77

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**Development of a Management - Oriented
Dynamic Simulation Model for
Cotton Production**

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Names of Investigators:

Principal Investigator: A. Marani

Cooperating Investigator(s): D.N. Baker

Name and Address of Affiliated Institutions:

Principal Institution: Hebrew University of Jerusalem, Israel

Cooperating Institution(s): U.S.D.A, A.R.S., Crop

Simulation Research Unit, Mississippi State

Project's starting date: April 1, 1981

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Signatures:

Principal Investigator

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Institution's Authorizing Official

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TABLE OF CONTENTS.

	Page.
Abstract	2
Objectives	3
A. Water stress effects on canopy photosynthesis, temperature, transpiration and shedding of leaves and fruit in cotton.	4
B. The effect of moisture stress on stomatal resistance and photosynthetic rate in cotton (<i>Gossypium hirsutum</i> L.)	24
C. The simulation of irrigation practices and the effects of moisture stress in the cotton model.	45
D. The simulation of nitrogen fertilizer application and the effects of nitrogen stress in the cotton model.	61
Description of cooperation	77
Evaluation of research achievements	77
Appendix	78

The following graduate students contributed to this research : A. Ben-Porath, J.E. Ephrath. Also participated Professor B-A Bravdo, and Mrs. Yael Rekah, research assistant.

Abstract

This project's objectives have been to modify the cotton system model and to make it more useful for crop management, especially for irrigation and nitrogen application. A number of experiments have been conducted to provide data about the effects of water and nitrogen on the growth and development of the cotton plant, and the results have been used to develop the cotton model COTMOD.

The effects of moisture stress on photosynthesis, canopy temperature, stomatal resistance, transpiration and dry weight partitioning of cotton plants have been determined under controlled conditions in the USA. These effects were also evaluated in Israel under field conditions, by imposing constant levels of leaf water potential by using a drip irrigation system.

The results were used to recode the routines describing the effects of water and nitrogen on developmental processes in the cotton model. The predictions of the model were compared to some sets of validation data from Israeli field experiments, and the meaning of the stress factors used in the model have been discussed.

Objectives

The objectives of this research project have been :

(a) To improve existing cotton simulation models by implementing better routines for soil-water balance, effects of moisture stress on plant processes, soil-nitrogen balance, and nitrogen dynamics in the plant. These improvements were to be based on experiments in the field and under controlled conditions.

(b) To construct a management-oriented simulation model, which cotton growers would be able to use to help them in decision making about the management of their crop, especially about the timing and amounts of irrigation and nitrogen application.

A.

WATER STRESS EFFECTS ON CANOPY PHOTOSYNTHESIS, TEMPERATURE,
TRANSPIRATION AND SHEDDING OF LEAVES AND FRUIT IN COTTON.

A. BEN-PORATH, D.N. BAKER, and A. MARANI.

ABSTRACT

The effects of water stress on photosynthesis, canopy temperature, transpiration and dry weight partitioning of cotton plants were measured in 3 controlled-environment chambers (SPAR units). 77-day-old potted plants were transferred from the nursery into the chambers. Drip irrigation with a nutrient solution was applied in pulses of 60 ml per pot. The treatments were 12, 8, and 4 pulses per day: control, moderate stress and severe stress ("C", "M", and "S", respectively). Leaf water potential was measured biweekly. Fallen leaves and fruit were collected every other day.

After 10 days of stress, midday leaf water potentials were 1.5, 2.7, 3.8 MPa and canopy minus air temperature values ($T_c - T_a$) were 1.0, 1.7, 3.6 °C for "C", "M", and "S" plants, respectively. The transpiration of "S" plants was reduced to 15% and their photosynthetic efficiency was reduced to 42% of "C" plants. After 11 days of stress, "S" plants were harvested, and all plant parts were counted, oven-dried and weighed. "S" plants shed 29, 95, and 19% of their leaves, small fruit, and large bolls, respectively. "C" plants shed only 5, 48, and 10%, respectively, of these organs. Later on, other potted plants were transferred into the "S" chamber.

During 35 days of measurements in the SPAR units, more than 1500 simultaneous measurements of canopy and air temperature, photosynthesis, transpiration and solar radiation were obtained. The relevant observations (those made on non-cloudy days and after 8.00 a.m.) of the 3 chambers were pooled and regression equations were calculated for all the parameters involved. 26 observations of leaf water potentials throughout the experiment were related to concurrently recorded parameters.

Analyses of dry weight partitioning data indicated that during a short period of severe water stress, the plants gained about 120 g m⁻². The gain was in small roots, large bolls, and

stem (43, 33, and 24% respectively, from the total gain in dry weight).

MATERIALS AND METHODS

Nursery site:

Cotton (Gossypium hirsutum L.) var. 'Stoneville 825' plants were grown outdoors, in 7 liter pots, at the nursery site of the Crop Simulation Research Unit at Mississippi State in the summer of 1983. The growing medium was pure sand. Lime and 0-24-24 fertilizer were mixed into the top 15 cm of the pots each at rates equivalent to 100 g m⁻². The plants were arranged in rows, similarly to the usual field configuration (one plant in a pot, 10 pots per 1 m of row, 1 m between rows).

The pots were irrigated to excess with a nutrient solution (Hoagland solution modified to 50 mg l⁻¹ N until flowering, and later to 100 mg l⁻¹ N). While the plants were in the nursery, they were irrigated 12 times per day (with one dripper of 1 liter hour⁻¹ capacity in each pot). The daily amount of water applied (0.2 to 0.8 liter per pot) was controlled by a computer (MODCOMP 2) and modified according to the pan evaporation data from a nearby weather station. Soil water potential in the pots was measured by tensiometers and maintained throughout the experiment in the range of 5 to 40 KPa. The pots were covered with black polyethylene to keep out rain as far as possible.

Plant Monitoring:

When the nursery plants were transferred to growth chambers for water stress treatments they were randomized and destructive samples of ten random plants were taken for measuring plant growth and dry weight distribution. This sampling was made in order to characterize the nursery plants before the application of stress. Plants were similarly measured at the end of each water stress experiment in the growth chambers,

At each destructive harvest, mainstem height and node number, as well as total leaf number and leaf area were measured and recorded. The shoots were divided into blades, petioles, stems, squares, and small and large bolls. All plant parts were later oven dried at 80 °C and weighed. Roots were carefully washed from the sand on a 1/8 inch hardware cloth, and later floated in a water bath, for final separation. After that the roots were grouped into two categories: (a) "taproots" - the main woody frame of the root system, including taproot and root branches, and (b) "small roots"- fine and flexible (unsuberized) roots, which separated easily from the main woody frame.

