followed several very warm nights.

The curve of the time of the average maximum and minimum diameter is shown in Fig. 6. In order to orient these times in the daily solar cycle, the time of sunrise, solar noon and sunset are also given. The data showed only a relatively small scatter between plants and between days. Based on 465 samples, an average time of maximum radius occurred at 06 64 $\pm$ 0.29 h MST and an average time of minimum radius of 15.33 $\pm$ 00.41 h MST. Relative to mean solar noon, these times are -5.76 ± 0.29 h and $+2.93 \pm 0.41$ h, respectively.

In order to determine the information content of the daytime stem diameter variation, the various definable properties such as maximum difference, area subtended by the daytime diameter decrease (as de-

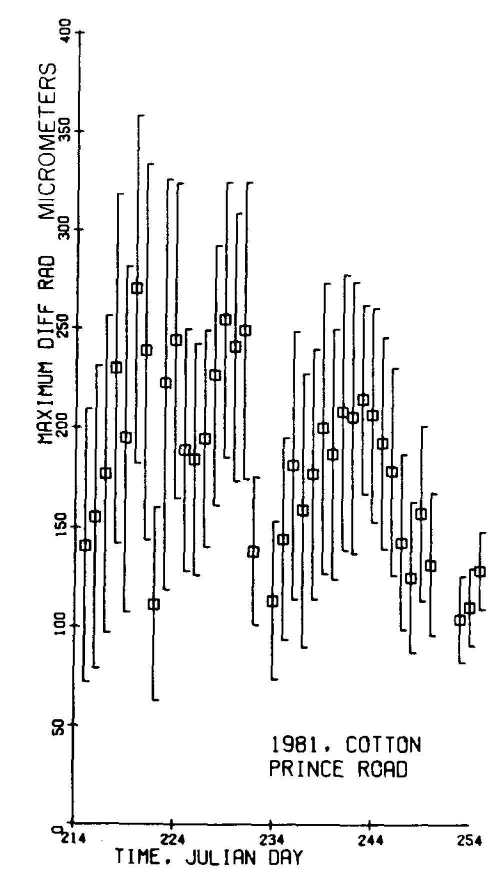

Fig. 4. Mean and standard deviation of the maximum daytime difference in stem radius for all 12 sensors.

fined previously) and morning slope were linearly correlated against each other. The results are shown in Table 1. Also included in Table 1 are the linear correlation coefficients resulting from a comparison of maximum diameter and temperature and the comparisons of area against several pertinent environmental variables.

An auxiliary test on 15 plants in 1980 at the Avra Valley Site using the same cultivar was made to determine the wet and dry radius of the lower stem. The main stem of the plant was cut at ground level and the stem diameter immediately measured. Then the excised plants were placed at the side of the field and allowed to dry in the sun for 2 days. After this, the diameter of the stem was measured again. A mean diameter change of 2.07 ± 0.37 mm was recorded. This yields an absolute value of maximum contractile diameter change in the trunk approximately 5 cm above the ground.

DISCUSSION

The results given above must be analyzed in terms of the two objectives of the study. Consider the first objective: What is the essential information content in the daytime stem diameter variations?

As seen in Table 1, there is a close linear correlation between the area formed by the integration of the magnitude of change below a certain base line and the maximum differential diameter. This means that these two indices of the daytime fluctuation yield essentially the same information. The time at which the maximum and minimum stem diameter occurs falls within a surprisingly tight range. This factor

