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**Vegetative physiology of cotton as related to the Crop Water
Stress Index**

Alou, Abdourahamane, M.S.

The University of Arizona, 1989

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**VEGETATIVE PHYSIOLOGY OF
COTTON AS RELATED TO THE
CROP WATER STRESS INDEX**

by

ABDOURAHAMANE ALOU

A Thesis Submitted to the Faculty of the

DEPARTMENT OF PLANT SCIENCES

**In Partial Fulfillment of the Requirements
For the Degree Of**

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In the Graduate College

THE UNIVERSITY OF ARIZONA

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STATEMENT BY AUTHOR

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ABSTRACT

This study was undertaken to investigate *Gossypium hirsutum* L. reproductive physiology and metabolic activities as they relate to the Crop Water Stress Index.

Five treatments were established based on the CWSI. These were the maximum stress levels allowed for each treatment. The indices investigated were .16, .35, .36, .40, and .62. Daily tagging of opened flowers in each treatment was conducted throughout the season. Diffusive resistance, transpiration, apparent photosynthesis, and yield were measured.

There was no significant difference in treatment yield. Plants irrigated at stress level either below .30 or above .40, tended to yield relatively low compared to plants maintained between .30 and .40. Floral production, abscission and boll retention were negatively correlated to CWSI. Negative relationships were also found between apparent photosynthesis, transpiration, leaf area and CWSI. A two day lag response was observed between a decrease in CWSI values resulting from irrigation, and daily flowering increase.

INTRODUCTION

With the increasing world population, more land is being put into production to meet the demand for food and fiber. More and more arid land is being turned into productive agricultural land to meet the challenge of an expanding world. The most restricting element by far which impedes the use of these lands for agricultural production are the availability and cost of the water.

Warm desert lands, such as those found in Arizona, can become highly productive with irrigation (Cox and Atkins, 1979). The high water use of agriculture in Arizona and the scarcity of this commodity caused legislators to pass the 1980 Ground Water Management Act which restricts agricultural water consumption. Thus, wise and efficient use of the water on Arizona farm land is imperative if agriculture is to remain viable.

With the development of space age technology, techniques have been developed for remotely assessing soil moisture (Idso et al., 1975, 1978), plant water stress (Tanner, 1963; Gates, 1964; Idso et al., 1977; Jackson et al., 1981), pest infestations (Idso et al., 1975; Pinter, 1980), crop yield (Idso et al., 1977), and various other factors affecting crop productivity. The infrared thermometer can be used to assess various environmental and physiological parameters affecting crop productivity (lb.). Idso et al. (1981a) and Jackson et al. (1981) developed an index which can be used to make efficient use of irrigation water based on a remotely obtained canopy-air temperature differential and air vapor pressure deficit.

This experiment investigated the relationships between Crop water Stress Index (CWSI) and cotton flower production, abscission, and retention.

Furthermore the crops vegetative growth was also investigated in relation to the treatments CWSI. Additionally, this research examined the usefulness of the CWSI as developed by Idso et al. (1981), for efficient irrigation scheduling, and yield prediction on differentially irrigated cotton (*Gossypium hirsutum* L.).

LITERATURE REVIEW

CROP WATER STRESS INDEX

In recent years, considerable interest has been given to remotely assessing the water status of plants (Idso et al., 1980). The development of the infrared thermometer provides a means for achieving this goal (Tanner, 1963; Aston and Bavel, 1972; Ehrlter, 1973; Idso et al., 1977; Jackson et al., 1977; Ehrlter et al., 1978).

Transpiration is an important physiological process which cools plants thus reducing the net radiation load (Gates, 1964). Transpiration proceeds at higher rates in healthy non-stressed plants than in stressed plants (Gates, 1964; Jackson, 1982). Continued transpiration depletes the soil water and subsequent water stress induces the partial closure of stomates (Wiegand and Namken, 1966; Jackson et al., 1977; Idso et al., 1981a) thus reducing the transpiration rate. The resulting decrease in latent heat exchange causes the leaf temperature to increase (Tanner, 1963; Gates 1964) due to the shift in the energy balance of the system. Several workers have recognized the potential use of leaf temperature measurements (Tanner, 1963; Wiegand and Namken, 1966) and canopy temperature measurements (Bartholic et al., 1972; Idso et al., 1977; Idso et al., 1981a; Jackson et al., 1977; Choudhury, 1986) to assess the plant water status.

Measurements of leaf temperature by early workers showed tremendous variability. Different environmental variables act singly or in combination to modify the leaf temperature (Gates, 1968a; Carlson et al., 1972). Carlson et al. (1972)

found a negative relation between the leaf temperature and relative water content of two soybean (*Glycine max* L. Merr.) cultivars. The position of the leaves on the stem influences the leaf temperature of potato (*Solanum tuberosum* L.) and tomato (*Lycopersicon esculentum* L.) (Waggoner and Shaw, 1952). Under clear days, the upper leaves, which are exposed to more sunlight than the lower leaves, are warmer than the air temperatures. The lower leaves, because of the shading effect, are cooler than air temperature. The orientation of the leaves with regard to the insolation also affects their temperatures. Leaves that are parallel to the insolation (upright leaves) are cooler than leaves perpendicular (horizontal) to the insolation (Waggoner and Shaw, 1952; Stevenson and Shaw, 1971). The water status of the plant also affects the leaf temperature (Gates, 1968a). Leaf-air temperature differential of peas (*Vigna sinesis* L. (Endl.) var. Burgundi) showed that leaf temperature was lower than air temperature in well watered peas, whereas in water-stressed peas the leaf temperature was higher than the air temperature (Clark and Hiler, 1973). Similarly, Sumayao et al. (1980) found leaf temperature of well watered corn (*Zea mays* L. cv. Prairie Valley) and sorghum (*Sorghum bicolor* L. cv. SG-40 GBR) was lower than the air temperature when the latter exceeded 33°C. The fluctuation of leaf temperature resulting from stress constitutes the basis for using infrared thermometry to assess plant water stress (Aston and Van Bavel, 1972; Bartholic et al., 1972; Idso and Ehler, 1976; Blad and Rosenberg, 1976; Ehler et al., 1978; Idso et al., 1978), to schedule irrigation (Jackson et al., 1977; Pinter and Reginato, 1982), and to predict yield (Idso et al., 1977, 1980, 1981b).

Infrared thermometry is a non-contact method which provides a rapid, non

destructive, and cost effective means of assessing various physiological parameters of plants and soil (Pinter, 1980; Jackson, 1982). The infrared thermometer is an instrument which measures the surface temperature of a target by simply pointing the thermometer toward the target (Jackson, 1982). The thermometer measures thermal infrared wavelengths between 8 and 14 μm , which is the infrared region the most useful for temperature readings (Jackson et al., 1980; Idso, 1981; Jackson, 1986). The atmospheric absorptivity is zero within this spectral band range except between 9.6 and 9.8 μm where little absorption occurs in the ozone layer (Oke, 1987). Thus long wave radiation emitted by surfaces could be read without atmospheric interference. Most portable infrared thermometers have lenses that allow only the energy within the narrow far infrared region between 8 and 14 μm to reach the sensor (Jackson et al., 1980; Jackson, 1982). Others lenses may filter out all energy except for an even narrower range of 10.5 to 12.5 μm (Jackson et al., 1980). The instrument measures radiant energy emitted by the target (crop field, soil, canopy, etc.) in the far infrared and relates this energy to the fourth power of the target's absolute temperature according to the Stefan-Boltzmann blackbody law (Jackson et al., 1980; Jackson, 1980; Pinter, 1982). This energy is radiated by all objects with an intensity proportional to the fourth power of the surface temperature and the emissivity of the surface (Gates, 1968b). As the object temperature increases, it emits energy in shorter and shorter wavelengths (Everest, 1986). The energy from infrared radiation flows from the hotter to the cooler object (Everest, 1986). It is this flow of energy which makes measurement of the net infrared radiation possible (Everest, 1986). Temperature

measurements are taken by pointing the thermometer at the target and reading the temperature from the meter on the rear of the instrument (Gates, 1968b; Everest, 1986).

On a sunny day a target is irradiated by both direct and diffuse sunlight (Jackson et al., 1980). Upon striking the target the solar radiation is either absorbed, reflected, or transmitted (Jackson et al., 1980). The amount of infrared radiation received by each object depends on the quantity of infrared radiation (ir) emitted by the sun, the ground surface, the atmosphere and clouds, the scattered skylight, the reflected sunlight and the sky light (Gates, 1968b). The radiation reflected by the target, known as the radiance (Jackson et al., 1980), is collected by the front and optical telescope of the thermometer and refocused on the infrared sensors within the thermometer (Jackson et al., 1980; Everest 210). The sensors convert the radiance into a proportional electrical signal which by calibration is converted to an equivalent digital number (Everest, 1986).

Various factors intervene to complicate temperature readings. A serious drawback in the use of infrared thermometry for plant canopy temperature measurement is that the instrument receives energy from all objects within its field of view (Jackson et al., 1980; Jackson, 1981). Unless the target (canopy) completely fills the thermometer field of view, composite reading of target and background is obtained (Jackson, 1981; Everest, 1986). If the instrument beam is gets slightly over the target, erroneous readings may result due to background influence (Everest, 1986). Other important limiting factors are the emissivity of the different surfaces, the geometry of the canopy, and the angle of view (Jackson,

1981).

The emissivity of an object is an indicator of how efficiently the object emits radiation (Jackson et al., 1980). It is defined as the ratio of infrared radiation given off by a non-blackbody, to that given off by a blackbody at the same temperature (Jackson et al., 1980; Everest, 1986). The emissivity is a number between 0 and 1 (Jackson, 1980). The emissivity of blackbody is 1 and it is high (.93 to .99) for most natural surfaces in the spectral band between 8 and 14 μm (Lorenz, 1968; Idso et al., 1969; Jackson, 1982). The emissivity of most plant and soil ranges between .93 and .97 (Jackson et al., 1980), with most plant leaves being between .97 and .98 (Jackson, 1982). The emissivity of complex canopy is expected to be close to 1 because of the irregularities in the canopy geometry (Jackson et al., 1980; Jackson, 1982). Jackson (1982) indicated that even if one assumed a unit canopy emissivity, the error induced by such an assumption would not influence temperature reading in excess of 1°C . Different surfaces have different emissivities especially at high temperature (Everest, 1986) and the emissivity of various surfaces increases with increasing temperature (Jackson, 1982).

The amount of background soil detected by the instrument sensors is determined by the canopy architecture (Jackson, 1981). The canopy architecture itself depends on the leaf shape, density of plants, the cropping system, the method of planting, and the plant height (Jackson, 1981). The canopy architecture determines the directions in which radiation from plant surfaces is reflected (Pinter et al., 1986; Jackson and Pinter, 1986). On the erectophile canopy, the vertical leaves reflect more radiation within the canopy, thus reducing the amount reflected

outward especially toward a point directly above the canopy (lb.) The planophile canopy, with horizontal leaves, reflects most radiation upward and very little is reflected inward. A sensor above an incomplete canopy will view a composite scene including sunlit and shaded soils as well as sunlit and shaded plants (Jackson, 1981, 1982). The largest temperature differential on agricultural fields is found between fully transpiring plants and dry sunlit soil. The composite temperatures of these surfaces is more dramatic with wide row crops than with broadcast or narrow drilled crops (Jackson, 1981, 1982). The relative fractions of sunlit and shaded soils and plants depends on the canopy architecture, the sun elevation, and azimuth angles.

As previously indicated, canopy temperature measurements are affected by the view angles. Viewing a target at right angles or obliquely to any object present in the field allows the instrument to view the maximum amount of vegetation (Jackson, 1980). The effect of the view angle on the measured temperature was known by early workers (Fuch et al., 1967). Fuch et al. (1967) observed temperature difference of 1.5°C between different target areas by changing only the instrument viewing angle. They found that the viewing angle has little effect (less than 10) on temperature readings when the angle was intermediate, but when the incident angle was inferior to 15° or over 60° , lower temperatures were recorded with a 30 degree field-of-view instrument. Small angle temperatures were low because the instrument was sensing temperatures deeper in the canopy. At wide angles the instrument views plant tips and background surfaces. Similarly, Kimes et al. (1980) found that changing the view angle from 0° to 80° from nadir

generates a temperature differential of 13°C for wheat (*Triticum aestivum* L.) canopy. This huge differential is due to the canopy geometry (Kimes et al., 1980; Jackson, 1981) and to the vertical temperature distribution within the canopy (Kimes et al., 1980). Changing the view angle from shaded to sunlit side of rows significantly changes the canopy temperature of row crops (Fuch et al., 1967).

A purpose of remotely measuring plant canopy temperature is to determine whether the plants are experiencing drought, thus allowing farmers to adequately schedule irrigation. Idso et al. (1977) and Jackson et al. (1977) have developed a Stress Degree Day (SDD) concept for yield prediction of *Triticum durum* Desf. They assumed that the crop canopy temperatures represent an integrated response of the plants to existing weather and soil conditions over some critical period. They defined the SDD as the summation of the canopy-air temperature differential over several days. The summation begins the first day of a critical period (ex. first day differential irrigation was applied) and ends at harvest. They predict that final yield will decrease linearly with increasing SDD. This inverse relation between final yield and SDD was confirmed on *Phaseolus vulgaris* L. by Walker and Hatfield (1979). If the SDD is positive, the plants are considered stressed, and if the SDD is negative the plants are considered non stressed. This SDD does not take into account environmental factors such as vapor pressure, net radiation, and wind speed which all affect crop canopy temperatures (Idso et al., 1981a).

To correct this problem, a crop water stress index (CWSI) that normalizes the SDD parameter for environmental variability was developed (Idso et al., 1981a).

This stress index requires the development of a non-water stressed baseline (Fig. 1; Appendix, A1). The non water-stressed baseline is expressed as a function of the foliage-air temperature differential ($T_f - T_a$ in °C), and air vapor pressure deficit (KPa). This baseline is established by providing the plants with ample supply of water so that transpiration proceeds at potential rate. The non-stressed baseline (lower baseline) describes a linear relationship between $T_f - T_a$ and VPD and this non-stressed baseline is available for several crops (Idso et al., 1982). The lower limit (Fig. 1; A1) is obtained through a linear regression analysis of the data on the daily temperature differential vs VPD (Idso et al., 1981a, b, c). The upper line (Fig. 1; A1), represents the upper limit at which $T_f - T_a$ is expected to rise (Idso et al., 1981a, b; Jackson et al., 1981). It depends on the crop species and the air temperature and is independent of VPD (lb.). It represents $T_f - T_a$ at a point where transpiration has ceased on the water stressed baseline. Idso et al. (1981a, b, c) and Jackson et al. (1981) used different approaches to derive the upper baseline from the lower baseline. Idso and colleagues (1981a, b, c) consider that since the temperature differential increases in response to a decrease in VPD, reducing VPD to zero and below (super saturated atmosphere) provides an indication of the upper limit by drawing the intercept of the non-stressed baseline and the line of constant ambient temperature (Fig. 1). As the sun rises, the foliage temperature, which at night was below air temperature by 7°C, rises relative to air temperature. This rising continues for at most 3 hours and then the fully open stomates allow the plants to reach full potential transpiration. As transpiration proceeds and cools the leaves, the foliage temperature decreases relative to ambient temperature (Idso