Water stress treatments and measurements:

These consisted of 12, 8, and 4, irrigation pulses per day for the control ("C"), moderate stress ("M"), and severe stress ("S") treatments, respectively. The treatments were applied in three naturally illuminated controlled - environment soil - plant - atmosphere research (SPAR) units. Each unit consisted of a

chamber with an area of 0.5 by 2.0 m and a height of 1.5 m. The temperature in the chambers was maintained at 32 °C during the day and at 20 °C during the night.

Ten randomly selected potted plants were transferred to each chamber. The plants in each SPAR units were arranged in two rows (5 plants in a row 0.5 m long and 1.0 m between rows). They were irrigated, as in the nursery, by one dripper per pot, with the same nutrient solution. The number of irrigation pulses per day was the only difference between the three chambers. As the plants grew larger, the amount of water applied in each pulse was increased from 30 to 60 ml per pot. The stressed plants in the "M" and "S" treatments, were thus irrigated with 2/3 and 1/3, respectively, of the amount applied to the control plants ("C"). On cloudy days, however, the irrigation amounts applied to the stressed plants were reduced further.

Two successive water stress experiments were carried out, each in three SPAR units. The first experiment provided data on plant growth rate, organ senescence and dry weight partitioning. Plants for this experiment emerged on May 1, 1983 in the nursery and they were transferred to the SPAR units at an age of 47 days. These plants were harvested when they were 90 days old (at about midbloom).

In the second experiment we collected, in addition to the above data, data of photosynthesis, transpiration, solar radiation and canopy and air temperatures. More than 1500 simultaneous observations were recorded by the data acquisition system of the SPAR units. The plants used in this experiment emerged in the nursery on June 21, 1983, and were transferred in their pots to the chambers 77 days after germination. The severely stressed plants ("S") were harvested 11 days later, at an age of 88 days, and other plants of the same age, taken from the nursery, replaced them. All the three units were later harvested on October 22, at a plant age of 123 days.

Mainstem leaves were tagged at their unfolding stage, at the nursery or in the SPAR units, throughout the two experiments. A destructive sample of five fully open mainstem leaves (usually the fourth leaf from the apex) from 5 different plants was taken twice a week in each chamber. These leaves were used for various measurements: leaf water potential was observed using the pressure bomb technique; blade area was recorded with a planimeter; and also leaf parts (petioles and blades) were oven-dried and weighed.

During the two experiments, morning and midday leaf water potential measurements (at 8 a.m. and 1 p.m., respectively) provided 26 data points. These data of leaf water potential were compared with other parameters that were recorded concurrently by the SPAR unit data acquisition system. When the leaves were sampled, the chamber door had to be opened for short time, door causing the data acquisition system to discard the data recorded for a 15 minute period. Therefore, the term "concurrent

parameters" means the average value of the parameters 45 minutes before the time of a leaf water potential observation.

Flowering was observed for a period of 45 days, in the nursery and later in the chambers, by counting the new flowers which opened daily. Fallen plant parts were collected every other day from the chamber floor, and sorted into leaves, squares, small and large bolls. These were counted, oven dried and weighed.

Photosynthesis measurements: The computer monitored CO_2 concentration and CO_2 injection time in each SPAR unit. The net CO_2 exchange by the plants was calculated every 15 minutes, with corrections for respiration rate and leakage. Solar radiation data were integrated over the same 15 minute periods and stored in a file, together with the apparent photosynthesis data, at the end of each day. Gross photosynthesis rate (PS) was calculated by adding dark respiration to the apparent photosynthesis rate. However, since the respiration was measured in the dark only, photorespiration was included in the "gross photosynthesis".

The daily curves of PS versus solar radiation flux density were analyzed by fitting a rectangular hyperbola equation. Each day's data set consisted of 44 to 52 points (each being an average of 15 minute periods). After the elimination of some outlier points (usually, early morning data recorded after the chamber temperature was changed from 20 to 32°C, or data recorded after the chamber doors were opened) the equation was estimated by a non-linear regression technique.

Temperature and evaporation measurements:

Each SPAR unit was thermostatically controlled with a fan-coil box that was attached to its northern side. This box contained a heater and a secondary cooling system. Chamber air temperature, as well as leaf temperature, were continuously recorded by the data acquisition system. Canopy temperature was measured by five small thermocouples which were attached to five fully open leaves on different plants in each unit. The difference between leaf temperature and chamber air temperature ($T_c - T_a$) was calculated.

Evapotranspiration was estimated by measuring the water vapor condensed on the coolant manifold. The amount of water drained from the base of the fan-coiled box, which was accumulated in a special tube, was recorded every 15 minutes. This measurement was much less accurate than the other data recorded by the system. While signals of temperatures, CO_2 concentration, and solar radiation were acquired every 10 seconds and averaged by the computer for 15 minute periods, evapotranspiration was estimated by a single measurement.

RESULTS AND DISCUSSION

Radiation, evapotranspiration, canopy temperature and photosynthesis data for four selected days are shown in figures 1

to 4. These figures clearly indicate that the rate of photosynthesis of stressed plants was reduced to about one half of that of the control plants. In the control plants, the maximum rates of photosynthesis followed the midday radiation peaks, whereas the stressed plants reached their maximal rates at about 10 a.m. Photosynthesis of water stressed plants was apparently limited by stomata, since the transpiration of these plants was reduced simultaneously with the photosynthesis. Leaves in canopies with reduced transpiration were found to be warmer, with their $T_c - T_a$ (the difference between canopy and air temperatures) being raised by up to 5°C.

The development of water stress is expressed in figures 5 to 10, in which daily values of three parameters are described: (1) daily evapotranspiration (Figs. 5 and 8) ; (2) daily gross photosynthesis (Figs. 6 and 9); (3) the rate of gross photosynthesis (Figs. 7 and 10), interpolated for a constant arbitrary value of solar radiation flux density of 1 langley min^{-1} (697 W m^{-2}). Daily gross photosynthesis data, as well as the interpolated value, were calculated from the fitted rectangular hyperbola curves.

The first period (September 6 to 15, 1983) is shown in Figs. 5 to 7. The highly stressed plants were harvested at the end of this period and replaced by other nursery plants. The same parameters were recorded for the next 24 days (September 17 to October 10, 1983), and these are given in Figs. 8 to 10. Note that the fresh plants from the nursery, at the beginning of the severe water stress treatment, were similar to the control plants.

Evapotranspiration was reduced as the water stress was prolonged. The photosynthesis of water stressed canopies was also declining. However, although the transpiration of the stressed plants was further reduced after the fifth day of stress, the rate of photosynthesis assumed somewhat higher values after that day. This slight increase in photosynthesis after the first five days of water stress might be the result of osmotic adjustment.