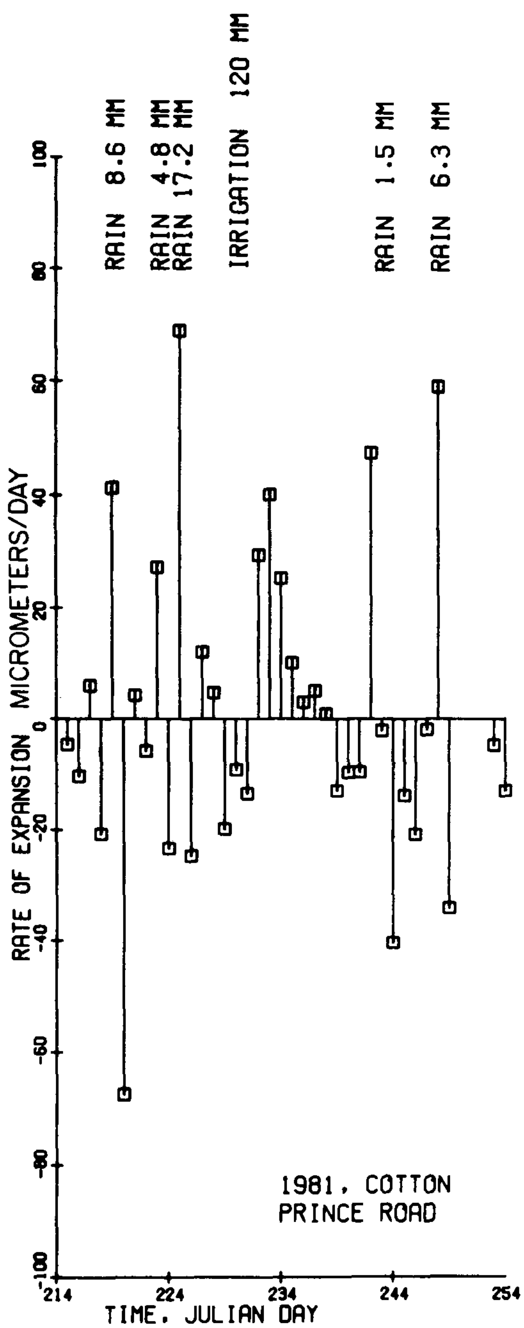

Fig. 5. Mean of the rate of expansion of the daily maximum value of stem radius. An algebraically positive value indicates an expansion, an algebraically negative value indicates a contraction.

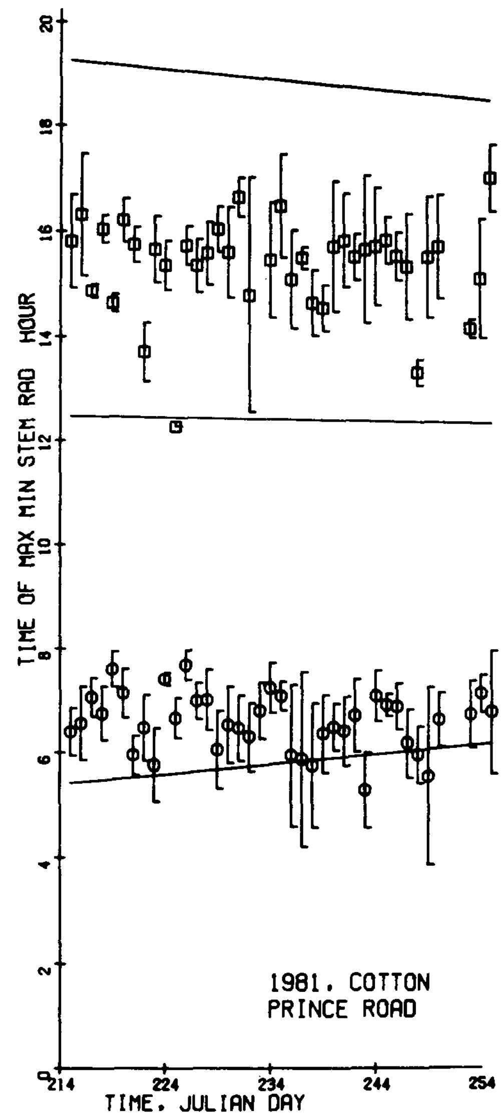

Fig. 6. Mean and standard deviation of the time of stem radius maximum (circle) and minimum (square). The top line is the time of sunset, MST; the middle line is the time of solar noon, MST; and the bottom line is the time of sunrise, MST.

coupled with the correlation of area and maximum differential indicates the same information may be obtained by monitoring the plant during approximately two 1 h intervals during the 24 h period. The close correlation of area and maximum differential also suggests the cause of the contraction is due to some roughly proportional process. The latter type of process would yield an area curve which could be approximated by a pair of triangles. One triangle to describe the traverse down to a minimum diameter and one triangle to describe the return to the dawn diameter.