EMPIRICAL CROP WATER STRESS INDEX BASELINES

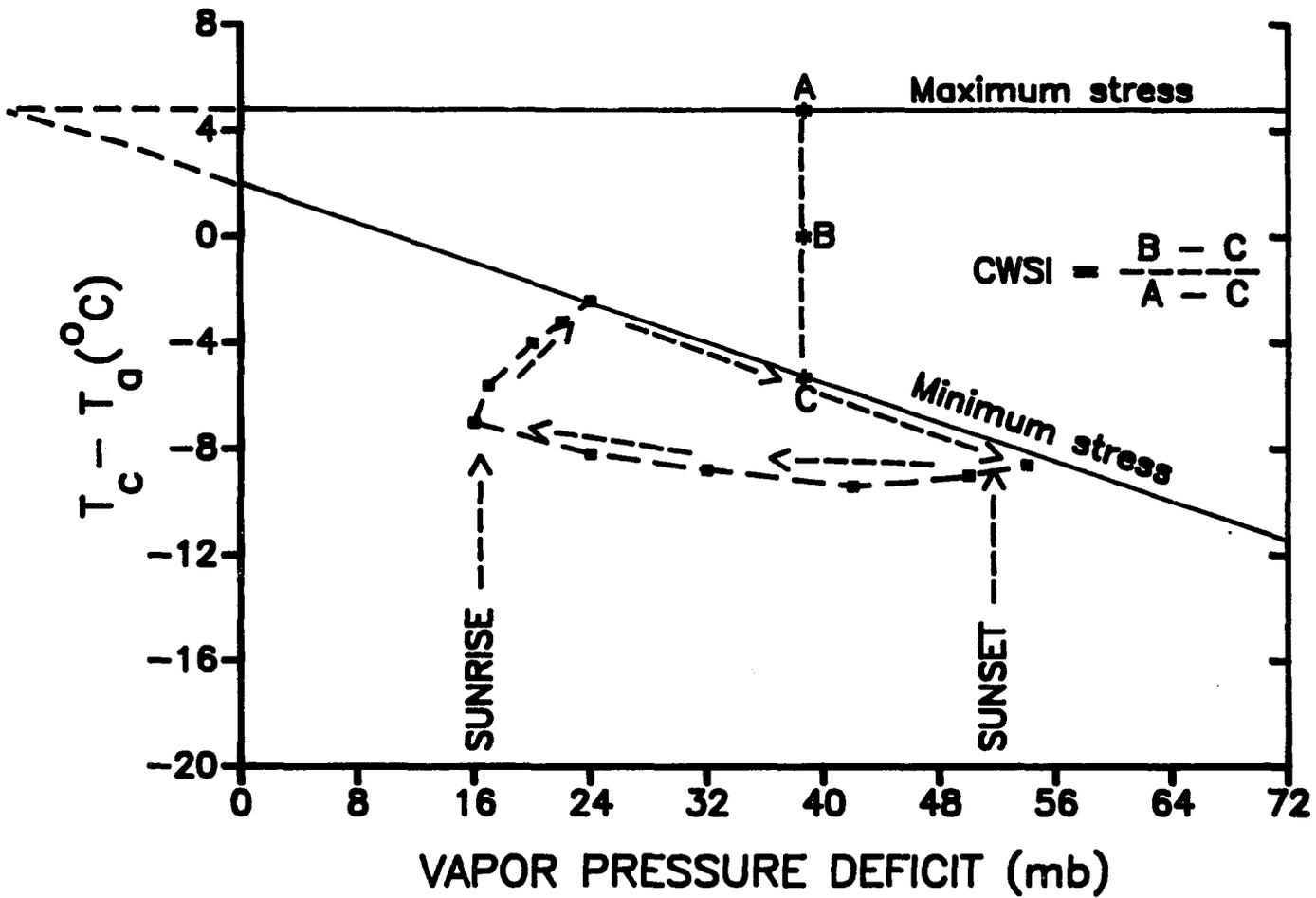


Figure 1. Graphical representation of the empirical model

et al., 1981). This process continues down the baseline (Fig. 1), until few hours before sunset (2 to 3 hours), at which time the stomates close and air temperature decreases relative to foliage temperature. This relative decrease of the air temperature brings about a relative increase in the foliage-air temperature differential as compared to its sunset value. The nighttime value of this differential is determined by the prevailing radiation balance. This nighttime value persists until sunrise as the stomates gradually reopen in response to the warming of the leaves, and the whole process starts again .

Jackson et al. (1981) calculated the upper and lower limit through energy balance considerations (Appendix, A2). They considered that the canopy resistance of non-transpiring plants is infinity (A2), thus the canopy air temperature differential representing the upper boundary becomes proportional to the product of the air resistance and the net radiation and inversely proportional to the product of the air density and air heat capacity. In Jackson's model, the lower limit is calculated by plugging a zero canopy resistance into the energy balance equation (A2).

In both approaches the upper and lower boundaries represent respectively the non-transpiring (maximum water stress) and the fully transpiring plants (minimum water stress). Any point that falls between these two lines is considered to be experiencing some degree of stress (Idso et al., 1981a; Jackson et al., 1981; Jackson, 1982) and this water stress is represented by a ratio ranging from 0 (ample supply of water) to 1 (no available water). This index can sometimes be greater than unity or lower than zero (Reginato, 1983). The water stress index of

a crop at a given foliage-air temperature differential and air vapor pressure deficit, is defined by Idso and colleagues (1981), as the ratio of the actual foliage-air temperature differential (Fig.1, B), minus the expected foliage-air temperature differential of the fully transpiring plants (Fig.1, C), and the difference between foliage-air temperature differential of the non-transpiring plants (Fig.1, A).

The CWSI is sensitive to various environmental factors (Jackson et al., 1981; Jackson, 1982). Using data collected by other workers, Jackson et al. (1981) showed that an increase of 8 m/s in wind speed causes a doubling of the CWSI in well-watered crops with representative environmental parameters (net radiation, T_a , VPD). Other sources of error in using CWSI are a rapid change in cloudiness and the factors previously indicated as capable of influencing the infrared thermometer .

Idso and Reginato (1982), and Choudhury (1986) showed that an inverse linear relationship exists between CWSI and net photosynthesis on cotton and Reginato (1983) observed similar relationships between CWSI and available water on guayule (*Parthenium argentatum*). Crop yield also appears to be linked to CWSI through an inverse relationship (Reginato, 1983). A curvilinear relationship appears to exist between CWSI and stomatal conductance (Reginato, 1983) and between canopy net photosynthesis and CWSI given a high internal CO_2 concentration (Choudhury, 1986). Under low internal CO_2 the relation between CWSI and canopy net photosynthesis becomes more linear. In order to make good use of the CWSI in irrigation scheduling, Jackson (1982) suggested that irrigation should be applied when the CWSI value is between 0.3 to 0.5. Within this interval,

vegetative growth rate is only reduced. The reduction depends on the plant species, nutrient availability, plants health etc. Above 0.5, growth will stop and yield loss may occur (Jackson, 1982).

The empirical model developed by Idso et al. (1981a, b) is apparently becoming more successful in terms of number of users, than the theoretical model. Jackson (1987) attributes some of this success to the fact that the empirical model, because of its simplicity, is more attractive to the users than the theoretical model. Some of the concerns with the empirical model are that it does not incorporate fundamental environmental factors such as wind speed and net radiation received by a field (Jackson, 1987). The simplicity of the empirical model lays in the fact that it integrates in its CWSI calculations, only two environmental components and one plant factor. The environmental factors taken into account by the empirical model are the air temperature and the air vapor pressure deficit, and the plant factor is the canopy temperature. Factors such as plant density, foliage density, plant growth stage, and plant height are not taken into account. The plant and foliage densities affect the percent ground cover and subsequently the percent reflected radiation. The above two factors also influence the composite temperature read by the thermometer. The soil fraction of this composite varies with the crop type and growth stage. As previously indicated, the soil fraction is more important during the early stage of the plant development, before the ground coverage is total. The plant height is very important because the vapor pressure deficit is usually evaluated at 1 m above the vegetation cover (Idso, 1982). It has been fairly well established that the zone of zero displacement is at approximately

two-thirds of the plant height (Oke, 1987). Above this height, the wind speed increases in a logarithmic fashion. So it is reasonable to think that at a meter above the canopy the wind speed is higher than that experienced by the plant. Thus, some adjustment of the vapor pressure deficit taken a meter above the canopy is needed. In addition, the empirical model depends on air vapor pressure. Although the relative humidity affects stomatal aperture and consequently transpiration, it is questionable as to how closely one can relate the air vapor pressure deficit to the actual stress experienced by the plants.

Another concern with the empirical model is the establishment of the baselines. The lower baseline (non-stressed plants) is established by taking the temperature and vapor pressure deficit readings over the course of a day or two. In a season, this lower baseline shifts upward or downward, depending on the plants' growth stage and flower development (Idso, 1982). Jackson (1987) has indicated that the estimation of the upper limit for the empirical model is based on highly ambiguous methods.

The complexity linked to the determination of the upper limit was also reported by Idso (1982). How accurate can one be in determining the point at which transpiration has completely stopped and particularly how it is possible to take only canopy temperature readings when the plants are wilted beyond repair? A consequence of this wilting is the appearance of an extremely large soil fraction which undoubtedly influences the temperatures read by the thermometer. To avoid such composite reading, one is reduced to taking very close readings with the aid of narrow opening thermometer. Once such readings are obtained, how

representative are they of actual temperature experienced by the canopy as a whole? Is it reasonable to assume that single leaf temperatures of non-transpiring plants are identical to that of the whole canopy? Or should such temperatures be used only as good approximation of canopy temperature? In either case, using single leaf temperatures as representative of canopy temperatures ignores the fact that factors such as wind speed affect the canopy and the leaf differently. The canopy as a whole is more subject to turbulent air flow, eddies, and advective heat (Oke, 1987). Transpiration in a single leaf is more affected by laminar air flow that constantly moves the boundary layer.

The theoretical model, although incorporating more environmental parameters than the empirical model, also has its share of difficulties to overcome. Since the theoretical model is based on an energy balanced system, it incorporates factors such as the net radiation, heat exchanges, aerodynamics, and the canopy resistances (Jackson, 1987). Aerodynamic resistance is defined as the turbulent air flow over canopies and that affects the evaporative processes (Oke, 1987). The canopy resistance is obtained by considering the canopy as a giant leaf (Oke, 1987). In the calculation of the canopy resistance, it is assumed that stomates on all leaves act together in a parallel fashion and yield a mean stomatal resistance. It is the ratio of this mean stomatal resistance to the leaf area index that is considered to be the canopy resistance (Oke, 1987). A major problem with the theoretical model is its complexity that may render it almost impracticable to farmers without some kind of computing device. Aside from its complex formulation, the theoretical model carries two technical difficulties. The first being

the difficulties associated with assessing correctly the canopy resistance and the second is determination of the aerodynamic resistance. Jackson (1987) took another look at the aerodynamic resistance as it concerns the theoretically calculated CWSI. He found that the traditional values of aerodynamic resistance, obtained through wind profile measurements, should be adjusted to account for the vertical air motion that constantly crosses the canopy. This adjustment is needed because an impossibility results through the use of the traditional aerodynamic formula. Usage of the classic aerodynamic formula shows that as wind speed declines to zero, the aerodynamic resistance increases to infinity. As the aerodynamic resistance increases to infinity, so does the canopy temperature, meaning that the plants would literally be burning. To avoid this situation of nonsense, Jackson (1987) devised an equation principally based on experimental data. In this new equation of the aerodynamic resistance, both the horizontal and vertical components of the air current in the canopy are accounted for. Under this new formulation, the resulting vertical resistance decreases as the wind speed decreases to zero.

Black et al. (1970) showed that it is not easy to measure the canopy resistance directly, for it is a function of plant, air, and soil resistances. They pointed out that many canopies cannot be considered as single layered and that it is only in the case of a loose canopy that the concept of canopy resistance could be applied. This application also requires evaporation from the soil surface to be negligible. Oke (1987) indicated that on trees, aerodynamic resistance and canopy resistance act in series to restrict vapor transfer. Of the two resistances, he indicated that the

canopy resistance is the dominant. It can thus be inferred that on trees at least, the aerodynamic fraction can be ignored and measurements can concentrate mainly on obtaining a good canopy resistance.

COTTON REPRODUCTIVE PHYSIOLOGY

The reproductive branches of a cotton plant originate at the base of vegetative leaves (Mauney, 1979, 1986). The growth rate of these vegetative branches is dependent on environmental factors such as temperature (Hesketh et al., 1972; Mauney, 1986) and water stress (Benedict, 1984; Mauney, 1986). The axillary primordia that give rise to the flower primordia originates from a transformed vegetative meristem (Mauney, 1986, 1986). Consequently, all factors that affect the growth and development of vegetative branches also affect the reproductive branches. Mauney (1966) indicated that floral buds could start differentiating as early as 14 days after emergence, and as late as 52 days after emergence. It takes about 40 to 50 days for a flower to develop completely from bud differentiation to anthesis (Mauney, 1986). These wide ranges in floral initiation time are principally due to day-night temperature differences (Mauney, 1966, 1984, 1986) and day length (Christiansen, 1986, Mauney and Phillips, 1963, Waddle et al., 1961). Increasing night temperatures result in the delaying of the flower initiation (Mauney, 1966). This delaying effect is even more accentuated when high night temperatures are combined with high day temperatures. Although environmental factors such as low temperature during germination, light intensity, and duration affect the floral position and initiation, the floral production is mainly

dependent on the combination of day and night temperature (Mauney, 1966; Mauney and Phillips, 1963). While low temperatures during germination tends to lower the position of the first floral node (Mauney, 1966; Low, 1969), the light intensity and duration affect the position of the first flower to open (Mauney, 1966, 1986). Chilling temperatures during germination delay cotton plant flowering with regard to the time of exposure to the chill (Christiansen and Thomas, 1969). The coupling of low night temperature with high day temperature enhances the flowering of cotton plants (Mauney, 1966). This enhancement is due to both a lower nodal position of the first sympodium and to the earliness of the floral initiation. Gipson (1974) showed that the stimulating effects of low night temperatures exist only when the night temperature is not below 20°C. Below that temperature, he found the days to first bloom linearly increases with decreasing night temperature. Depending upon the cultivars under study and on the growth stage at which the plants experienced the low temperatures, the nodal position of the first sympodium shift upward or downward. Gipson (1974), found that night temperatures between 10 to 15°C produce squaring delay of up to 15 days, when compared to the time to squaring when night temperatures were between 20 to 25°C. Moraghan et al. (1968) found that the earliest squaring occurs at night temperatures between 22 to 25°C with the day temperature below 33°C. Low day temperatures counteract the effects of night temperatures to affect the node of the first floral branch (Mauney, 1966). The temperatures prevailing from planting to appearance of the first true leaf are of major importance for it is during this period that the nodal position of the first sympodium is fixed (Gipson, 1986). The nodal

position of the first sympodium is important because it provides an indication on a given cultivar earliness and its ability to produce large amounts of flowers (Gipson, 1974; Mauney, 1984, 1986; Munro, 1971). Earliness is a measure of cotton yield potential (Ray and Richmond, 1966; Munro, 1971). It is based on morphological and physiological changes experienced by a crop from vegetative to reproductive stages. These measures include the node level of the first sympodium, the vertical flowering interval, the horizontal flowering interval, and the dates of appearance of first squares and flowers (Joham, 1979). From an agronomic point of view earliness refers to the fraction of crop harvested at first pick and to the number of days needed to reach that stage (Leffler, 1979; Mauney, 1986). Earliness is controlled by genetic, environmental, and cultural factors (Ray and Richmond, 1966; Low et al., 1969; Munro, 1971; Mauney, 1986). The temperature dependency of earliness lead Low et al. (1969) to conclude that earliness can be induced at an early stage of the seedling development through a cold treatment. Ray and Richmond (1966) and Munro (1971) provided some analyses on the important components of earliness. Kerby and Buxton (1978) indicated that the vertical and horizontal fruiting patterns along the main axis and the branches respectively, are also important components of earliness. Hesketh et al. (1972) showed that both the rate of vertical flowering and horizontal flowering are temperature dependent. The horizontal flowering being about 2.16 to 2.68 times faster than the vertical flowering for *G. hirsutum* (Mutsaers, 1983) and 2.68 to 2.78 for *G. barbadense* (Hearn, 1969).

Another factor of great influence on cotton flowering is the soil moisture

availability. Once the cotton plants begin flowering, the development of additional sympodia and fruiting sites are dependent upon the vegetative growth of the plants (Mauney, 1984, 1986). The vegetative growth of the plants is greatly dependent on the soil water availability. Jordan (1986) considers the soil moisture to be one of the primary factors influencing and controlling the production of potential fruiting sites. Furthermore, the lack of adequate soil moisture results in shedding of the flowers and squares and bolls. Bruce and Römken (1965) found that plant growth rate and the square initiation were greatly reduced by water stress applied during the first four weeks of flowering. They also reported that though frequently irrigated cotton plants produced a great number of flowers, these plants shed most of their squares. Rijks (1965) showed that plants exposed to early water stress retain 75% of the bolls as compared to 46% for plants with ample supply of water. Associated with ample water supply are high yield large numbers of fruiting branches, high square shedding, and low boll retention. Premature boll shedding is characteristic of the genus *Gossypium* (McMichael et al., 1973). A cotton plant can shed anywhere between 10 to 70% of the fruit load under limited stress (McMichael et al., 1973; Mauney et al., 1980). The shedding phenomenon may occur without the plants experiencing any water stress (Guinn and Mauney, 1984). Early researchers have estimated that cotton plants could lose up to 70% of the potential yield, as a result of premature shedding (Walhood, 1957). Severely stressed cotton plants can abort as much as 78% of boll set. McMichael and coworkers (1973) showed that stress induced abscission of fruit and leaf increased linearly with a decreasing leaf water potential.