Correlation between concurrently measured parameters:

During the 35 days of the second water stress experiment, more than 1500 data points of 15-minutes averages of temperature, radiation, photosynthesis and transpiration were recorded. About 500 observations had to be discarded (those made under very low radiation conditions, or those made early in the morning following the change in chamber temperature). The remaining 1114 observations were pooled for all the three treatments, and a multiple linear regression equation was calculated from these data.

$$[1] \quad (T_c - T_a) = 0.264 + 0.003341(\text{Rad}) - 2.733(\text{Et})$$

Fig. 1. Average hourly values of measurements made in the three SPAR units on 10 September, 1983. (A) Solar radiation, in Watts m^{-2} . (B) Rate of net photosynthesis, in $\mu mol\ CO_2\ m^{-2}\ s^{-1}$. (C) Rate of evapotranspiration, in $mm\ hour^{-1}$. (D) The difference between canopy and air temperatures, in $^{\circ}C$.

Fig. 2. Average hourly values of measurements made in the three SPAR units on 13 September, 1983. (A) Solar radiation, in Watts m^{-2} . (B) Rate of net photosynthesis, in μmol CO_2 m^{-2} s^{-1} . (C) Rate of evapotranspiration, in mm $hour^{-1}$. (D) The difference between canopy and air temperatures, in $^{\circ}C$.

Fig. 3. Average hourly values of measurements made in the three SPAR units on 14 September, 1983. (A) Solar radiation, in $Watt\ m^{-2}$. (B) Rate of net photosynthesis, in $\mu mol\ CO_2\ m^{-2}\ s^{-1}$. (C) Rate of evapotranspiration, in $mm\ hour^{-1}$. (D) The difference between canopy and air temperatures, in $^{\circ}C$.

Fig. 4. Average hourly values of measurements made in the three SPAR units on 15 September, 1983. (A) Solar radiation, in Watts m⁻². (B) Rate of net photosynthesis, in $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$. (C) Rate of evapotranspiration, in mm hour⁻¹. (D) The difference between canopy and air temperatures, in °C.

Fig. 5. Daily total evapotranspiration, in mm day^{-1} , in the three SPAR units during the first stress period, which started on 6 September, 1983.

Fig. 6. Daily gross photosynthesis, in $\text{mol CO}_2 \text{ m}^{-2}$ ground area day^{-1} , in the three SPAR units during the first stress period, which started on 6 September, 1983.

GROSS PHOTOSYNTHESIS at 697 W/m² micromol CO₂ per m² per sec

Fig. 7. Rate of gross photosynthesis, interpolated value for a radiation level of 697 Watts m⁻², in $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ ground area s}^{-1}$, in the three SPAR units during the first stress period, which started on 6 September, 1983.

DAILY EVAPOTRANSPIRATION mm per day

Fig. 8. Daily total evapotranspiration, in mm day⁻¹, in the three SPAR units during the second stress period, which started on 17 September, 1983.

DAILY GROSS PHOTOSYNTHESIS mol CO₂ per m² per day

Fig. 9. Daily gross photosynthesis, in mol CO₂ m⁻² ground area day⁻¹, in the three SPAR units during the second stress period, which started on 17 September, 1983.

GROSS PHOTOSYNTHESIS at 697 W/m² micromol CO₂ per m² per sec

Fig. 10. Rate of gross photosynthesis, interpolated value for a radiation level of 697 Watts m⁻², in μ mol CO₂ m⁻² ground area s⁻¹, in the three SPAR units during the second stress period, which started on 17 September, 1983.

Canopy minus air temperature ($T_c - T_a$) is expressed in $^{\circ}\text{C}$, radiation flux density (Rad) in W m^{-2} , and evapotranspiration (Et) in mm hour^{-1} . About 60% of the variation in the ($T_c - T_a$) temperature could be explained by the radiation and the chamber evapotranspiration values.

From these 1114 observations, 540 with good concurrent photosynthesis measurements were chosen for further analysis. The following multiple linear regressions were found:

$$[2] \quad (T_c - T_a) = 0.336 + 0.004957(\text{Rad}) - 1.796(\text{Et}) - 0.0613(\text{PS})$$

$$[R^2 = 0.73]$$

$$[3] \quad \text{PS} = 5.327 - 5.585(T_c - T_a) + 0.04046(\text{Rad})$$

$$[R^2 = 0.73]$$

Rate of photosynthesis (PS) is expressed in $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ ground area sec}^{-1}$.

The relationship between canopy minus air temperature and the leaf water potential (LWP, the absolute value expressed in MPa), for the 26 data points where both were measured, is given in Fig. 11. The following linear regression was found between these variables:

$$[4] \quad (T_c - T_a) = -0.057 + 0.9014(\text{LWP}) \quad [R^2 = 0.64]$$

The relationship between the daily evapotranspiration (DET), expressed in mm, and the leaf water potential measured at noon, for the 13 available data points was expressed by the following regression (Fig. 12) :

$$[5] \quad \text{DET} = 10.764 - 2.500(\text{LWP}) \quad [R^2 = 0.82]$$

The relationship between the rate of photosynthesis and the leaf water potential, both measured at noon, for those 13 data points was expressed by the following regression (Fig. 13) :

$$[6] \quad \text{PS} = 44.091 - 7.491(\text{LWP}) \quad [R^2 = 0.46]$$

The relationship between the daily net photosynthesis (DPS), expressed in $\text{mol CO}_2 \text{ m}^{-2} \text{ day}^{-1}$, and the daily total evapotranspiration (DET) in mm day^{-1} , for the 93 observations in all the treatments, was expressed by the following second degree polynomial regression (Fig. 14) :

$$[7] \quad \text{DPS} = 0.2786 + 0.23632(\text{DET}) - 0.01464(\text{DET}^2)$$

$$[R^2 = 0.57]$$

The relationship between the hourly average values of photosynthesis and concurrent rates of evapotranspiration for 490 observations in all the three treatments was expressed by the

($T_c - T_a$) AND LEAF WATER POTENTIAL
Canopy-air temperature difference ($^{\circ}\text{C}$)

Fig. 11. The relationship between canopy and air temperature difference, in $^{\circ}\text{C}$, and the concurrently measured leaf water potentials, in MPa (absolute values).

DAILY ET AND LWP AT NOON
Daily evapotranspiration in mm

Fig. 12. The relationship between daily evapotranspiration, in mm day^{-1} , and the leaf water potentials, in MPa (absolute values), which was measured at noon on the same day.

CER AND LWP AT NOON

Fig. 13. The relationship between gross photosynthesis, in $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ ground area s}^{-1}$, and the leaf water potentials, in MPa (absolute values), both measured at noon on each day.