This result supports the analysis of Molz and Klepper of the stem diameter variation based on Fick's Laws of Diffusion which resulted in a curve of basically triangular shape (8).

The less decisive correlation between slope of the stem diameter change and maximum differential diameter is surprising since a linear relation between area and maximum differential would imply a close correlation between slope and maximum differential. The lower correlation coefficient may be due to the selection of the slope interval. It is also of interest to observe that the maximum diameter occurs at a post dawn time. This indicates the recovery period extended through the entire night interval.

The post dawn maximum agrees with the measurements of Klepper et al. (4) under considerably different humidity conditions. Their results indicate a maximum at an even later time at higher humidity and lower radiation levels.

The time of maximum and minimum diameter does not appear to change as the day length shortens. The variation of solar noon is only 10 min over the data acquisition interval. This once again suggests a dependence of the time of the maximum and minimum values primarily on insolation as opposed to time of sunrise and sunset.

The almost constant phase difference between solar noon and the minimum stem diameter arises directly from the diffusive dehydration process of transferring water from the phloem and related tissue to the xylem. The 3 h phase lag measured in these experiments is considerably greater than the 1.6 h phase lag between solar noon and the minimum stem diameter calculated by Molz and Kleper (8). The value is based on the calculation of solar noon by the present authors at 1236 h on 20 July 1968.

Table 1. Linear correlation analysis between the maximum diameter difference, area, slope and environmental variables.†

Variables	Correlation coefficient
1. Maximum diameter difference and area	0.95
2. Maximum diameter difference and slope between 0700 and 1200 hours	0.78
3. Area and slope	0.75
4. Maximum diameter difference and maximum temperature	0.17
5. Maximum diameter difference and maximum temperature difference	0.03
6. Area and maximum temperature difference	0.03
7. Area and integrated wind over 24 h	0.26
8. Area and pan evaporation	0.20

† The area is formed by drawing a line between two successive stem diameter maxima over 24 h and then integrating the difference between the value on this line and the measured value. The slope is the variation in diameter between 0700 and 1200 h per unit time.

The second objective of the investigation concerns the stem diameter variation due to a shift in soil water content. The curve of average maximum differential shown in Fig. 4 indicates the differential showed no perceptible response to the 8.6 mm of rain measured on day 220. The differential dropped in response to the 4.8 and 17.2 mm of rainfall measured on day 224 and 226, respectively. However, the level of stem radius differential returned quickly to the prerain value as indicated by the 225, 241 and 249 μm changes on days 229, 230, and 231, respectively. The irrigation on day 232 produced a decisive shift in the maximum differential level. The value dropped to 113 μm on day 223 and began a slow recovery to higher levels of contraction until day 243 at which time a peak value was achieved. The level of contraction decreased steadily after that due to a moderation of the temperature. This decrease in stem diameter contraction occurred in the absence of any appreciable rainfall or irrigation.

The curve in Fig. 6 yields two numbers that can serve as benchmarks for further investigation. At this level of plant development and under the environmental conditions of August in southern Arizona, the average maximum differential radius varies between 100 and 250 μm. The significance of these numbers should be considered against a total variable radius differential of 1035 μm as seen from the ancillary control tests. These results indicate the expandable tissue changes between 10 and 25% of its maximum value.

The low values of correlation coefficients with temperature, wind, and pan evaporation indicate the stem diameter variation is not easily related to these environmental variables. Pan evaporation is presumed to be a variable that integrates the influence of the basic environmental variables. However, the correlation analysis of the full measurement period as well as an examination of partial acquisition intervals indicates no apparent correlation. The disparity is especially true in the comparison of differential diameter before and after irrigation. The maximum differential diameter obtained on day 233 immediately following a heavy irrigation was the same value obtained two weeks later in the absence of any rainfall or irrigation.