Two dominant theories attempt to explain fruit abscission on cotton plants. The nutritional approaches held by many early researchers (Mason, 1922; Wadleigh, 1944) considers that assimilate production and distribution constitute the major limiting factors to a large number of boll retention by a cotton plant. As the boll load increases, the supply of carbohydrate drops and the fruit are aborted. Vegetative growth resumes following irrigation. This regrowth competes with existing bolls for carbohydrates and nitrogen (Stockton et al., 1961). This competition causes bolls to abscise. The hormonal approach to boll abscission considers the hormone interaction and shift in hormone balance as the main cause of boll abscission (Guinn, 1982, 1986). Upon stress, ethylene production increases in cotton plants (Hall et al. (1957); McMichael et al. (1972)). Fruit abscission succeeding water stress or high boll load is presumably due to a shift in the balance between auxins and ethylene concentrations in the abscission zone (Guinn, 1986). An increase of ethylene concentration in the abscission layers is associated with a decrease of auxin (lb.). Ethylene reduces auxin activity and increases the activity of cell wall degrading enzymes in the abscission cells. Guinn (1986) indicated that " the interaction of plant growth regulators may be more important in controlling boll abscission than concentration of any single one".

This study was undertaken to determine the stress indices which will result in the highest lint yield, while saving on water used to grow a field of cotton. Previous workers have estimated that stress level between .30 and .50 can be used for irrigation scheduling. Five Crop Water Stress Indices (.16, .30, .35, .36, .40, .62) were investigated to refine the above range. The relationships between

CWSI and floral production, abscission, and retention were investigated. In addition, plant heights were measured and apparent photosynthesis, transpiration, and diffusive resistance activities were examined as they relate to the CWSI.

MATERIALS AND METHODS

FIELD DESIGN AND SEEDING

Seeds of short staple cotton (*Gossypium hirsutum* L. cv. DPL 90), were planted on 7 May 1987 at University of Arizona Campus Agricultural Center, Tucson AZ. The seeding was done on a uniform Coarse-Loamy, Mixed Thermic Typic Torrifluent soil, of the Gila loam series. A north-south row orientation and one meter row spacing was used. A randomized complete block design was used for this research. The .61 ha field was divided into twenty equal plots each covering an 8 meter x 15 meter area. Each plot was 8 rows wide. Sowing was accomplished using a standard four-row planter at a planting rate of 13 Kg/ha. Five water treatments, each replicated four times, were used in this experiment.

Each plot was independently provided with water through a semi- automatic underground drip system. The drip system consisted of two sand filters, a pressure regulator, a timer, an electrical pump, various pipes, and a series of twenty pressure gauges and valves each controlling water delivery to a single plot. The system used two-walled tape (14 mil tape) buried 20 cm beneath the soil surface. The tape orifices were spaced at 23 cm intervals.

Nutrients were injected into the system through a venturi. A commercial brand urea fertilizer (Solution 32, 32-0-0) was the main fertilizer injected through the system. Overall, 134 Kg/ha of nitrogen were used on this field. Herbicides and insecticides were not used in this field. Weeds were removed by hand and the use of insecticide was deemed not necessary.

The field was defoliated with sodium chlorate on 19 October and first picked 10 days later. The second pick was done on 2 November.

WATER TREATMENT

Irrigation treatments were scheduled based on the crop water stress index (CWSI). The CWSI values .16, .35, .40, .62, and .36 were respectively designated wet, medium, dry, very dry, and Azmet treatments. These values represented the maximum water stress level each of the treatments was allowed to reach on the average. The above treatment names refer to the stress level at irrigation rather than to the amount of water applied. Irrigation was applied on the average when these values were reached. However during periods when water stress was imposed on the plants, the CWSI values were exceeded. These water stress periods resulted when plants within the same treatment but in different plots, depleted unequal amounts of soil water. During the whole season, the field received 40 mm of rainfall.

The wet treatment was established to receive abundant water, much in excess of the plants need. The wet treatment was irrigated 10 times during the season. That amounted to 80 cm of water. The medium, dry, and Azmet treatments were established as to receive adequate amount of water, within the range of what a farmer would use for proper irrigation. These treatments were each irrigated 7 times throughout the season. They received respectively 70, 73, and 69 cm of water for the season. Plants in the very dry treatment were irrigated 6 times, which amounted to 67 cm of water applied. Prior to planting all treatments received 16

cm of water.

CANOPY TEMPERATURE AND CWSI

Canopy-air temperature differential was measured under clear sky, three times a week (Monday, Wednesday, Friday), when weather permitted. An Everest Interscience Surface Thermometer (Model 110) was used. This special model, was built with a germanium lens. This infrared gun remotely sensed the temperature at the crop canopy. The temperature differential was measured by viewing individual plot canopy at an angle about 30° from the horizontal, between 1000 Mountain Standard Time (M.S.T.) and solar noon. Prior to canopy establishment (first flower stage), individual leaf temperatures were recorded instead of partial canopy temperatures. For all readings, the thermometer was set at the fast position. This position reads instantaneously any change in canopy temperature resulting from sudden changes in environmental conditions. The data were recorded only upon stabilization of the temperatures read. Temperature was measured on both east and west sides of each plot. Temperatures were measured while walking either northward or southward within an alley. To avoid background variability effects on the readings, the same areas were measured throughout the season. These areas were marked by flags delimitating a 2 m² area. These 2 m² areas were reserved for the flower study. On each side of all plots canopy temperature was read three times and the average of both readings was recorded as the plot canopy temperature. It took about 7 minutes to obtain the temperature of all 20 plots. Thus the vapor pressure deficit was recorded once

canopy temperature was obtained for half of the field. Although the thermometer was calibrated by the manufacturer, its calibration was frequently checked against that of a calibration box. The calibration was done by checking the thermometer's temperature against that of a blackbody . The gun was pointed at the blackbody, and both temperatures were recorded. To check the gun's accuracy, temperature recording was performed every 30 minutes from early morning to 1500 M.S.T. The recorded temperatures were then plotted to check the range at which the thermometer readings depart from those of the blackbody. During the course of this study, no major deviation was observed in the thermometer temperature readings. Thus the manufacturer's calibration was maintained throughout the season.

The vapor pressure deficit (VPD) was calculated using the wet and dry bulb method. The wet and dry bulb temperatures were obtained with a portable electric psychrometer (Psychron, model 566 series). The soil moisture was measured on the third row from the west side of each plot with a neutron probe 2 to 3 hours before canopy temperature was read. The neutron probe was used to determine the amount of soil moisture depleted on the first four treatments (wet, medium, dry, very dry). Soil moisture readings were taken only at 30, 61, 91 cm. For the Azmet treatment, the amount of water needed to bring the plots to field capacity was established through the consumptive use method. The crop coefficient for this field was calculated by Dr. Paul Brown, micrometeorologist, Soil and Water Science Department of the University of Arizona.

The CWSI values for each plot were calculated using the empirical method

developed by Idso et al. (1980). The initial baseline was established using the predicted equation ($Y_1 = 2.0 - 2.4 * X$) established for *G. hirsutum* by Idso et al. (1982). In the above equation, X is the VPD measured in KPa, and Y predicted canopy-air temperature differential. Based on previous observations (Garrot et al., 1987) and in accordance with observations by Idso et al. (1982), the lower baseline shifted upward as the reproductive stage began. The new predicted baseline ($Y_2 = 2.65 - 2.10 * X$) was previously established by Garrot et al. (1987). In mid-July the baseline shifted again upward to a new position determined by the regression equation Y_3 ($Y_3 = 3.7 - 2.1 * X$). In late July, the baseline shifted back to the initial position (Y_1). Measurements for the lower baseline were done over a day or two, starting two days after irrigation. In order to encompass a wide range of VPD, the readings were extended from 1000 to 1500 M.S.T.

FLOWER STUDY

The flowering pattern of the cotton plants was studied in a 2 x 1 m area selected within each plot. This area was consistently selected on the third row from the east side of each plot. Within a selected row, the 2 m² area was chosen to be as representative of the plot as possible. These areas were then delimited with flags. The flowers were tagged with colored plastic tags. Tagging was conducted throughout the flowering period on a daily basis. The plastic tags were attached to the pedicel of flowers which had opened within the last 24 hours. These flowers were identified by their yellow color. The tagging was consistently started between 0630 and 0700 M.S.T. and terminated upon completion of all 20

plots. Tagging started on the week of 6 July and proceeded without interruption until 20 September. Each tag was coded to indicate week of tagging.

Starting on week 4 of tagging (28 July), and continued through week 11, the tagging day was also coded on the tags. This combination of coding provided the exact day on which a given tag was put on the flower. This information was used to study the water stress effect on the flower and fruit abortion.

To study flower abortion, tags dropped on the ground were picked up daily. The collection of the dropped tags was started on 21 July and proceeded to 29 September. Since the tags from aborted fruits and flowers were collected daily and the CWSI was measured only three times a week, the abortion data were grouped with the dates when CWSI data were collected. Tags collected Saturday through Monday were grouped with Monday CWSI data, tags from Tuesday to Wednesday and tags from Thursday to Friday were grouped respectively with Wednesday and Friday CWSI data.

Plant height was measured weekly. Height of three plants, picked randomly within the 2 m² flower tagging area, were taken every Wednesday starting on week 2 of tagging and stopped on week 8 of the tagging period because of lodging problem in the wet treatments.

METABOLIC ACTIVITIES MEASUREMENTS

Photosynthesis, transpiration, and diffusive resistance data were collected 26 August and 11 September. A LiCor steady state porometer (LI-1600) was used to obtain the leaf transpiration ($\mu\text{g cm}^{-2}\text{s}^{-1}$), diffusive resistance (s cm^{-1}), the cuvette

temperature ($^{\circ}\text{C}$), and leaf temperature ($^{\circ}\text{C}$). The data were collected between 1100 and 1400 M.S.T., on both 26 August and 11 September. Data were read on the first or second fully developed leaves of a selected plant. Leaves selected were fully exposed to sun light and in good health. The selected leaf was enclosed between the broadleaf aperture cap and the cuvette. This enclosure was done in such a way that the thermocouple surmounting the cuvette was on the abaxial side of the leaf. Data were recorded upon stabilization of the readings, which usually occurred in about 20 seconds.

The CO_2 gas exchange data were obtained with the syringe method (Clegg et al., 1978, Ehleringer and Cook, 1980, Cock et al.,1985). A plexiglas leaf chamber with an internal volume 2.36 liters enclosed an upper, sunlit, and fully developed leaf. The chamber gases were circulated with a small battery driven fan. The air inside the chamber was sucked out with two 6 cm^3 plastic syringes (Monoject). The syringes penetrated the chamber through two rubber septa mounted on one side of the plexiglas chamber. The leaf was inserted in the chamber in such a way that the petiole passed through a sealed opening on the side opposite to the syringes. The fan was turned on after the leaf was properly enclosed in the chamber. The first syringe was pulled 5 seconds after the motor was turned on. The second syringe was pulled 30 seconds later. The syringes were then removed from the chamber, stopped with a rubber stopper, and placed in an ice container. The leaf was clipped and inserted within a plastic bag which was placed on ice. In each of the 20 plots, the data were collected on three plants located on the same row. The photosynthesis and porometer data were collected

on the same rows where the flower study was performed.

The CO₂ content of each syringe was determined with an open system infrared gas analyzer. The system included a nitrogen gas carrier, a drying column for water removal, an infrared gas analyzer (Beckman model 865), a fluke multimeter, and a flow meter. Prior to readings, the system was calibrated using gases from two standard tanks containing 411 and 354 ppm CO₂. The leaf area was measured with a LiCor area meter (Model 3100). Upon measurement of the area, the leaf dry weight was determined following a 36 hour drying period. The leaves were dried in a constant temperature cabinet (Blue M), at 75 °C, then weighted on an electric scale (Mettler PC 2200).

The data were analyzed using the Statistical Analysis System software package. Means were separated using the Least Significant Difference technique for the smaller samples size, and the Duncan's Multiple Range test for large samples size. Linear correlations were performed to study relationships between variables.

RESULTS AND DISCUSSION

CROP WATER STRESS INDEX

Five water stress levels were established with success using the Crop Water Stress Index (CWSI) (Tables 1, 2). The treatments were designated wet, medium, dry, very dry, Azmet and based on the CWSI level at which the plants were irrigated. For the first four treatments, the soil moisture depletion was measured with a neutron probe. For the fifth treatment, the amount depleted was based on cotton consumptive use of water.

The lower baseline shifted 3 times during the season. The initial lower baseline used was $Y_1 = 2.0 - 2.4 * X$ (Fig.2). This baseline was established at the United States Water Conservation Laboratory in Phoenix Arizona, by Idso et al. (1982). The first upward shift of the lower baseline occurred as the plants were changing from vegetative to reproductive stage. Within the week flowers started opening in all treatments, the lower baseline moved upward from the predicted equation Y_1 to equation Y_2 (Fig. 2). This upward movement is attributed to an increase in plant temperature within the few days following floral initiation. Such increase in temperature could result from the high temperature of the non transpiring floral parts. These non transpiring floral parts are the most exposed to solar irradiation. They assumably convert the incoming radiation into sensible heat which increases the canopy temperature. Idso (1982) found a similar shift of the lower baseline in the period just after heading of wheat (*Triticum durum* Desf. var. Produrum) and barley (*Hordeum vulgare* L.). The second shift of the minimum stress baseline (from Y_2 to

Table 1. Treatments and seasonal Crop Water Stress Indices

TREATMENT	SEASONAL CWSI	IRRIGATION CWSI
WET	.04	.16
MEDIUM	.11	.35
DRY	.13	.40
VERY DRY	.22	.62
AZMET	.14	.36

Table 2.**Daily CWSI Values of each treatment**

Days After Planting	Treatments					P-Value
	Wet	Medium	Dry	Very Dry	Azmet	
66	.048	.082	.10	.14	.12	.11
70	.025 b	.093 a⁺	6.121 a	.130 a	.146 a	.008
74	.024 b	.087 a	.112 a	.143 a	.134 a	.0031
78	.037 b	.085 c	.109 b	.178 a	.132 ab	.0007
82	.038 c	.092 b	.106 b	.168 a	.146 ab	.0001
96	.033 c	.105 b	.123 b	.189 a	.117 b	.0001
106	.035 c	.097 b	.116 b	.178 a	.128 b	.0001
116	.043 c	.113 b	.141 b	.221 a	.131 b	.0001

⁺Values followed by same letter within a row are not statistically different based on Duncan's multiple range test mean separation technique (p=.05).