DAILY CER AND EVAPOTRANSPIRATION

Fig. 14. The relationship between daily gross photosynthesis, in $\text{mol CO}_2 \text{ m}^{-2} \text{ ground area}$, and daily evapotranspiration, in mm.

$$[8] \quad PS = 8.41 + 34.62(ET) - 6.0292(ET^2) \\ [R^2 = 0.57]$$

The relationship between the hourly average values of photosynthesis and concurrent radiation levels for the same 490 observations was expressed by the following second degree polynomial regression :

$$[9] \quad PS = 1.66 + 0.066(RAD) - 0.000041(RAD^2) \\ [R^2 = 0.39]$$

The data points were widely scattered, due to the effects of moisture stress, and only a small fraction of the variation in PS could be explained by its regression on RAD. However, when only the 152 observations from the growth chamber with no water stress were taken, the following regression equation (Fig. 16) was obtained:

$$[10] \quad PS = 1.82 + 0.078(RAD) - 0.0000405(RAD^2) \\ [R^2 = 0.90]$$

Leaf water potential:

The observed values of leaf water potential were correlated with concurrent measurements of radiation, transpiration, photosynthesis, and canopy temperature. The data for these concurrent parameters were taken from the data acquisition system as the average for the period of 45 minutes before the LWP was measured. These concurrently measured data are shown in Figs. 11-13. In Fig. 11 and in equation [4] it is clearly indicated that canopy temperature was linearly related to midday LWP values ($R^2 = 0.64$). Values of 1.5 and 3.8 MPa of LWP were associated with differences of 1 and 3.5°C, respectively, between canopy and air temperature.

Linear relationships were also found between the daily total evapotranspiration and midday LWP (Fig 12, equation [5]). The midday values of evapotranspiration were found to have a much lower correlation with the midday LWP, because of the very high experimental errors involved in single measurements of ET by the device we used, especially, immediately before the chamber was opened.

The relationship between net photosynthesis rate and midday LWP was also linear (Fig. 13 and equation [6]).

Leaf expansion:

Leaf expansion rate was drastically reduced as a result of water stress. There were no direct non-destructive measurements of leaf area in these experiments, but the effect of water stress can be calculated from the biweekly samples of tagged mainstem leaves. All the data for blade area of these destructive samples from the two SPAR experiments were grouped together. The average leaf area was compared among the three treatments (Figs. 17-18). From these limited observations it appears that fully-expanded leaves of high-stress plants were 20-40% smaller than leaves of same age of well irrigated plants (Fig. 18).

HOURLY CER AND EVAPOTRANSPIRATION

Fig. 15. The relationship between hourly average values of the rate of gross photosynthesis, in $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ ground area s}^{-1}$, and the concurrent rates of evapotranspiration, in mm hour^{-1} , for all the stress treatments.

HOURLY CER AND RADIATION

Fig. 16. The relationship between hourly average values of the rate of gross photosynthesis, in $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ ground area s}^{-1}$, and the concurrent solar radiation levels, in Watts m^{-2} , for SPAR unit #6 (no stress treatment) only.

% Reduction area of young leaves. Low stress, 1983

Fig. 17. Per cent reduction in the leaf area in the low stress treatment, relative to the no stress treatment.

% Reduction area of young leaves. High stress, 1983

Fig. 18. Per cent reduction in the leaf area in the high stress treatment, relative to the no stress treatment.

Young leaves of low-stress plants continued to grow, but at a lower rate than leaves of well irrigated plants. After 30 days of moderate water stress, the size of fully developed leaves was about 70% than that of leaves from the well irrigated plants (Fig. 17). Actually, 10 days of severe water stress caused a similar effect on leaf expansion as 30 days of moderate stress (Figs. 17 and 18).

Flowering rate and shedding of squares:

Water stress affects flowering rate in two ways. There is a direct effect of stress, which in addition to reducing turgor, photosynthesis and growth rate, also reduces the rate of formation of new squares. Secondly, water stress accelerates senescence and shedding processes of leaves and squares. Probably, the shedding of squares affects the flowering rate more than the slowing down of growth. As can be seen from Fig. 19, the effect of water stress on flowering was cumulative.

Data of cumulative square shedding are shown in Fig. 20. After few days of water stress the high-stress plants shed most of their squares, and this is probably the main reason why new flowers did not appear. The low-stress plants continued to add some flower buds, but their flowering rate was slower, and square shedding rate higher than those of the control plants.

Shedding of leaves and large bolls:

Data for shedding of leaves and of large bolls are shown in Figs. 21 and 22. A severe water stress caused an immediate shedding of many leaves and large bolls, whereas the effect of a moderate water stress was slower and of a smaller magnitude. According to Table 1, the high-stress plants shed within 11 days almost all their squares and small bolls, 29% of their leaves and 21% of their large bolls. The low-stress plants (Fig. 21) shed some of their leaves, and then probably adjusted their evaporation rate to the reduced irrigation rate, and after about 16 days of stress leaf shedding was stopped. Similarly, after about 10 days of moderate stress, the plants stopped to shed large bolls.

Table 1. Shed and harvested plant parts, after 11 days of a severe water stress. The numbers are average values of 10 plants, expressed on a single plant basis. Shedding percentage was calculated from the totals (shed + harvested).

	Number of fallen parts				Dry weight (g)			
				%				%
	Shed	Harv.	Tot.	Shed	Shed.	Harv.	Tot.	Shed.
Leaves	7.8	34.7	42.5	28.7	7.30	18.18	25.48	28.7
Squares	8.9	.9	9.8	90.8	.36	.01	.37	97.3
Small bolls	6.5	.1	6.6	98.5	1.41	.03	1.44	97.9
Large bolls	2.3	8.7	11.0	20.9	1.20	29.30	30.50	3.9

Accumulation of Flowers, Sep.-Oct. 1983

Fig. 19. Cumulative number of flowers, per m², in the three stress treatments. X = high stress; Y = low stress; Z = no stress.

Fig. 20. Cumulative shedding of squares and small bolls, number per m^2 , in the three stress treatments. X = high stress; Y = low stress; Z = no stress.

Shedding of leaves, Sep.-Oct. 1983

Number of leaves per m²

Fig. 21. Cumulative shedding of leaves, number per m², in the three stress treatments. X = high stress; Y = low stress; Z = no stress.

Shedding of large bolls, Sep.-Oct. 1983

Number of large bolls per m²

Fig. 22. Cumulative shedding of large bolls, number per m², in the three stress treatments. X = high stress; Y = low stress; Z = no stress.

Dry weight partitioning:

Table 2 compares the results of monitoring plants before the stress experiment (at an age of 77 days after emergence) and after 11 days of severe water stress. Although the destructive samples were made on different plants, the results indicated that only three types of organs did grow during the 11 day period of severe water stress: large bolls, small roots, and stems, which increased their dry weight by 15.8%, 137.6% and 16.5%, respectively.

Table 2. Dry weight distribution of plants before and after a severe water stress. Result of destructive harvests of 2 samples, 5 plants in each (0.5 m of row). Means and standard deviations expressed on a single plant basis.