The discussion up to the present has been largely focused on the contraction during the daytime interval and the subsequent recovery in the late afternoon. A second area of analysis of the data is concerned with the expansion of the stem diameter. This is the most difficult area of analysis since an obvious physiological basis of comparison such as water status measurements are lacking. The discussion which follows is based on an examination of the maximum value of stem diameter measured at just past dawn. This cardinal point was selected because it is least sensitive to the normal daytime reaction of the stem to insolation levels. It is a variable measured after a long period of relative stability in the environment.

The daily maximum stem diameter has two definable characteristics. It can change in both directions: algebraically positive in the long term to yield growth and algebraically negative to yield a contraction. Examples of the two are given in Fig. 1, 2, and 3. In addition, the expansion may be temporary or permanent.

Out of the 12 plants monitored, three experienced periods of sustained expansion. In all three, the sustained positive expansion began after either rainfall or irrigation. The magnitude of the daily expansion was highly variable, from zero to a maximum of 75 μm over a 24 h period.

The negative expansions commonly observed were also highly variable in magnitude. The magnitude of the daily declines in diameter were in general smaller than the expansions.

The most interesting expansions in the stem diameter occurred on a transient basis, i.e., a positive expansion followed by a negative expansion, all within a single 24 h period. An example of a transient expansion is shown on day 220 in Fig. 2. This expansion occurred shortly after sunset. The onset of the expansion was precipitous. It began as if triggered and proceeded in a roughly exponential manner. The next day the plant returned to its original diameter. This type of expansion lasts only 24 h, or at most, 48 h.

Since the absolute value of stem diameter obtained had little meaning because of the sensor set up procedure, the only meaningful measurement was the change in the value of maximum stem diameter from one day to the next. Plots of this change, or approximate derivative of maximum stem diameter yielded a very striking similarity in all 12 plants, independent of whether they were in a long term growth or contraction phase. The data indicates a brief positive expansion followed each rainfall. This is in close agreement with Koslowski's observation with oak following rainfall (7).

Figure 5 shows this pattern averaged over all 12 plants. Although not shown in this figure for clarity, the standard deviation was low indicating that all 12 plants acted in the same manner.

In summary, the maximum daily variation in stem diameter is closely correlated with the curve of daytime diameter change. The time at which the maximum and minimum values occur were relatively constant over an extended period during which there was a heavy irrigation and rainfall.

Stem diameter expansions occurred temporarily after rainfall and permanently after a heavy irrigation.

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REFERENCES

1. Climatological Data: NOAA Environmental Data and Information Service National Climatic Center. Asheville, N.C.
2. Diaz-Munoz, F. 1980. Determination of the water status of cotton plants by sensing stem diameter. Proc. Nat. Electron. Conf. 34:177–181.
3. Huck, M.G., and B. Klepper. 1977. Water relations in cotton. II. Continuous estimates of plant water potentials from stem diameter measurements. Agron. J. 69:593–596.
4. Klepper, B., V.D. Browning, and H.M. Taylor. 1971. Stem diameter in relation to water status. Plant Physiol. 48:683–685.
5. ———, H. Taylor, M. Huck, and E. Fiscus. 1973. Water relations and growth of cotton in drying soil. Agron. J. 65:307–310.
6. Kozlowski, T.T. 1967. Diurnal variations in stem diameters of small trees. Bot. Gaz. 128 (1):60–68.
7. ———, C.H. Winget, and J.H. Torrie. 1962. Daily radial growth of oak in relation to maximum and minimum temperature. Bot. Gaz. 124 (1):9–17.
8. Molz, F.J., and B. Klepper. 1972. Radial propagation of water potential in stems. Agron. J. 64:469–73.
9. ———, and ———. 1973. On the mechanism of water stress induced stem deformation. Agron. J. 65:304–306.
10. ———, ———, and V.D. Browning. 1973. Radial diffusion of the free energy in stem phloem: An experimental study. Agron. J. 65:219–222.
11. Namken, L.N., J.F. Bartholic, and J.R. Runkles. 1969. Monitoring cotton plant stem radius as an indication of water stress. Agron. J. 61:891–893.