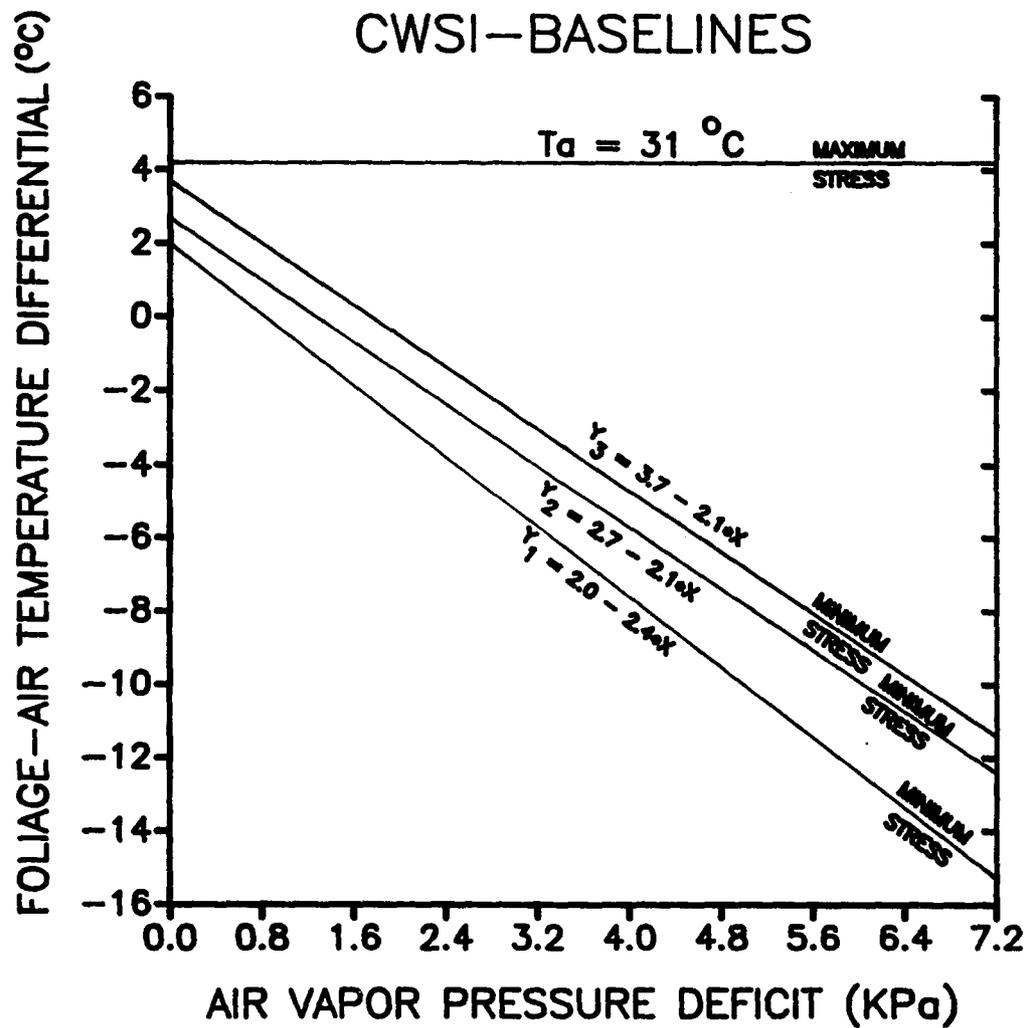


Figure 2. CWSI baselines used during the season

Y_3), occurred in late July. This baseline was used on only two consecutive sampling dates. This upward move of the baseline, was attributed to high relative humidity ($R_h=89\%$) prevailing on these days. The fourth and last shift occurred when the minimum stress line moved back to its initial position (Y_1). The relative humidity dropped to between 30% and 38% for about a week and ensuing this reduction of the relative humidity, the plants transpiration increased. This increase of plant transpiration could cause the lowering of the minimum stress line. The minimum stress line remained in this position for the remaining weeks of the season presumably because the green bolls which were set during the maximum flowering period were contributing significantly to transpiration. Daily canopy temperature readings were terminated on 31 August because of leaf senescence.

The lowest CWSI values averaged over the season were obtained in the wet treatment and the highest in the very dry treatment (Table 2). The values shown in Table 2 represent the average water stress indices at which the plants were maintained for the season. But the treatments were actually established at the maximum water stress indices, retained for each treatment as irrigation scheduling flags (Table 1). For each treatment, the average irrigation CWSI value at which water was applied was three times higher than the seasonal average. Thus plants in the wet treatment were maintained at .04 but irrigated at .16, in the medium the plants were maintained around .11 for the season, and irrigated at .35. For the dry, very dry, and Azmet treatments, the plants were maintained respectively at .13, .22, and .14 for the season, and irrigated at .40, .62, and .36, respectively.

REPRODUCTIVE PHYSIOLOGY AND CWSI

Flowering started in all plots on average 61 to 62 days after planting. Opening dates of first flower vary greatly with environmental conditions, locations, and cotton varieties. For upland varieties, Munro (1987) indicated that in tropical regions such as Ugandan and Malawi the first flower opens 45 to 70 days after planting. Temperature is the major factor controlling the number of days to first flowering. Under warm temperature, the number of days to first flower is greatly reduced as compared to cooler ambient temperature. In the cotton growing regions of the United States the first flowering usually occurs 70 to 80 days after planting (Longnecker and Erie, 1968). Kittock et al. (1981) indicated that for Southern Arizona the dates to first blossom vary from 54 to 97 days after planting depending on the planting date. The earlier the planting date, the longer the pre-flowering period. They reported that for a 7 May planting date, the number of days to first flower is about 50. Planting of this field was done on 7 May which is relatively late for Southern Arizona.

Emergence of cotton seedlings is maximum when the soil temperature at 20 cm ranges between 15°C and 21°C (Wilkes and Corley, 1968). These temperatures ranges occur by early April in Southern Arizona. The 10 day delay observed for opening of the first flower can be attributed to increasing night temperatures combined with the high day temperatures. Mauney (1966) indicated that this usually results in delaying flower initiation and raising the position of the first flower node. After flower initiation, the floral development proceeded quickly to peak for plants in all treatments by the fourth week of flowering (Fig. 3a). The

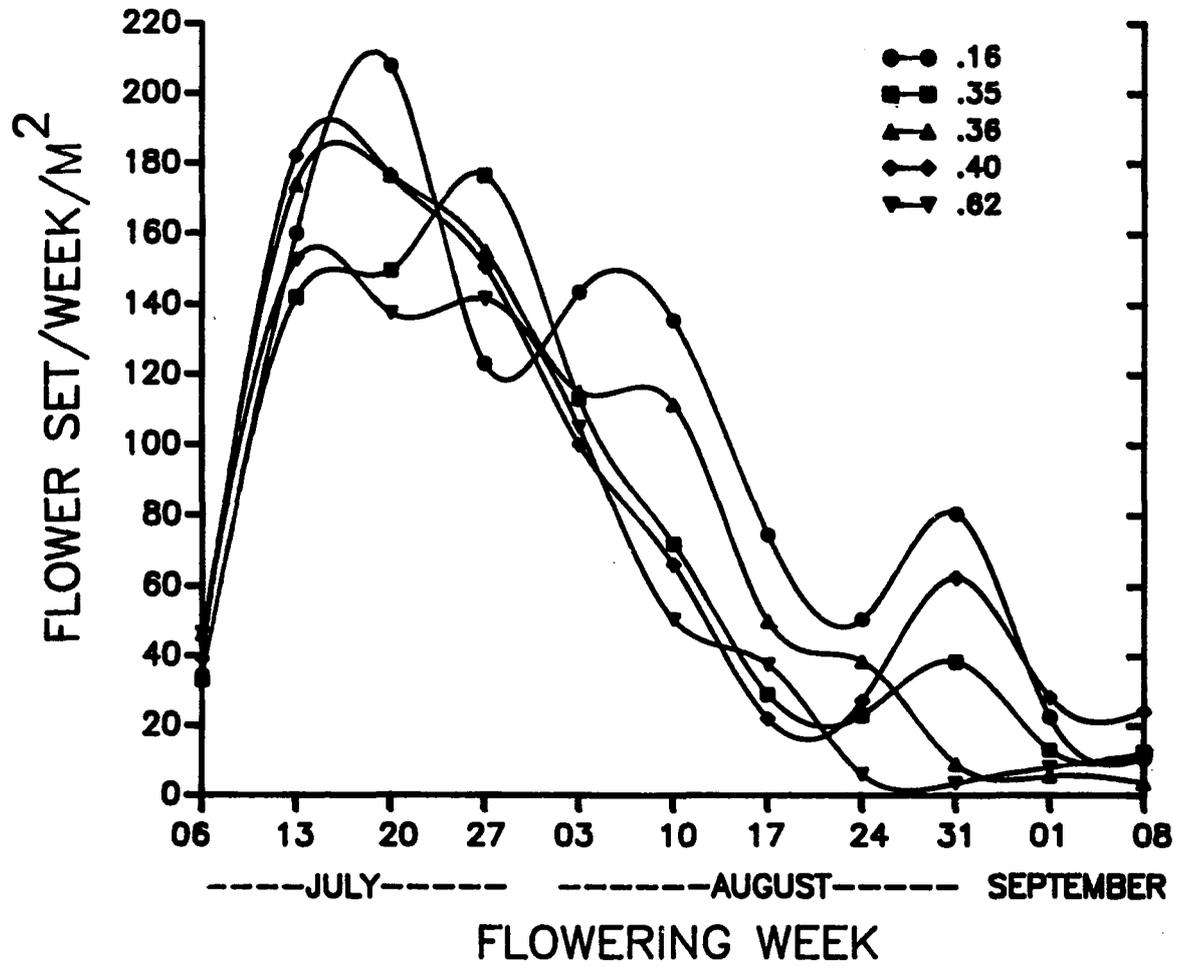


Figure 3a. Seasonal flower production of all treatments

peak flowering date was reached earliest by the plants in the dry and very dry treatments.

Plants in these two treatments respectively peaked within the second week of flowering (Fig. 3a). Differential water treatment was initiated for all treatments on 18 June. Thus the above treatments peaked about 28 days after water treatment was initiated. By then these treatments had received respectively 26 and 32 cm of water. The peak flowering periods of the Azmet, and wet treatments occurred a week after the dry and very dry peaked. For the medium, this peak period came 2 weeks after that of the dry and very dry (Fig. 3a). The Azmet, wet, and medium treatments received respectively at the time of their flowering peak 41, 53, and 40 cm of water.

Statistical comparisons of the daily mean flowering of plants in all treatments are shown in Table 3. Five weeks after flowering began in all treatments, that plants in the wet treatment started producing significantly more flowers than plants in the medium, dry, and very dry treatments. The dry and very dry treatments peaked the earliest presumably because of the high CWSI values at which these plants were irrigated. Analysis of the water deficit experienced by the plants from planting date up to the time of their peak flowering, shows that the lowest daily water deficit was in the wet treatment and that the soil moisture deficit experienced by the dry and very dry treatments were among the highest (Table 4). Several workers have indicated that water stress imposed early in plant development speeds up flowering and boll production of cotton plants. McMichael et al. (1972) reported that water stress induces ethylene production in a cotton plant. Hall et

Table 3.**Daily Mean Flower production**

Days After Planting	Treatments					P-Value
	Wet	Medium	Dry	Very Dry	Azmet	
78	8.17	6.61	7.17	8.33	8.41	.1547
82	8.64	7.00	7.41	8.66	8.68	.1370
96	9.49 a	9.28 ab	8.95 ab	8.47 ab	8.05 b	.0048
106	9.07 a	7.61 bc	7.91 abc	7.07 c	8.75 ab	.0004
116	7.85 a	6.26 bc	6.61 b	5.57 c	7.15 ab	.0003

Values followed by same letter within a row are not statistically different based on Duncan's multiple range test mean separation technique (p=.05).

Table 4. Daily Mean Soil Water Deficit

Days After Planting	Treatments					P-Value
	Wet	Medium	Dry	Very Dry	Azmet	
66	5.87 c⁺	6.96 b	7.26 ab	6.71 bc	8.05 a	.0009
70	5.28 c	7.63 ab	8.03 ab	7.01 b	8.66 a	.0001
74	5.31 c	7.26 b	7.65 ab	7.29 ab	8.31 a	.0001
78	5.66 c	7.11 b	7.47 ab	7.85 ab	8.13 a	.0001
82	5.46 c	7.39 b	7.54 ab	7.75 ab	8.38 a	.0001
96	5.56 c	7.34 b	7.79 ab	8.23 a	8.08 ab	.0001
106	5.38 c	7.14 b	7.65 ab	7.85 a	7.72 ab	.0001
111	5.51 c	7.24 b	7.59 ab	7.62 ab	8.26 a	.0001
116	5.33 c	7.24 b	7.75 ab	8.26 a	7.82 ab	.0001

⁺Values followed by same letter within a row are not statistically different based on Duncan's multiple range test mean separation technique (p=.05).

al. (1957) suggested that ethylene production induces early flowering in cotton. This induction of flowering by ethylene occurs in fruit trees such as mangos (*Mangifera indica* L.) and also in bromeliads (*Bromelad humilis* L.) (Salisbury and Ross, 1985). Cutout occurred around 3 August (Fig. 3a). This hiatus in flower production is a natural phenomenon in the genus *Gossypium* and it occurs without any stress being applied to the plant (Mauney, 1986). Though flowering cessation reflects a normal physiological stage in a cotton plant development, it is markedly influenced by the plant genetic makeup and various environmental stresses. A second peak in flower production occurred about 24 August. This second peak is an indication of a regrowth which produced the new sympodia needed for the flowering increase in late season. These new sympodia were mainly produced by the plants in wet, dry, and medium treatments. These treatments received respectively for the season 80, 73, and 70 cm of water, and these quantities represent the highest irrigation water applied.

The boll production curves (Fig. 3b), indicated that boll maturation occurred in a pattern that closely resembles the weekly flower production. The highest flowering weeks (Fig. 3a) also retained to maturation, the highest number of bolls (Fig. 3b). In all treatments, the peak boll retention occurred in the second week of flowering.

The cumulative flower production curves show that floral production had leveled off by the 8 th week of flowering for plants in all treatments excepted the wet treatment (Fig. 4a). The wet treatment, having experienced the least water stress, continued accumulating flowers until early September.