Plant Character	Before water stress (77 day plants, nursery)	After 11 days of stress (88 day plants, Unit #4)	Diff.
Height (cm)	88.6 ± 0.2	93.6 ± 0.4	+ 5.0
Leaves (#)	44.20 ± 1.98	34.70 ± 2.12	-9.50
Squares (#)	13.10 ± 1.56	0.90 ± 0.70	-12.20
Small bolls (#)	3.10 ± 0.98	0.10 ± 0.14	-3.00
Large bolls (#)	12.20 ± 0.28	8.70 ± 1.28	-3.50
Leaf DW (g)	25.05 ± 0.56	18.18 ± 1.71	-6.87
Stem DW (g)	17.18 ± 1.00	20.01 ± 0.23	+ 2.83
Taproot (g)	6.51 ± 0.89	7.07 ± 0.44	+ 0.56
Small root (g)	3.75 ± 0.44	8.91 ± 1.54	+ 5.16
Small fruit (g)	1.43 ± 0.28	0.04 ± 0.04	-1.39
Large bolls (g)	25.29 ± 1.39	29.30 ± 1.10	+ 4.01

The dry weight of leaves and small fruit (squares and small bolls) was actually reduced, because of a severe shedding of these organs. The taproots gained some dry weight during the stress period, but the difference (0.56 g plant⁻¹) was within the standard deviation of the samples. Assuming that the total gain in dry weight of "S" plants was about 12 g plant⁻¹ (total weight increase in these three organs), the weight increase of the small roots, large bolls, and stems was about 43, 33, and 24%, respectively, of the total photosynthates accumulated during the stress period.

The developing bolls are considered to be the main sink of the plant during this period, and the initiation of new roots is known to be a typical response of a water-stressed plants. The growth of large bolls and of small roots can therefore be easily explained. The significant growth of stem dry weight during the stress period, however, was quite unexpected. The increase in stem weight (16.5%) was only partly related to the increase in plant height (5.6%) during this period. It may therefore be concluded that the stem of the cotton plant probably serves as a sink for excess carbohydrates, not used by other plant organs whose growth rate was reduced by the water stress.

B.

THE EFFECT OF MOISTURE STRESS ON STOMATAL RESISTANCE AND PHOTOSYNTHETIC RATE IN COTTON (*Gossypium hirsutum* L.).

J.E. EPHRATH, A. MARANI and B-A BRAVDO

ABSTRACT

The effect of moisture stress, as measured by leaf water potential, on stomatal resistance and on photosynthetic rate was studied in cotton under field conditions. Experiments were conducted in commercial fields in 1984 and in 1985, using a drip irrigation system. Moisture stress was evaluated by measuring the minimum mid-day leaf water potential (LWP). LWP was kept at two levels (-1.6 and -2.4 MPa) during each of two phenological periods. Stomatal resistance increased and photosynthetic rate decreased as a result of moisture stress. Stomatal resistance was slightly increased by radiation when the plants were subjected to moisture stress, but was decreased by it in the well irrigated treatments. An exponential asymptotic relationship was found between photosynthetic rate and stomatal resistance. Stomata were found to limit the photosynthetic process in well watered plants, while mesophyll resistance was found to be the main factor reducing it under moisture stress conditions. Mesophyll resistance was also found to cause an increase in the internal CO_2 during the day in the moisture stressed treatments.

INTRODUCTION

Two major factors which determine crop yield are the photosynthetic rate and the partitioning of photosynthates to the various parts of the plant. These are directly affected by the water relations of the plant. Reduction of photosynthetic rate in cotton by moisture stress is well documented (Ackerson et al. 1977, Bielorai and Hopmans, 1975, Sung and Krieg 1979, Hsaio 1973, Harris 1973). Ackerson et. al. (1977), and McMichael and Hesketh (1982) have found a close relationship between photosynthetic rate and leaf water potential (LWP) for glasshouse and field grown cotton. The reduction in photosynthetic rate in cotton usually commences when LWP reaches a value of about -1.6 MPa and continues as long as LWP decreases (Constable and Rawson 1982, El-Sharkawy and Hesketh 1964, Jordan and Ritchie 1971, Sung and Krieg 1979).

For moderate values of LWP, the increase in stomatal resistance is relatively small, but below a certain threshold of LWP, there is a

sharp increase in stomatal resistance (Cutler and Rains 1977, Jordan and Ritchie 1971). Water stress affects stomatal resistance in potted cotton plants differently than in field grown cotton (Jordan and Ritchie 1971) .

The reduction in photosynthetic rate as a result of water-stress is modified by the phenological stage of the plant (Sung and Krieg, 1979) and by light intensity (Bjorkman and Powels, 1984, Turner et al, 1986). Turner et al. (1986) showed that at high photon flux densities, photosynthetic rate and leaf conductance decreased progressively when LWP was reduced from -1.9 MPa to -3.5 MPa;

The inhibition of photosynthesis under water-stress can be attributed to both stomatal and non-stomatal factors, depending on the species and on the particular environmental conditions (Hutmacher and Krieg 1983). Boyer (1976), Jones (1973a, b) reported that stomatal resistance is the principal limitation to photosynthetic CO₂ assimilation. On the other hand, Farquhar and Sharkey (1982) reported that the effect of moisture stress on the photosynthetic rate is through non-stomatal factors. Similar results, reported by Ogren and Oquist (1985), indicated that only under moderate moisture stress conditions there was an effect of stomata on the photosynthetic rate, whereas non-stomatal factors became the dominant limitation to CO₂ assimilation under severe moisture stress conditions. Bjorkman and Powles (1984) reported that water stress predisposes the leaves to photoinhibition and that recovery from this inhibition is very slow.

The objectives of the work presented here are to determine the effect of water stress conditions on stomatal resistance, leaf water potential and the photosynthetic gas exchange in cotton under field conditions. Two series of experiments were carried out: (1) constant levels of moisture stress were achieved by using a drip irrigation system; (2) fluctuating moisture stresses were imposed by using sprinkler irrigation.

MATERIALS AND METHODS

The experiments took place in the coastal plain of Israel, on an alluvial clay-loam soil, in 1984 and 1985. The cultivar 'Acala SJ-2' of cotton (*Gossypium hirsutum* L.) was used in the experiments and it was planted on 31 March 1984 and on 9 April 1985 in east-west rows spaced 97 cm. There were, on the average, 11 plants per m of row.

A drip irrigation system was used. The experimental design was a 2X2 factorial with 6 replicates in randomized blocks. Plot size was 12X24 m. The drip lines were laid along each row, with 2 liter per hour drippers spaced 0.5 m. The experimental treatments consisted of different amounts of water applied at two phenological stages. The season was divided into two main periods. The first period (PD1), characterized by strong vegetative growth, was from the beginning of the irrigation period (on 10 June 1984 and on 15 June 1985) until the appearance of some full sized bolls (on 19 July 1984 and on 17 July 1985). Irrigation was applied to the various treatments twice a week, so that two levels of leaf water potential (LWP), -1.6 and -2.4 MPa,

were maintained at noon before each irrigation. Each treatment was split into the same two irrigation regimes during the second period (PD2), which was characterized by boll growth and fiber development, and was continued until the end of the irrigation season (10 Sept. 1984 and 8 Sept. 1985). This design made it possible to test the effects of the history of the water regime as well as of the actual moisture stress on photosynthesis and on related physiological processes. Data from only one treatment in 1985 are presented in this paper. Treatment codes and actual amounts of water applied are given in table 1.

TABLE 1.

Treatment codes, prescribed leaf water potential at noon and water amounts in the two phenological periods.

TREATMENT			LEAF WATER POTENTIAL		AMOUNT OF WATER		
			MPa		mm		
YEAR	CODE #	PERIOD	1	PERIOD 2 ##	PERIOD 1	PERIOD 2	TOTAL
1984	T11	-1.6	-1.6	152	244		396
1984	T13	-1.6	-2.4	145	21		176
1984	T31	-2.4	-1.6	27	172		199
1984	T33	-2.4	-2.4	18	48		66
1985	T13	-1.6	-2.4	147	144		291

For details see Materials and Methods. ## Period 1 = 10 June to 19 July 1984, or 12 June to 17 July 1985. Period 2 = 20 July to 10 September 1984, or 18 July to 8 September 1985.

The soil was saturated to field capacity to a depth of at least 150 cm by winter rainfall. 50 mm of water were applied at the beginning of the irrigation period to all -1.6 MPa treatments on PD1. The amount of water applied in each irrigation was determined by daily measurements of a class 'A' evaporation pan. In addition to that, the canopy cover coefficient was estimated each week for each treatment from leaf dry weight measurements. The amount of water to be applied in each irrigation treatment was usually calculated by multiplying the amount of water evaporated by the cover coefficient (Marani and Ephrath, 1985). When LWP deviated from the prescribed value of any treatment, the amount of water was recalculated by adding to the cover coefficient, or subtracting from it, 0.05 units for each

deviation of 0.1 MPa. Irrigation was activated by an irrigation control computer 'MATAROL 2000' (Motorola, Israel).

Leaf water potential (LWP) was measured by an Ari I (Arimad, Israel) pressure chamber (Scholander et al. 1965). The youngest fully expanded leaf, usually from the 4th or 5th node from the top, was cut off and immediately put in a closed box with a wet rag to avoid water loss from the leaf. LWP was measured within an hour. The measurements for water application decision were made at noon (11:30-13:30), four times a week on six replicated leaves. On some dates, in conjunction with other measurements, LWP was measured throughout the entire day in some of the treatments.

Photosynthesis was measured by the LI-6000 Portable Photosynthetic System (Licor, USA). The data measured by this system included the photosynthetic rate, stomatal resistance, initial transpiration rate, leaf and air temperature (inside the chamber), photosynthetically active radiation (PAR, 400-700 nm) and the relative humidity and CO₂ concentration (inside the chamber). All the measurements were conducted on the same type of leaves on which the LWP measurements were carried out (i.e., youngest fully expanded leaves from the 4th or 5th node from the top).

RESULTS

Most of the results presented here are for two representative dates in the 1984 experiment. Data taken on other dates, as well as in the 1985 experiment, confirm these results.

The seasonal course of leaf water potential (LWP) measured at noon is presented in Fig. 23. Due to the frequent irrigations (twice a week), a fairly constant LWP was maintained in all the treatments, until the irrigation regime was changed. Rapid changes in LWP were then recorded in treatments T31 and T13. The diurnal LWP (Fig. 24) has changed in the well irrigated treatments from a high value in the morning to lower values at noon. In the moisture stressed treatments, the initial values in the early morning were lower than in the well irrigated treatments. This difference increased until noon, and decreased in the late afternoon.

The stomatal response to the various irrigation treatments is presented in Fig. 25. Treatments T11 and T31, which were well irrigated on the dates presented here, had a low stomatal resistance, while the severely stressed (-2.4 MPa at noon) treatments T13 and T33 had a high stomatal resistance. Treatment T33 had a lower stomatal resistance than T13 on both dates, although these treatments had similar LWP values (-2.4 MPa at noon).

In the well irrigated treatments, the initial stomatal resistance values at early morning were relatively high, 6 to 7 m² s mol⁻¹ on August 19 (Fig. 25,a), and 12 to 14 m² s mol⁻¹ on August 23 (Fig. 25,b). As radiation intensity increased there was a rapid reduction of stomatal resistance in these treatments. In the moisture stressed treatments, however, stomatal resistance remained high during all day.

Fig. 23: Leaf water potential throughout the season, measured at noon in four irrigation treatments, 1984 experiment. The arrow indicates the date of changing irrigation regime (19 July).

Fig. 24: Diurnal changes in leaf water potential in four irrigation treatments on two representative dates, 1984 experiment. A - 19 August, B - 23 August. SE values are presented.

Fig. 25: Diurnal changes in stomatal resistance in four irrigation treatments on two representative dates, 1984 experiment. A - 19 August, B - 23 August. SE values are presented.

Fig. 26: Diurnal changes in photosynthetic rate in four irrigation treatments on two representative dates, 1984 experiment. A - 19 August, B - 23 August. SE values are presented.

The photosynthetic rate in the two well irrigated treatments (T11 and T31) was similar despite their different irrigation histories (Fig. 26). Thus, a full recovery of photosynthesis after increasing the irrigation rate was attained in T31. The diurnal curve in these treatments is characterized by a rapid increase in the photosynthetic rate throughout the morning, from a minimum of about $8 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ to a maximum of about $24 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, and a decrease during the afternoon.

Photosynthetic rate was higher in the well irrigated treatments in comparison to the moisture stressed ones during all the day. It reached its maximum values at noon in the well irrigated treatments, while in the moisture stressed treatments it reached its maximum value earlier in the day. In contrast to the well irrigated treatments, no peak in the photosynthetic rate was apparent at noon under the moisture stressed conditions, although a slight increase occurred in the morning, when radiation intensity increased. Maximum photosynthetic rate was about $9 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in the two stressed treatments.

A constant internal CO_2 concentration (C_i) was found in the well irrigated treatments during the day (Fig. 27a). C_i was somewhat lower in treatment T31 than in treatment T11, a phenomenon that can be explained by a lower ratio of mesophyll to stomatal resistances. Although a low C_i resulting from high stomatal resistance in the moisture stressed treatments was expected, C_i was actually much higher than in the well irrigated treatments. The diurnal ratio of photosynthetic rate to C_i , which is usually associated with carboxylation efficiency (Krieg and Hutmacher, 1986), was higher in the well irrigated treatments than in the moisture stressed ones (Fig. 27b).