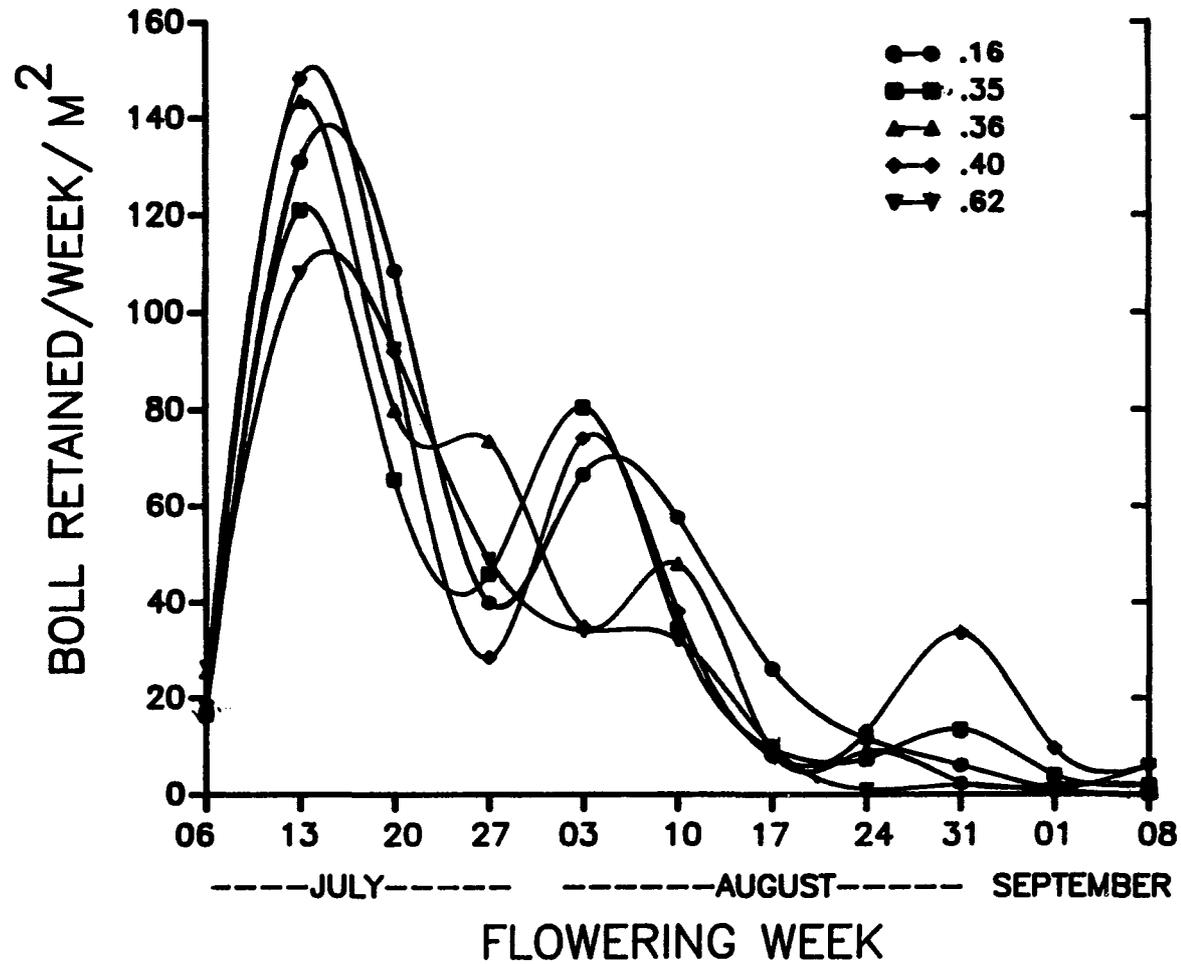


Figure 3b. Weekly boll retention in all treatments

CUMULATIVE FLOWER PRODUCED

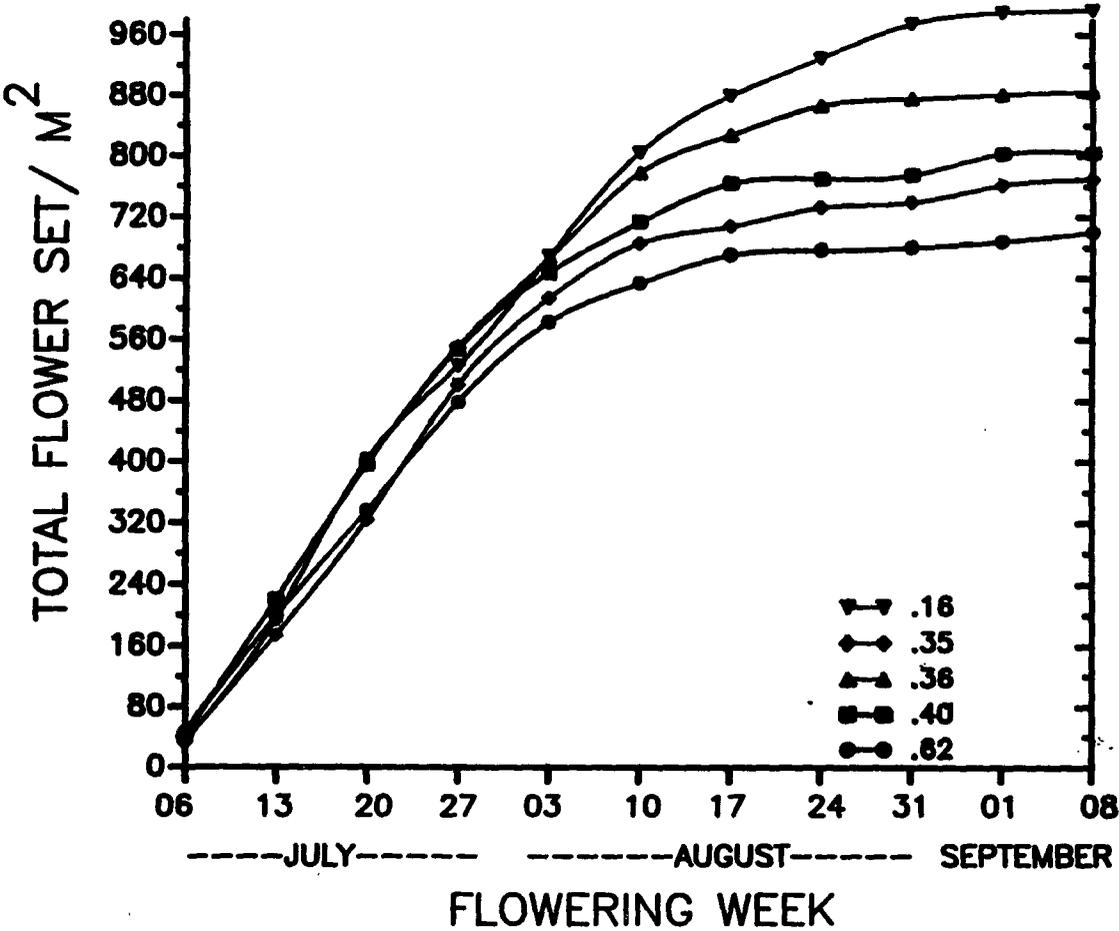


Figure 4 a. Cumulative flower production

The observed leveling off occurred presumably because of competition for carbohydrates between the boll load and the growing parts. The plants, unable to provide to the needs of both the growing shoots and the developing bolls, favor the boll maturation. Thus during the periods subsequent to 8 August, a high percentage of squares and flowers would be expected to abscise.

The cumulative boll retention per week of flowering (Fig. 4b), showed also a levelling off in boll retention following the 8th week of flowering. The dry and the wet treatments, retained the highest amount of boll produced per week of flowering, and per square meter (Fig. 4b).

Developing bolls are strong sinks and the strength of this sink reaches its maximum 20 to 30 days after anthesis (Pinkhasov and Thachenko, 1981). The period of intense flower production extended from 13 July to 3 August. During this period the weekly flowering was over 100 flowers/m². Thirty days after this period, the high demand for carbohydrates by bolls set during the previous high flower setting periods brought about this early leveling of the flower production in all treatments except the wet treatment. Throughout the season the wet treatment had significantly more soil moisture available to the plants (Table 4). Thus plants in this treatment were able to maintain a longer flowering period. However, most of the late flowering occurring in the wet treatment did not result in a yield. This is because the largest percentage (53%) of flower and boll abscission occurred in this treatment (Fig. 5). The abscission and retention percentages are based on the total flowers produced by each treatment. The lowest fruit and flower abscission percentages occurred in the dry treatment. Plants in this treatment were able to

CUMULATIVE BOLL RETENTION

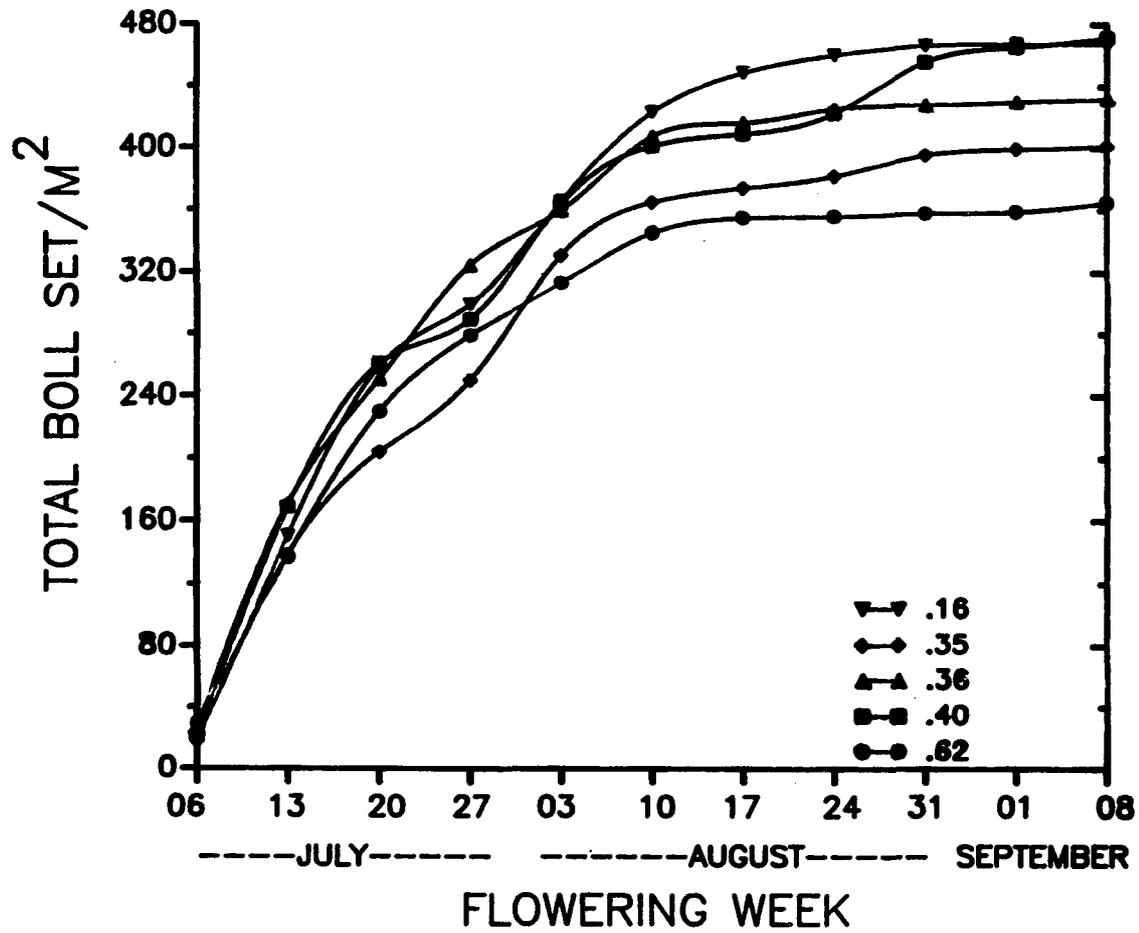


Figure 4b. Cumulative boll production

BOLL RETENTION AND ABSCISSION PER TREATMENT

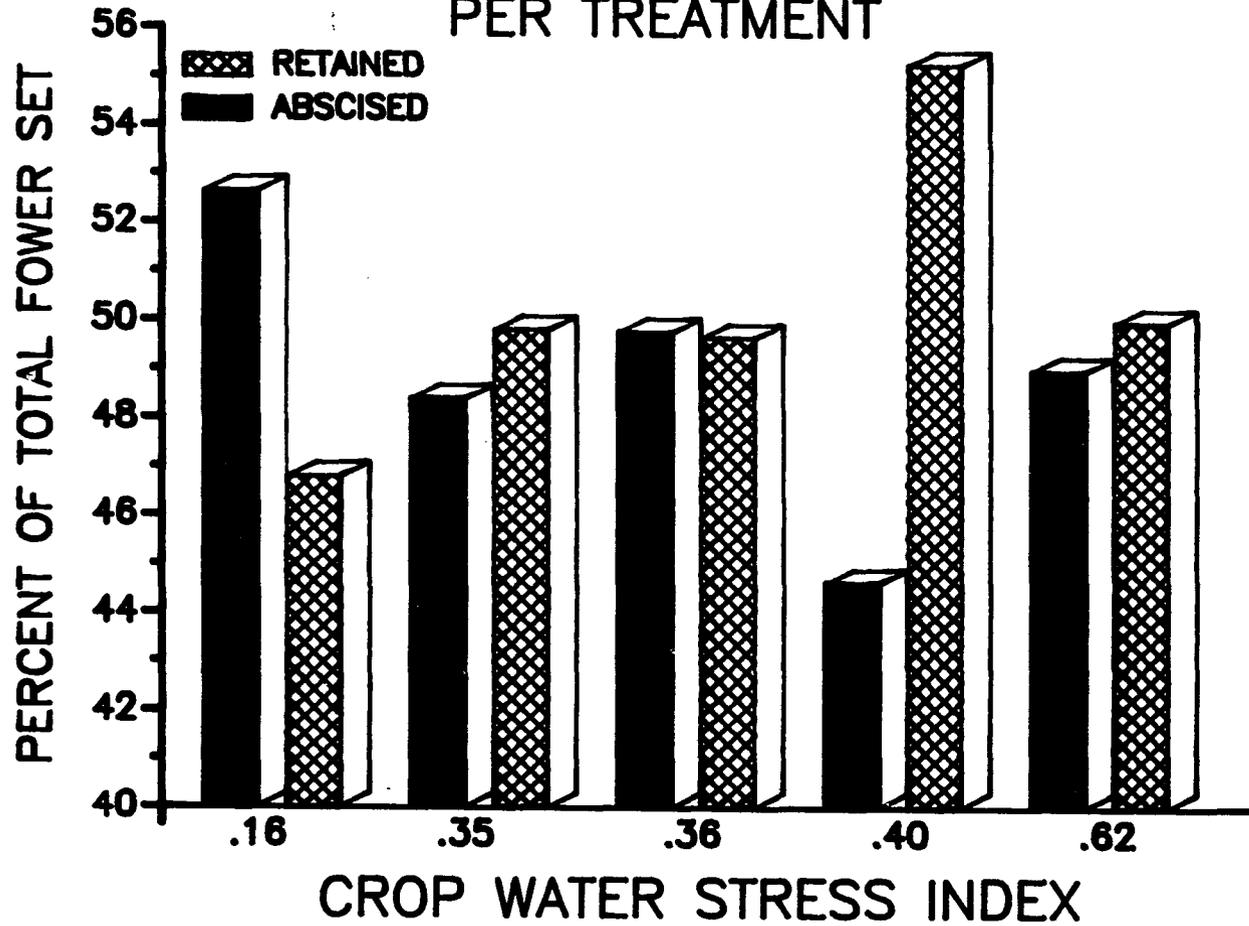


Figure 5. Relationships between total flower production, boll abscission, and boll retention

retain about 56% of the total flowers produced. The medium, Azmet, and very dry treatments, although they did not produce the same number of flowers, retained about the same percentage of fruits and flowers (48% to 50%). The relatively low retention percentage of the medium as compared to the Azmet is due to an unexpected high number of bolls that were not open at harvest.

In all treatments, flowers set early in the season contributed the most to final yield (Fig. 6). The later in the season a flower was set, the more likely it would abscise. This is because early in the season the sink strength of the boll load is not yet strong enough to cause abscission of added flowers. Thus the plants capitalized on early set bolls and provided them with enough carbohydrates to ensure their fast development. Kittock et al. (1981, 1983) indicated that the boll maturation period increases as the season advances. A longer boll maturation period means that assimilates flow into these bolls over a long period.

METABOLIC ACTIVITIES AND CWSI

Analysis of mid-season (26 August) photosynthesis and transpiration data shows significant but conflicting results (Table 5). While plants in the wet treatment were transpiring the most, their photosynthesis rate was the lowest. Higher transpiration rates indicate more widely opened stomates. Under such conditions it is reasonable to expect photosynthesis rates higher than those actually measured for the wet treatment. The highest photosynthesis rates were observed in the medium and dry treatments. Prior to photosynthesis measurement, the wet treatment was last irrigated on 19 August, the medium and dry treatments on 18

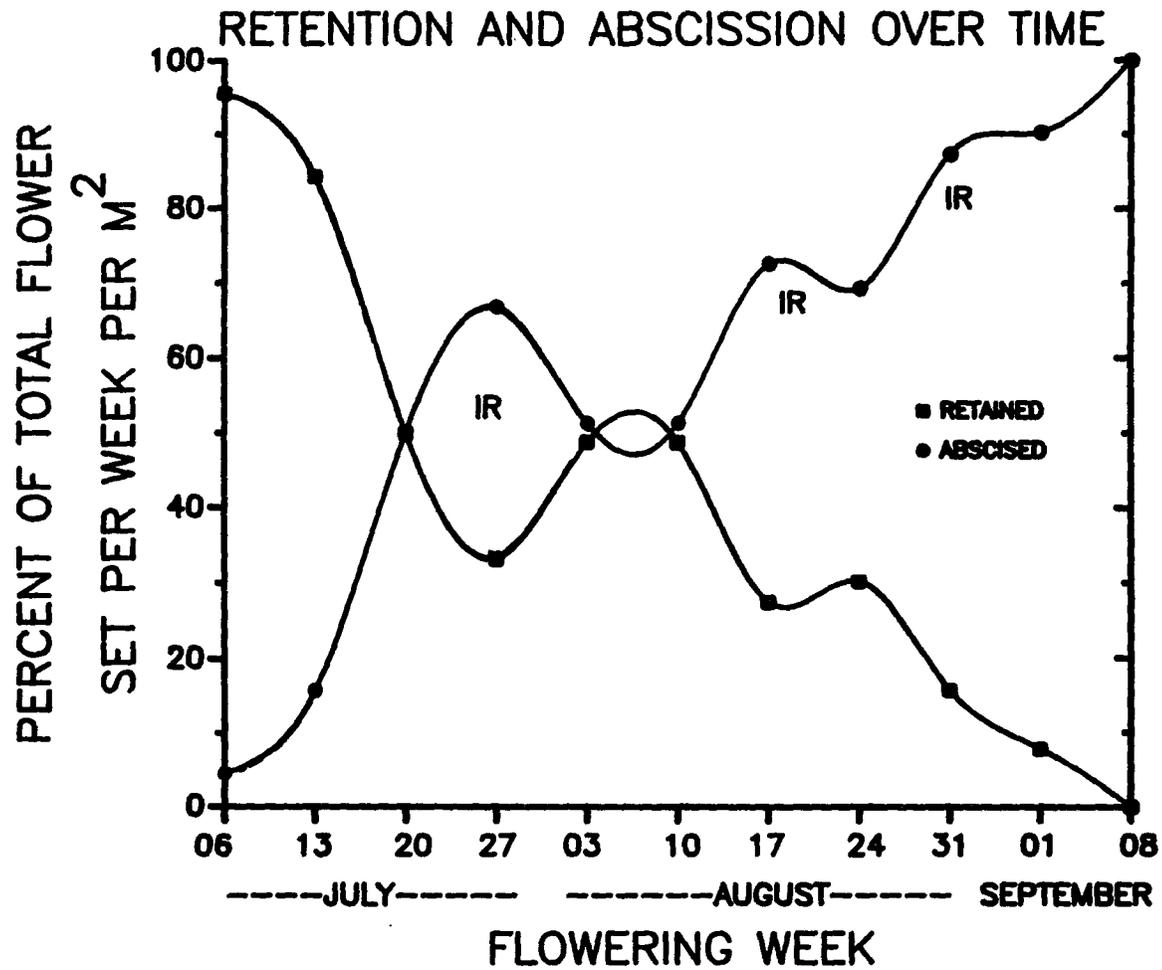


Figure 6. Relationships between boll maturation and boll abscission over time

Table 5. Photosynthesis, transpiration, diffusive resistance, and leaf area (26 August).

Variables	Treatments					P-Value
	Wet	Medium	Dry	Very Dry	Azmet	
App. Phot. (mg/dm ² /h)	20.31 b ⁺	25.75 a	26.53 a	23.21 ab	18.93 b	.0110
App. Phot. (mg/g/h)	31.71 bc	41.19 a	40.17 ab	30.04 c	27.41 c	.0154
Transpiration (μ g/cm ² /s)	27.78 a	24.66 ab	20.30 abc	17.92 c	22.14 bc	.0900
Diff. Resis.(s/cm)	.61 a	.73 ab	.90 bc	1.36 c	.74 ab	.1000
Leaf Area (dm ²)	.95	.85	.83	.89	.89	.7900
Leaf Temp. (°C)	30.1 c	30.4 bc	31.1 ab	31.4 a	30.6 abc	.0067
Leaf Dry Weight (g)	.61	.57	.55	.68	.63	.6300
Cuvette Temp. (°C)	32.0 a	31.9 a	32.1 a	32.0 a	31.9 a	.0001
CWSI++	.41	.47	.46	.60	.60	.1630

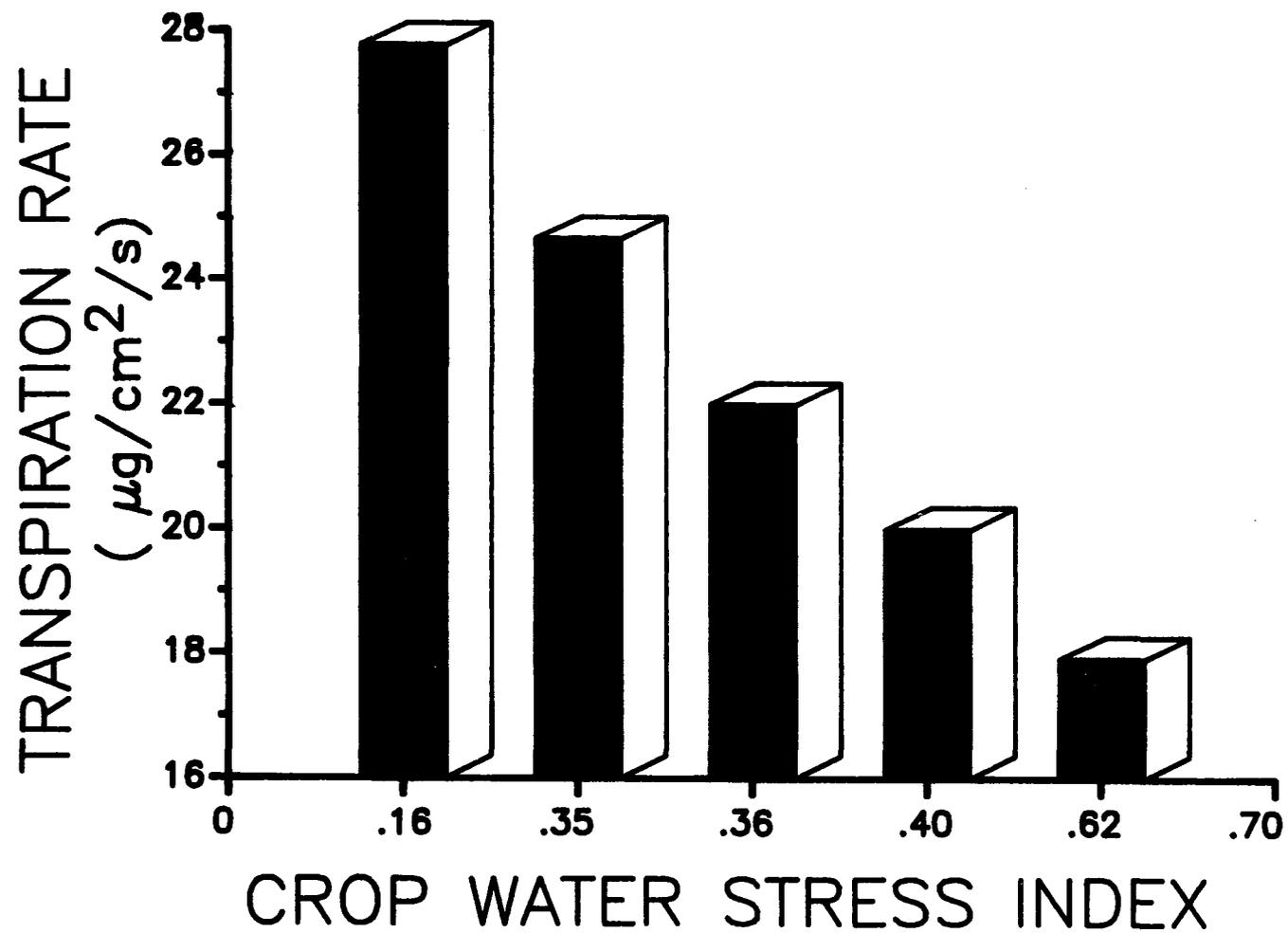
⁺Values followed by same letter within a row are not statistically different based on LSD mean separation technique (p=.05).

++ CWSI calculated based on theoretical model.

August, and the very dry and Azmet treatment on 13 August. The water deficits on the day photosynthesis was measured (day 111 on Table 4) were the lowest in the wet treatment. So the above irrigation dates and the soil water deficit indicate that the wet treatment should photosynthesize more. The low photosynthesis rates could be due to errors inherent to the technique or errors arising from the user. Operator errors could be improper timing between syringes both in field and in the lab, inadequate sealing of the plastic chamber, or unhealthy leaves. The low canopy temperature and high transpiration rate occurring in the wet treatment, indicate that the stomates of these plants were wide open. High gas exchange rates are expected when stomates are open. So the low photosynthesis rates observed in the wet treatment could be an artifact due to single leaf photosynthesis measurement.

Transpiration rates were the highest in the wet treatment and lowest in the very dry treatment. The transpiration rate decreases with increasing CWSI level (Fig. 7). Conversely, the diffusive resistance and leaf temperature increased linearly with increasing CWSI values.

There was no significant difference between leaf area and dry weight of plants in all treatments. However it is interesting to note leaves of plants in the wet treatment produced 6% more area than those of the very dry treatment and they weighed 10% less. This could be the result of higher cell numbers per unit leaf area and heavier cell materials resulting from the water stress in the very dry treatment (Cutler et al., 1977, 1978). Under stress (salt or water), the cells produce large and heavier stress proteins such as proline and betaine which help the cells



**Figure 7. Relationships between transpiration and CWSI
(Based on 26 August data)**

to osmotically adjust so that metabolic activities can proceed in spite of the stress (Brown et al., 1976; Jones and Gorham, 1983).

Photosynthesis data obtained on 11 September (Table 6) show no significant difference in the photosynthetic rate of all plants. Furthermore there was no trend between photosynthesis and treatments CWSI values. This lack of trend is attributable to the senescence observed in most treatments. In addition to the leaf senescence, a high degree of lodging was observed in the wet treatment. The decrease in average temperature from 41°C in mid July to 26°C in early September triggered fungal (*Verticillium dhalia*) attack on the wet treatment. Cool temperatures and wet conditions prompt *V. dhalia* attack on susceptible crop such as *G. hirsutum* L. (Gutierrez and Devay 1986). The disease was not severe enough to significantly reduce crop yield however. The above factors could be the cause of the inconsistency of the data in relation to the maximum CWSI values. The inverse relationship observed between the large leaf area of plants in the wet treatment and the high dry weight of plants in the very dry treatment was again observed on 11 September (Table 6). This inverse relationship is a definite indication that plants irrigated at stress levels above .60 have the tendency of producing heavier cells than those irrigated at stress indexes below .16. Although the analysis of variance of both leaf dry weight and leaf area were significant at 5% level, the treatment means were not far enough apart for the LSD-test to segregate them into distinct groups.

The apparent photosynthesis data collected on 26 August and 11 September indicate that though the plants in the wet treatment were still setting new flowers

Table 6. Photosynthesis, transpiration, diffusive resistance, and leaf area (11 September)

Variables	Treatments					P-Value
	Wet	Medium	Dry	Very Dry	Azmet	
App. Phot. (mg/dm ² /h)	12.41	17.35	16.06	22.7	22.0	.4300
App. Phot. (mg/g/h)	18.8	23.7	20.8	27.0	28.0	.6400
Transpiration (μ g/cm ² /s)	14.32 bc	14.03 c ⁺	15.96 bc	19.47 ab	21.55 a	.0420
Diff. Resis. (cm/s)	2.87 a	2.79 a	2.07 ab	1.71 b	1.50 b	.0488
Leaf Area (dm ²)	.80 a	.76 a	.73 a	.75 a	.80 a	.0540
Leaf Temp. (°C)	37.0 a	36.8 ab	36.1 abc	35.5 c	35.8 ab	.0430
Leaf Dry Weight (g)	.53 a	.58 a	.58 a	.65 a	.62 a	.0470
Cuvette Temp. (°C)	37.1 a	37.2 a	36.9 a	36.6 a	37.1 a	.0140

⁺Values followed by same letter within a row are not statistically different based on LSD mean separation technique (p=.05).

late in the season (Fig. 4a), the photosynthesis occurring in these plants was not high enough to produce the extra assimilates needed to ensure the growth and development of these newly produced bolls. Furthermore the photosynthetic demand by bolls set 3 weeks prior to 26 August was at its highest. Thus assimilates produced in the upper canopy were drawn to feed the bolls located within the middle to lower canopy. Pinkhasov (1981) and Pinkhasov and Khoang (1981) indicated that this drawing of assimilates by maturing bolls in the mid-canopy is enough to cause the shedding of about 80% of the newly set bolls. This explains the high percentage of boll abortion in the wet treatments following the 8th week of flowering (Fig. 5). During the last few weeks of flowering these plants aborted 70 to 100% of the flowers set during this period.

Following 28 August when all treatments were irrigated, water was turned off on all treatments until 1 October when all treatments were last irrigated. The lack of irrigation water and any significant rainfall during the period extending from 31 August to 11 September, reduced almost by half the plants apparent photosynthesis, transpiration, diffusive resistance as they relate to activities on 26 August. The reduction of plants photosynthesis and transpiration rates were visible in all treatments except for the very dry and Azmet treatments. Prior to 1 October all treatments were last irrigated on 28 August except the very dry treatment which received water on 30 August. During the period between 31 August and 11 September, the Azmet and very dry treatments had significantly more soil moisture than the other treatments. Plants in these treatments had comparatively low diffusive resistance and high transpiration. This high transpiration and low diffusive

resistance indicated that plants in the Azmet and very dry treatments had their stomata opened wider than stomata of plants in the wet, medium, and dry treatments.

It appears that plants stressed to a CWSI value of .60 (very dry) recover and maintain high transpiration up to 10 days after irrigation. This number of days is calculated from last irrigation dates (28 and 31 August) to the date photosynthesis and transpiration were measured (11 September). Although the values presented in Tables 5 and 6 are within previously reported range (Bielorai and Hopmans, 1975; Cain, 1984; Radin et al., 1988), the relatively high transpiration values for the very dry and Azmet treatments can be questioned in light of a previous work by Bielorai and Hopmans (1975). Their work showed that the transpiration rate of plants stressed to the wilting point (water potential of -1.62 MPa), peaks two days after irrigation at a rate three times greater than the pre-irrigation values.

CWSI, IRRIGATION AND YIELD

As previously indicated, the actual denomination of the treatments is with reference not to the amount of water applied, but rather to the stress level at which water was applied. There was no significant difference between the amount of irrigation water applied to the dry and medium treatments (Table 7). The plants in the dry treatments were irrigated at a significantly higher stress level (.40). Both treatments were irrigated the same number of times though. Thus by their respective irrigation time, plants in the dry treatment deplete more soil moisture than those of the medium treatment. Irrigating both treatments to field capacity re-

Table 7. Seasonal and irrigation CWSI, vegetative growth, irrigation water applied, and yield data.

Variables	Treatments					P-Value
	Wet	Medium	Dry	Very Dry	Azmet	
CWSI at Irrigation	.16 c ⁺	.35 b	.40 b	.62 a	.36 b	.0067
CWSI Seasonal	.04 c	.11 bc	.13 abc	.22 a	.14 ab	.0445
# irrigation	10	7	7	6	7	
Water Applied (cm)	80.21 a	70.31 bc	73.10 b	67.13 d	69.42 cd	.0001
Height (cm)	105 a	91 b	86 bc	80 c	82 bc	.0001
Seed cotton (Mg/ha)	4.76	4.20	4.54	3.76	4.62	.6471
Lint (Mg/ha)	1.67	1.70	1.72	1.41	1.72	.1112

⁺Values followed by same letter within a row are not statistically different based on LSD mean separation technique (p=.05).

-quired putting more water in the dry treatment as compared to the medium treatment. This explains why the dry treatment received more water than the medium.

The wet treatment (.16) yielded 1.67 Mg/ha of lint. This yield is within range reported by Garrot et al. (1987) for plants held at crop water stress index level of .15. The relatively high lint yields of the plants in the wet treatment indicates that at index values of .15 to .16, although they are associated with high irrigation frequencies, the amount of water actually applied does not cause water logging problems. In response to their high irrigation frequencies, plants in the wet treatment produced significantly more vegetative growth as measured by the plant height, than the others treatments (Table 7). Since these plants produced more vegetative parts, the fraction of their total assimilates which was devoted to reproductive parts was low as compared to what it would otherwise be under limited stress conditions. A consequence of that was the relatively low yield of the plants with high water, as compared to the yield of plants irrigated at stress levels between .35 to .40. The plants irrigated at .35, .36, and .40 yielded 1.70, 1.72, 1.72 Mg/ha lint respectively. This relatively low yield of plants in the wet treatment (Fig. 8) is in agreement with previous observations by Jordan (1986) who reported that yield increases parabolically with height. This mean plants at the two extremes of vegetative growth have lower yield as opposed to the high yield of plants with average vegetative growth.