A close relationship between stomatal resistance and radiation intensity was found in the well irrigated treatments (Fig. 28); correlation coefficients were -0.885 and -0.864 in T11 and T31, respectively. Lower correlations were found in the moisture stressed treatments, -0.629 and -0.559 in T13 and T33, respectively.

The relationship between stomatal resistance and the photosynthetic rate in all the four treatments is presented in Fig. 29. The increase in stomatal resistance was associated with a sharp reduction in the photosynthetic rate in the well irrigated treatments. In the moisture stressed treatments, however, there was only a moderate reduction in the photosynthetic rate. No further response of the photosynthetic rate was apparent when stomatal resistance rose higher than $20 \text{ m}^2 \text{ s mol}^{-1}$.

The effect of stomatal resistance on the photosynthetic rate in all the irrigation treatments can be expressed by a single non-linear regression equation, indicating that there were no specific effects of the various irrigation treatments on this relationship.

In both the well irrigated treatment (T11) as well as in the water stressed one (T13), photosynthetic rate did not reach saturation even at high radiation intensities (Fig. 30). Photosynthetic rate was

Fig. 27: Diurnal changes in (A) internal CO₂ concentration (Ci), and (B) the ratio between photosynthetic rate and Ci (carboxylation efficiency according to Krieg and Hutmacher, 1986) in four irrigation treatments, 23 August 1984. SE values are presented in(A).

Fig. 28: The relationship between radiation intensity (PAR, 400-700 nm) and stomatal resistance in four irrigation treatments, 1984 experiment. Correlation coefficients (r) are presented.

Fig. 29: The effect of stomatal resistance on photosynthetic rate in four irrigation treatments, 23 August, 1984. The line represents the non-linear regression function :

$$P = 4.53 + 40.75 * (\text{EXP}(-.1758 * S))$$

where P is the photosynthetic rate [$\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$] and S is the stomatal resistance [$\text{m}^2 \text{ s mol}^{-1}$].

Fig. 30: The effect of photosynthetically active radiation intensity (in the PAR range, 400-700 nm) on the photosynthetic rate in well irrigated (T11) and moisture stressed (T13) treatments, 26 August, 1984.

Fig. 31: The effect of leaf age and moisture stress on the photosynthetic rate on four dates in treatment T13, 1985 experiment. Each point in each date is an average of 4 measurements.

higher in the well irrigated treatment than in the moisture stressed treatment at all radiation levels.

The effect of leaf age and moisture stress on the photosynthetic rate in treatment T13 in 1985 is presented in Fig. 31. On the first date (July 17), when the plants were under well watered conditions (LWP of -1.6 MPa at noon), the maximum photosynthetic rate was about $24 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ and it was attained when the leaf age was 28 days. Five days after the plants have been subjected to moisture stress conditions (July 22), there was only a slight effect of moisture stress on the photosynthetic rate ($21 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, at a LWP of -2.3 MPa at noon), but the maximum photosynthetic rate occurred at an earlier leaf age. After being 14 days under moisture stress conditions (31 July), the photosynthetic rate decreased to the value of $9 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ irrespective of leaf age. Similar results were obtained two weeks later (14 August).

DISCUSSION

The drip irrigation system makes it possible to maintain constant levels of LWP (Fig. 23 1). Five days after increasing the water applied to treatment T31, LWP increased from -2.4 MPa to -1.6 MPa. An opposite phenomenon occurred in the treatment T13. Turner (1975) and Turner and Begg (1981) also reported a rapid reduction of LWP after reducing irrigation. The fast rate at which water shortage developed was accelerated by the large leaf area which was formed under the preceding well-irrigated conditions. The diurnal curve of leaf water potential which is characterized by a decrease in LWP from morning to noon, an almost constant level for about two hours at noon and a moderate increase during the afternoon, is typical for many plants (Hsiao, 1973).

Stomatal resistance increased during the day in the water stressed treatments, a phenomenon that was also reported by Moresnet and Falkenflug (1978). In the well irrigated treatments, however, stomatal resistance decreased during the morning hours (Fig. 25). Stomatal resistance was highly correlated with radiation intensity under good water conditions, but this correlation was lower under moisture stress (Fig. 28). The main factor affecting stomatal resistance in well watered plants is therefore radiation intensity, as was also reported by Ackerson et al. (1977) and Ackerson and Krieg (1977), who did not find any association between leaf water potential and stomatal resistance. Ludlow (1980), Turner (1975) and McMichael and Hesketh (1982) reported that stomatal resistance is affected by leaf water potential, but they did not report any association between these parameters and radiation intensity. This is similar to what we found in our experiments, when the plants were subjected to moisture stress.

Our results indicate that the relationship between photosynthetic rate and stomatal resistance depends on the severity of moisture stress. An increase in stomatal resistance caused a substantial reduction in the photosynthetic rate in the well irrigated treatments, when stomatal resistance was in the range of 3 to $15 \text{ m}^2 \text{ s mol}^{-1}$. In the water stressed treatments, however, when stomatal resistance was

higher, its effect on the photosynthetic rate was very small (Fig. 29). Similar findings were also reported by Farquhar and Sharkey (1982) and by Ogren and Oquist (1985).

The substomatal CO₂ concentration (C_i) in the well irrigated treatments remained constant during the day while in the moisture stressed treatments it increased, contrary to what would be expected on the basis of stomatal resistance data (Fig. 27a). This indicates that in the well irrigated treatments mesophyll and stomatal resistances changed simultaneously, whereas in the moisture stressed treatments mesophyll resistance increased more than did stomatal resistance, resulting in an increase of the C_i. Similar results were also reported by Sharp and Boyer (1986). They pointed out that the reduction in the photosynthetic rate due to moisture stress is related to a damage to the chloroplasts, which causes an increase of C_i under a severe moisture stress, and a decrease in C_i under a moderate stress.

Our results indicate that under a severe moisture stress photosynthesis is reduced primarily by non-stomatal factors. This conclusion is also confirmed by the ratio of the photosynthetic rate to the C_i (called the carboxylation efficiency, by Krieg and Hutmacher, 1986). In the moisture stressed treatments this ratio was found to be low, while in the well irrigated treatments it was high (Fig. 27b).

Photosynthetic rate in cotton usually increases with leaf age up to 25 days after leaf initiation, and later slowly decreases (Constable and Rawson, 1980, Moreshet et al, 1979, Nagarajah, 1975). We found that moisture stress affected the photosynthesis - leaf age relationship in two stages: at first, water stress decreased the leaf age at which photosynthesis was maximum (Fig. 31, July 22); later, there was a reduction in both the photosynthetic rate and in the age at which it was maximum (Fig 31, July 31 and August 14).