Vegetative growth alone may not account however for the relatively low yield observed in the wet treatment, with regard to the medium, dry and Azmet treat-

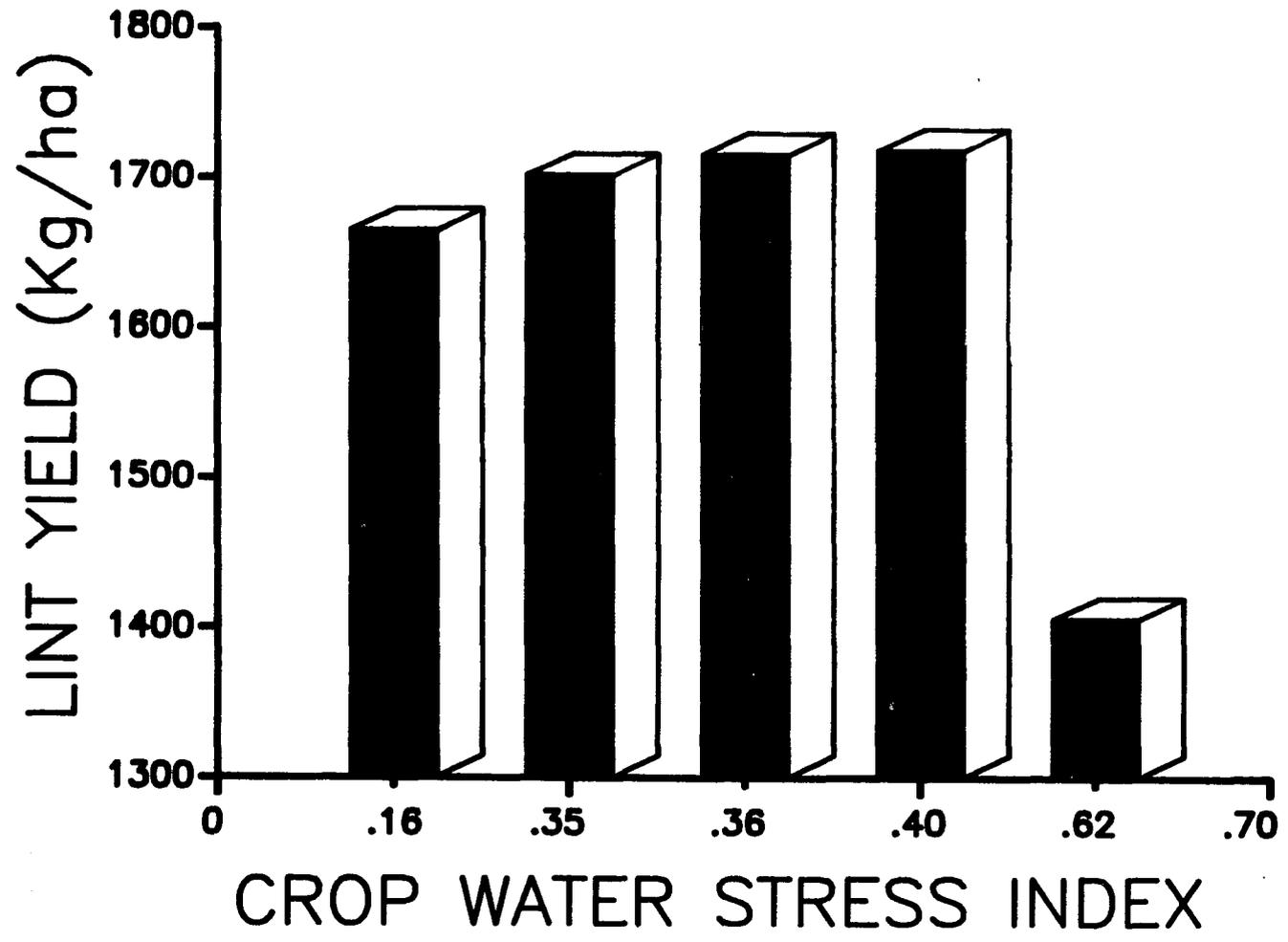


Figure 8. Treatment lint yield and CWSI

-ments. This is because analysis of the flower production in the wet treatment showed that though flower production was relatively slow compared to the Azmet, dry, and very dry treatments during the early flowering weeks (Table 3), plants in this treatment steadily increased their average daily flowering as the season advanced (Fig. 4a). The daily floral production of the wet treatment increased to the point where plants were producing significantly more flowers after first flower and proceeding steadily thereafter, plants in the wet treatment were producing significantly more flowers on daily basis (Table 3). More than half of the bolls set in the wet treatment were shed before reaching maturity however. Several authors have indicated that with a heavy boll load, a cotton plant sheds a large percentage of the boll set (Bruce and Römken, 1965; Rijks, 1965; McMichael et al., 1973; Mauney et al., 1980). The shedding percentage found in the wet treatment (53%) agrees with shedding percentage indicated by Rijks (1965). This high boll shedding percentage observed in the wet treatment was presumably due to the inability of photosynthesis to supply all the bolls set with an adequate level of assimilate. The lowest percentage of boll shedding occurred in the dry treatment. Plants in this treatment aborted about 44% of their boll load, thus giving the highest percentage of bolls that matured to harvest. The lack of significant difference in water consumed by the medium and dry treatments (Table 4) indicates that the observed difference in boll retention was due to the timing of water application which was determined by the CWSI.

Although there is no statistical difference between the seasonal mean CWSI values of the medium and dry treatments (Table 7), the relative difference of .05

stress index units at irrigation time may have been sufficient to allow plants in the dry treatment to retain and mature 5% more boll than the medium treatment. Plants within .35 to .40 stress indices, produced 63% of the total lint harvested. These plants were able to achieve this high production performance as a result of their high boll retention and maturation percentage. Plants irrigated within these water stress indices were stimulated by their moderate water stress to flower early and reach their peak period early.

Plants at the extreme CWSI yielded relatively low as compared to plants irrigated in the medium ranges (.35 to .40). The low yield of plants at the extreme was mainly due to the sharp increase in the percentage of bolls abscised (Fig. 5) when stress levels were either above .40 or below .16. When the stress index is over .40, the yield decline is much sharper than the yield decline resulting when the stress level is below .16. The reason for the lesser decline in yield of plants irrigated around .16 is that under high soil moisture, plants may produce more flowers and bolls than they can nurture. So although they abscised about 53% of their flowers, the 47% which matured to harvest still represented considerably more lint. On the other hand, soil water deficit corresponding to stress level of .60 and above considerably reduced the number of sympodia and fruiting sites by considerably depressing the plant growth (Fig. 9, Table 7). The development of new sympodia is dependent upon the vegetative growth of the plants. Consequently, plants such as those in the very dry treatment (.62 stress level) with relatively low vegetative growth (Fig. 9, Table 8), do not have a canopy sufficiently developed to promote the development of additional sympodia. These plants yiel-

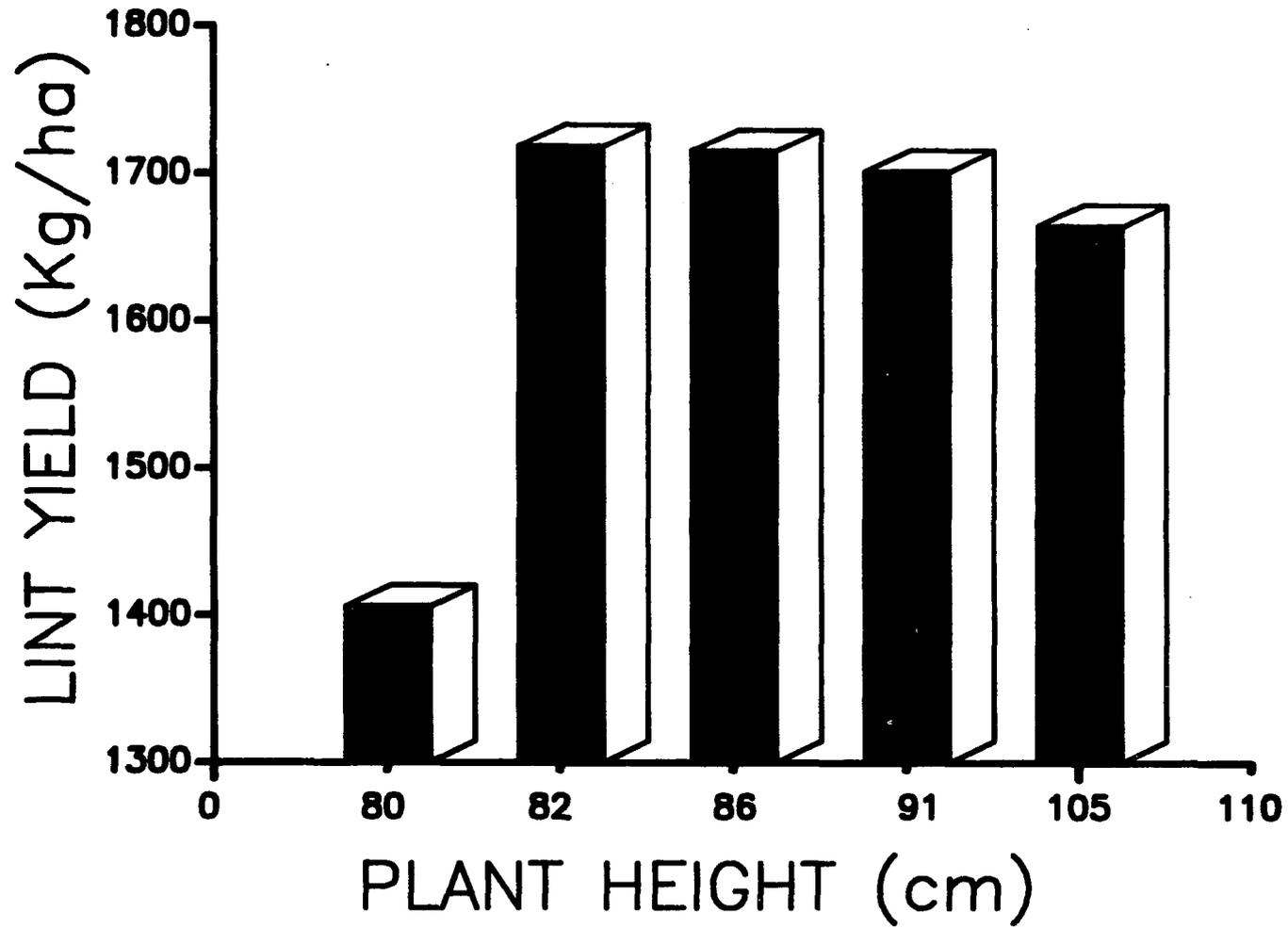


Figure 9. Relationships between lint yield and CWSI

Table 8 Correlation matrix of the flower production, abortion, retention, and CWSI.

	Bolls set	Retained bolls	Aborted bolls	Rotten bolls	%Retention	%abort.	%rotten
Bolls set		.961**	.935**	-.260	-.646	.417	-.100
Retain. bolls	.961**		.806+	.206	-.411	.164	.131
Aborted bolls	.935**	.806+		-.364	-.865*	.711	-.431
Rotten bolls	-.260	.206	-.364		.671	-.894*	.997*
%retent.	-.646	-.411	-.865*	.671		-.931*	.709
%Abort.	.417	.164	.711	-.894*	-.931*		-.917*
%Rotten	-.100	.131	-.431	.997**	.709	-.917*	
CWSI	-.909*	-.841+	-.891*	.119	.687	-.481	.178

**** Correlation coefficients significant at 1% error level**

*** Correlation coefficients significant at 5% error level**

+ Correlation coefficients significant at 10% error level

-ded 29% less lint than the plants in the best treatment (.40 stress level).

The plants in the wet treatment (.16 stress level) also had relatively low yield but high growth. These plants yielded less lint and seed cotton than plants in the optimum range (.35 to .40 stress level). This yield reduction may have been the result of the very high boll shedding that took place in this treatment. The nutritional insufficiency mentioned earlier is assumed to be the cause of this high shedding.

FLORAL PRODUCTION AND IRRIGATION

Study of the relationships between CWSI and flower production shows a 2 day lag response by the plants to a sharp decrease in CWSI values (Fig. 10). These sharp decreases in the daily CWSI values occur succeeding an irrigation or a substantial rainfall when plant stress is reduced.

This increase in flowering rate subsequent to irrigation is better observed by plotting the flower production versus the days plant were irrigated (Fig. 11). Flower production increased two to three days after irrigation (Fig. 11). Prior to irrigation, the flower abscission increases up to a day after irrigation. Floral abscission decreases for the next 2 to 3 days following irrigation.

CORRELATIONS MATRIXES

The correlation matrixes presented on tables 8 to 10 are based on average responses of the 2 days metabolic activities were collected. As expected a strong negative correlation exists between boll production and CWSI (Table 8). This con-

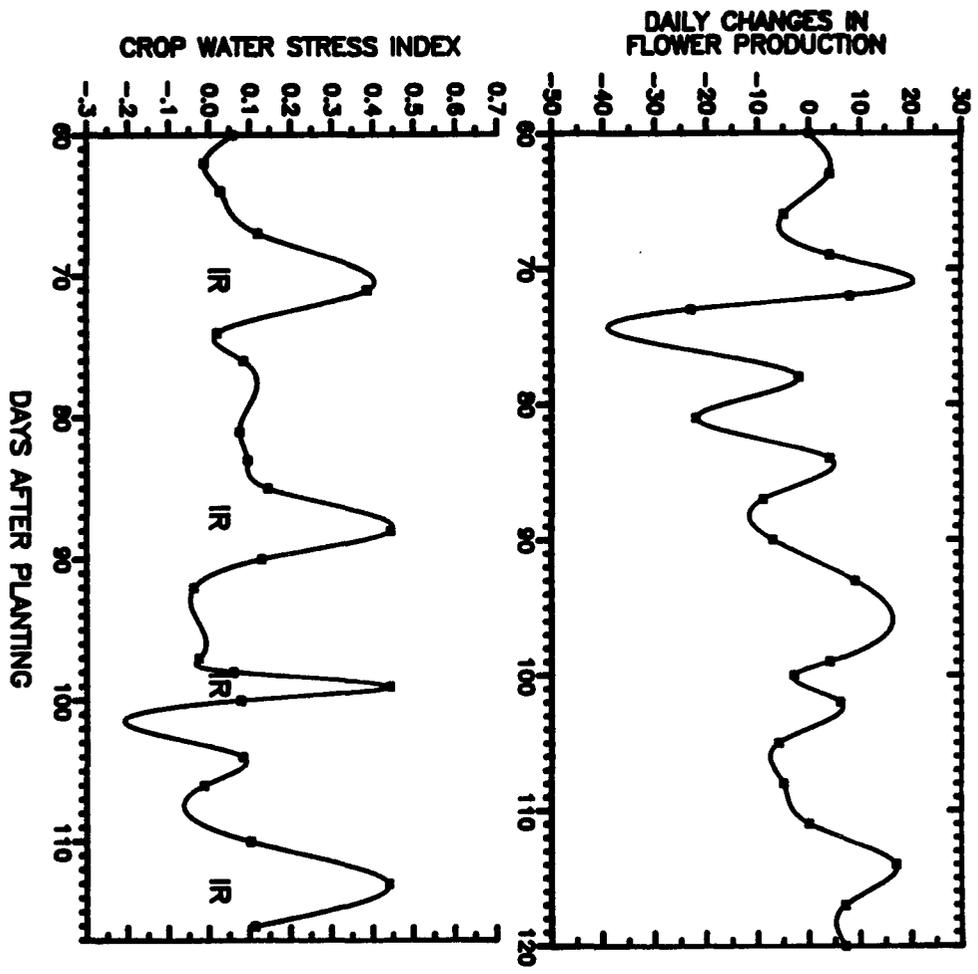


Figure 10. Relationships between decrease of daily CWSI and flower production

FLORAL PRODUCTION AND ABSCISSION IN RELATION TO IRRIGATION DATES

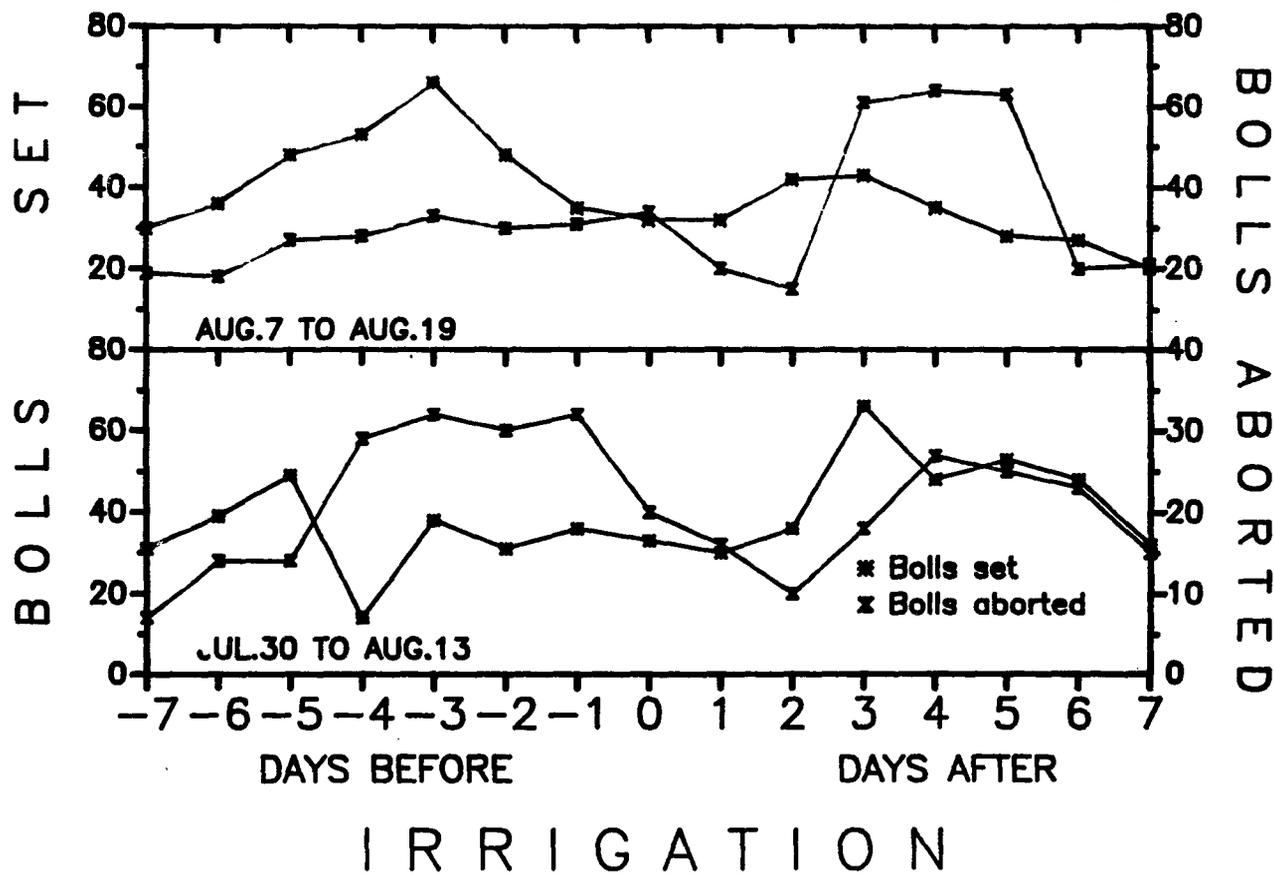


Figure 11. Change in floral production following irrigation

-firm the previously observed decreasing trend of boll production in relation to increasing water stress. Seed cotton production was correlated ($r = -.68$, $p = .001$) to both seasonal and irrigation CWSI. This low correlation coefficient is likely attributable to errors introduced by hand picking the seed cotton. No significant linear correlation exists between lint production and CWSI. This particular lack of significance is only true with regard to linear correlation. The nature of the relationship between lint production and CWSI is not linear but curvilinear (Fig. 12). This curvilinear relation shows a high coefficient of determination ($R^2 = .65$, $p = .001$). Furthermore on a small field, with many differentially irrigated plots adjacent to each other, it is reasonable to expect the presence of temperature and wind gradients across the field. Such gradients could result from the unequal amount of evapotranspiration proceeding in the different treatments. In turn, these gradients could create enough wind turbulence above the canopy to affect the canopy temperature readings. Water deficits measured in the top 60 and 91 cm of soil correlated well with CWSI. Jackson et al. (1981), reported a similar close relationship between CWSI and soil water deficit. Such correlations are to be expected for the CWSI is a measure of the plant response to existing soil water potential. Water deficit correlates well with most variables measured (Table 9). Lint yield on the other hand does not correlate with any other variable. Plant height correlates positively with the amount of water applied.

The correlation coefficients in Table 10 do not show any significant associations between the measured physiological parameters (transpiration, photosynthesis, and diffusive resistance) and CWSI. Several workers (Idso and

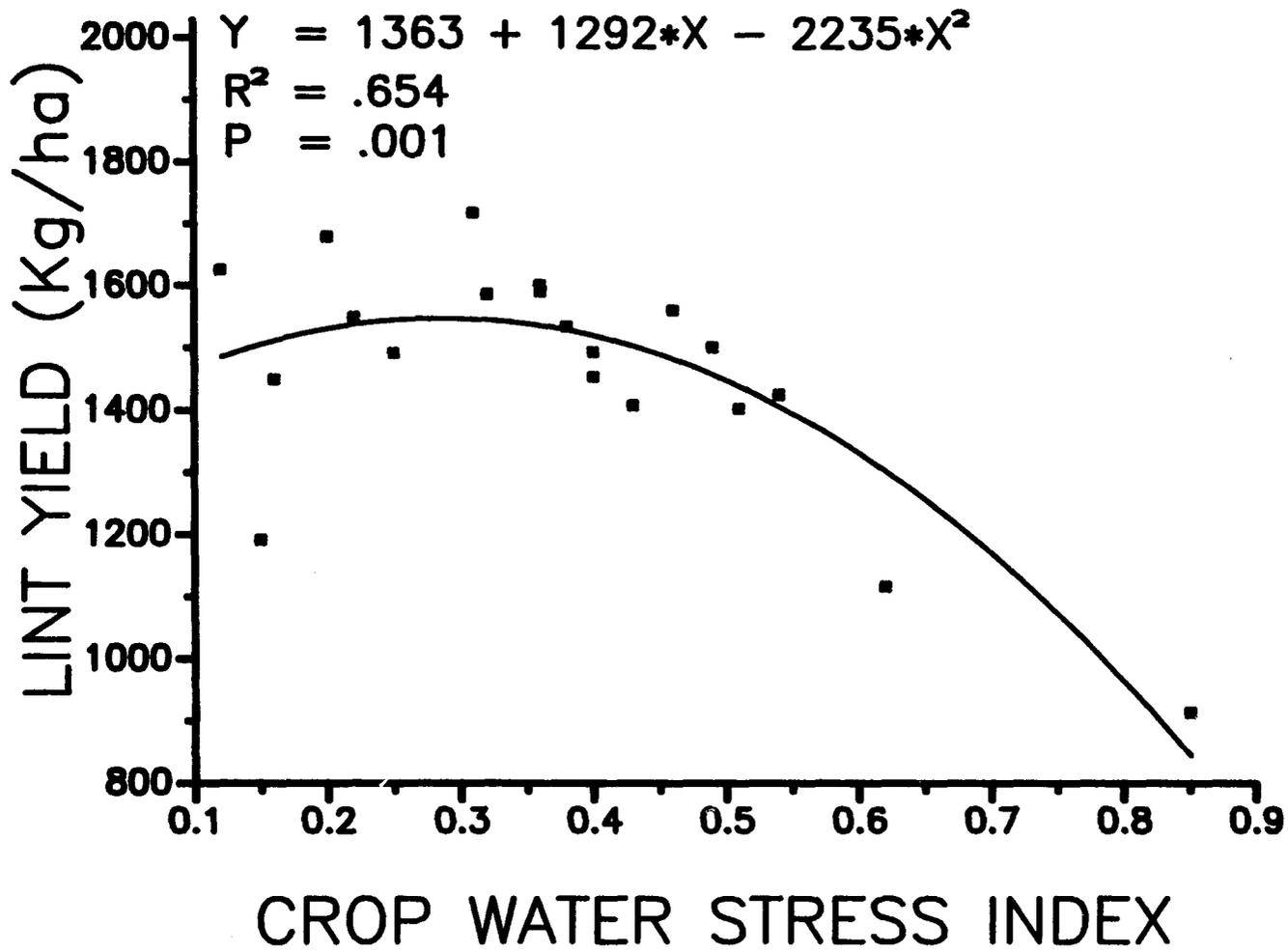


Figure 12. Quadratic relation between lint yield and CWSI

Table 9 Correlation matrix of water treatment, flowering data, yield, and vegetative growth.

	Water def1.	Water def2.	Water appl.	Height	Yield	Bolls set	Retained bolls	Aborted bolls
Def.1		.987**	-.961**	-.961**	-.462	-.913*	-.790	-.941**
Def.2	.987*		-.921*	-.994*	-.426	-.913*	-.695	-.903*
Water appl.	-.961**	-.921*		.927*	.418	.917*	.836+	.876*
Height	-.984**	-.994**	.927*		.414	.827+	.683	.883*
Yield	-.462	-.462	.418	.414		.607	.724	.412
Bolls set	-.913*	-.913*	.917*	.827+	.607		.961*	.935**
Retain. bolls	-.790	-.695	.836+	.683	.724	.961**		.809+
Abort. bolls	-.941**	-.903*	.876*	.883*	.412	.935**	.809+	
CWSI	.940**	.927*	-.862*	-.916*	-.721	-.909*	-.841+	-.891*

**** Correlation coefficients significant at 1% error level**

*** Correlation coefficients significant at 5% error level**

+ Correlation coefficients significant at 10% error level

Def.1: Soil moisture deficit in first 60 cm.

Def.2: Soil moisture deficit in first 91 cm.

Table 10 Correlation matrix of apparent photosynthesis, transpiration, and diffusive resistance

	APS1	APS2	TRANS. resis.	DIFF. resis.	CUVETTE temp.	LEAF temp.	LEAF area	LEAF weight
APS1		.999**	.0481	.138	.806	.366	-.972*	-.909*
APS2	.999**		.0481	.124	.807	.359	-.977*	-.909*
TRANS.	.0481	.0481		-.972*	-.528	-.915*	-.242	-.427
DIFF. resis.	.138	.124	-.972*		.652	.960*	.0826	.279
CUVET. temp.	.806	.807	-.528	.652		.831	-.683	-.528
LEAF area	-.972*	-.977*	-.242	.0826	-.683	-.168		.980*
LEAF weight	-.909*	-.909*	-.427	.279	-.528	.0298	.980*	
CWSI	.808	.814	-.476	.564	.985**	.772	-.717	-.577

** Correlation coefficients significant at 1% error level

* Correlation coefficients significant at 5% error level

+ Correlation coefficients significant at 10% error level

APS1 : Apparent photosynthesis leaf area based (mg/dm²/h).

APS2 : Apparent photosynthesis leaf dry weight based (mg/g/h).

Reginato, 1982; Idso et al., 1984; Choudhury, 1986;) reported close relationships between photosynthesis and CWSI. The lack of significance between photosynthesis and CWSI (Table 10) is assumed to be due to the imprecision of the technique used to measure field photosynthesis and to the limited readings taken during the season. The photosynthesis data obtained on 11 September might have been also affected by the senescence factor.

SUMMARY

The CWSI was calculated on the empirical model and three minimum water stress baselines were used for the whole season. The first minimum stress baseline ($Y_1 = 2.0 - 2.4 \cdot X$) was developed by Idso et al. (1982). This baseline was used for most of the season. Plant canopy was established using this model for the whole vegetative growth period. At the reproductive stage the plants canopy temperature increased considerably and that caused the minimum stress baseline to be higher than before ($Y_2 = 2.7 - 2.1 \cdot X$). The third upward shift occurred in late July and was maintained for only two consecutive readings. This last position was determined by the predicted equation ($Y_3 = 3.7 - 2.1 \cdot X$). This upward move of the baseline was ascribed to high relative humidity (Rh=89 %) prevailing on these days. Lastly the minimum stress line moved back to its initial position (Y_1). The relative humidity diminished to take values between 30% to 38% for about a week, and ensuing this reduction of the relative humidity, the plants transpiration increased. The lowering of plants canopy temperature was the basis for the assumption that the transpiration cooling fraction of plant canopy increased during that period. Such increase of plant transpiration would cause the lowering of the minimum stress line. The minimum stress line no longer shifted from the Y_1 position during the remaining days of the season. This was presumably because the green bolls set during the maximum flowering period, were contributing significantly to transpiration.

Flower production began in all treatments 60 to 61 days after planting.

Following flower initiation, the flower and boll production proceeded quickly to peak for all plants by the fourth week of flowering. This flower development followed the traditional cotton flowering pattern. Following peak flowering weeks, the flower development steadily declined in all treatments until 9 September when it ceased. Before it reached a complete halt, flower production levelled off in all treatments by 24 August. The daily flowering of plants in the wet treatment became significantly higher than that of the other treatments 36 days after flowering began. There was no significant difference in the daily flowering of plants in the medium, dry, and Azmet treatments. Plants irrigated at high water stress indices (.40, .62) peaked the earliest. The early water stress imposed on these plants, could have induced this early high flower production through hormonal change (McMichael et al., 1972; Guinn, 1986). It is speculated that since under water stress, *G. hirsutum* L. produces ethylene, this might have caused this early peak of the plants irrigated at high water stress indices.

A 2 day lag response after irrigation was noticed before flower production increased. The period of intense flower production extended from 13 July to 3 August. During this period the weekly flowering was over 100 flowers/m². The highest flower and boll production occurred at the stress level of .16, and the lowest at .62. The high boll production of the wet treatment did not produce the highest yield. This is because most of the bolls set in the wet treatment were aborted before reaching maturity. This high boll abscission percentage was due to the inability of the plants in the wet treatment to generate enough assimilates to sustain the need of the whole boll load. A further hindrance to the retention of all

bolts set was the high vegetative growth exhibited by plants in this treatment. The boll retention percentage in the wet treatment was among the lowest.

The dry treatment, maintained at a CWSI of .40, had the lowest boll abortion and the highest retention percentage. This high retention percentage allowed plants in this treatment to yield relatively more lint than any other treatment. The boll retention percentage of the medium, Azmet, and very dry treatments were similar. There were no statistical differences between the treatments mean lint production. Lint yield was 1.67, 1.70, 1.72, 1.72, and 1.41 Mg/ha for the wet, medium, dry, Azmet, and very dry, respectively. The relationship between lint production and CWSI appeared to be non linear, and was described by a simple quadratic formula. Lint yield was related to CWSI through $YIELD = 1363 + 1292 * CWSI - 2235 * CWSI * CWSI$. This predicted quadratic formula, described the data with a 0.65 coefficient of determination.

The CWSI calculation based on the empirical model has proven to be an efficient irrigation management tool. Water consumption was significantly reduced and yields were the highest in the treatments established between .35 and .40. The high variability observed within treatments lint production was an indication that the model was insensitive to others environmental factors not integrated into it. The treatment establishment is a clear indication of the potential for the CWSI to become a very useful irrigation management tool. For this potential to be fulfilled, solutions to some of the problems fore mentioned, are urgently needed before the model should be implemented as an effective farm management tool.

APPENDIX A1

CALCULATION OF CWSI BASED ON IDSO MODEL

$$\begin{aligned} \text{CWSI} &= \frac{B - C}{A - C} \\ &= \frac{(T_c - T_a) - (T_c^M - T_a)}{(T_c - T_a)_{\text{upper}} - (T_c^M - T_a)} \end{aligned}$$

T_c^M : well watered plants foliage temperature

T_a : air temperature

$(T_c - T_a)$: measured foliage-air temperature differential

$(T_c - T_a)_{\text{upper}}$: maximum foliage-air temperature differential
(transpiration stopped)

$(T_c^M - T_a)$: maximum foliage-air temperature differential expected for well watered crops

. If $B = C$ then

$$\text{CWSI} = \frac{C - C}{A - C} = 0 \text{ (fully transpiring plants)}$$

. If $B = A$ then

$$\text{CWSI} = \frac{A - C}{A - C} = 1 \text{ (non transpiring plants)}$$

APPENDIX A2

THEORETICAL JUSTIFICATION OF THE UPPER AND LOWER LIMIT JACKSON METHOD

$$T_c - T_a = \frac{r_a R_n}{c C_p} * \frac{d(1 + r_c/r_a)}{p + d(1 + r_c/r_a)} - \frac{(\theta_a^* - \theta_a)}{p + d(1 + r_c/r_a)}$$

. Upper limit ($r_c \rightarrow \infty$)

$$(T_c - T_a)_{\max} = \frac{r_a R_n}{c C_p}$$

. Lower limit ($r_c \rightarrow 0$)

$$(T_c - T_a)_{\min} = \frac{r_a R_n}{c C_p} * \frac{d}{p + d} - \frac{(\theta_a^* - \theta_a)}{p + d}$$

$$CWSI = 1 - ET_a/ET_p$$

$$= \frac{d(1 + r_c/r_a) - d(1 + r_{cp}/r_a)}{p + d(1 + r_c/r_a)}$$

. $r_c = r_{cp}$ (ample water)

$$CWSI = (CWSI)_{\min}$$

$$= \frac{d(1 + r_{cp}/r_a) - d(1 + r_{cp}/r_a)}{p + d(1 + r_c/r_a)}$$

$$= 0$$

. $r_c \rightarrow s$ (no available water)

$$\begin{aligned} \text{CWSI} &= (\text{CWSI})_{\max} \\ &= \frac{d(1 + r_c/r_a)}{d(1 + r_c/r_a)} \\ &= 1 \end{aligned}$$

T_c : Canopy temperature

T_a : Air temperature;

c : Air density

d : Psychrometric constant

R_n : Net radiation

r_a : Aerodynamic resistance

r_c : Canopy resistance

r_{cp} : Canopy resistance at potential evapotranspiration

ET_a : Actual evapotranspiration

ET_p : Potential evapotranspiration

e_a^* : Saturated vapor pressure

e_a : Actual vapor pressure

$$\text{VPD} = e_a^* - e_a$$

$$p = (e_a^* - e_a)/(T_c - T_a)$$

Adapted from Jackson (Jackson, 1982)

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