The supply of photosynthates to the bolls by the leaves affects boll development (Constable and Rawson, 1980) and lint quality (Schubert et al., 1973). Under well watered conditions (Figure 31, 17 July), high photosynthetic rates were recorded for leaves older than 12 days, with a maximum at the age of 25 days. When subjecting the plants to water stress, two stages in the reduction of the photosynthetic rate were observed. At first, the number of developing bolls was still relatively low, resulting in low demands for photosynthates. The main effect of water stress was on the leaf age at which photosynthesis rate was maximum, while the photosynthetic rate itself was only slightly affected (Fig. 31, 17 July). Later, when the number of bolls was high, a severe reduction in the photosynthetic rate occurred (Fig. 31, 22 and 31 July). Similar results, indicating that the demand for photosynthates affects the photosynthetic rate were reported by several workers (Mondal et al., 1978; Geiger, 1976; Thorne and Koller, 1974). The main effect of photosynthates shortage was on the leaf area and plant size (Constable and Rawson, 1980; Turner et al., 1986).

Cyclic oscillations of stomatal resistance were observed in the

stressed treatments on August 23 (Fig. 25,b). Similarly to the diurnal stomatal resistance curve, cyclic oscillations were also observed in the photosynthetic rate.

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C.

THE SIMULATION OF IRRIGATION PRACTICES AND THE EFFECTS OF MOISTURE STRESS IN THE COTTON MODEL.

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1. The main moisture-related processes in the system.

The main processes in the COTMOD model, which are related to the moisture regime in the plant and in the soil, will be briefly described in this section. A more complete description of these processes, and some general information about the model, may be obtained (see the appendix).

Rainfall and Class A pan evaporation are the climatic data needed as input for these processes. The potential evapotranspiration is calculated from the pan evaporation data, assuming a constant ratio between these variables. The potential evaporation from the soil surface (EVAP2) is modified by the value of the leaf area index (LAI), using an empirical function. This function is also modified for the case of drip irrigation.

If irrigation is specified on a certain date in the input, the specified amount of irrigation water is added to the soil. The simulation may also be run in the irrigation prediction mode. In this case, the total soil moisture above the wilting point is calculated up to a soil depth that may be defined by the user. The total available soil moisture between field capacity and wilting point is also calculated. When the ratio between these calculated variables reaches a pre-defined threshold, an irrigation is predicted. The amount of water to be applied is calculated as the amount needed to saturate the soil to field capacity.

To save computer time, it is assumed that each soil layer is wetted immediately to a soil water potential of 20 KPa, and the excess moisture moves down to the next layer. A "shape factor" of the wetted soil volume is used for the case of drip irrigation.

The simulation of the movement of water between soil layers is done in shorter time steps (of 6 hours). Empirical functions are used to calculate the hydraulic diffusivity, conductivity and the derivative of the conductivity by water content for each soil layer, as functions of its water content.

The differential equations for the movement of water between layers

are solved by a combination of implicit and explicit numerical methods. The implicit solution is calculated with a weighting factor R , and the explicit solution is weighted by $1-R$. Since the implicit method may not be accurate for the water balance, the new values of water content are adjusted by using their deviations from their previous values.

The matric soil water potential is calculated by using the constants that have been calculated for each layer at the start of the simulation. The empirical function is assumed to pass through three points: 30 KPa at field capacity, 1500 KPa at wilting point, and infinitely high values for air-dry soils. However, for very dry soils a limiting high value is used to avoid overflow errors.

Moisture stress factors are calculated on the basis of the soil moisture in soil layers with effective roots. This is assumed to be 0.9 of the root containing layers minus 1. The number of these layers however, is limited to a maximum of 10 (corresponding to a depth of 120 cm). The sum of available water (above wilting point, but not exceeding the field capacity) is calculated for these layers, and the potentially available water (between field capacity and wilting point) is calculated in a similar manner. Their ratio is calculated as SFAC, and this is used in an exponential function to calculate the component of moisture stress attributed to soil moisture deficit in the root zone. It can have any value between 0 (extreme stress) and 1 (no stress). The component of moisture stress attributed to meteorological conditions is calculated as a second degree function of the pan evaporation on this day. It also has a value of between 0 and 1. The moisture stress factor H2OST is obtained by the multiplication of these two components.

H2OST is used to calculate two special empirical factors: PTSRED expresses the effect of moisture stress on the rate of photosynthesis, and HFAC expresses its effect on the rates of vegetative growth and of several other processes in the plant.

The distribution of water uptake among the soil layers is calculated as a function of their water content, active root content, width of each layer, and its depth below the soil surface. The water content factor is a 3rd degree function of the soil water potential. The active roots are the sum of the weights of the young and medium-aged roots. The effect of depth is the square of its reciprocal.

The actual transpiration is modified by a function of SFAC and by the canopy-cover factor FLA. FLA is a function of the leaf area index (LAI) or of plant height. The actual transpiration (EP) is calculated by multiplying these factors by the potential evapotranspiration. The actual transpiration is then allocated to soil layers in proportion to the distribution factors that have been previously calculated.

The daily rate of photosynthesis is modified by multiplying it by the moisture stress factor PTSRED. The potential growth of all plant parts (the growth that may be achieved if there is a sufficient supply of available carbohydrates, and no other deficiencies occur) is not affected by moisture stress. Potential growths of leaves and of stems are functions of the physiological age of the plant before the initiation of the first square. Later, they are functions of the dry

weight of the active tissues of each part.

Potential root growth is affected by the moisture content of each layer. A soil moisture factor is calculated as a function of the volumetric soil moisture content of each layer. When drip irrigation is practiced, root development in each layer is modified by the factor FDRIP (which is equal to one otherwise).

The potential growth of the fruits, which is not affected by moisture stress, is based on the results of Marani (1979), and the parameters that are used describe the growth characteristics of squares and bolls of the cultivar 'Acala SJ-2'.

When carbohydrate supply is not sufficient for the potential growth requirements of all plant parts, the allocation of available carbohydrates for the growth of each part has to be computed. Allocation is affected by the carbohydrate balance as well as by moisture stress and nitrogen stress functions. Allocation to fruits has the first priority. There is some reduction in the allocation to the fruits by moisture stress, computed by using empirical functions of the stress factor HFAC. The effects of moisture stress on the growth rates of leaves and stems are similarly computed by using HFAC.

The "physiological age" of each age-group is increased by a temperature-related function. It is further increased by moisture stress to simulate the accelerated senescence under stress conditions. The state variable LEFWT is calculated as the total weight of active non-senesced leaves. These include all the leaves younger than the physiological age given by PAR(8), and a decreasing proportion of the leaves aged between PAR(8) and PAR(9). These age limits are modified by moisture stress, which lowers the age of leaf senescence. Older leaves are considered as completely senesced.

The formation of new main stem nodes is simulated by a procedure similar to that of GOSSYM (Baker et al, 1983). A delay in node formation, caused by moisture stress, effective only after the beginning of flowering, is computed and simulated. The daily growth in plant height is also modified by moisture stress.

There are several aspects of fruiting that are strongly affected by the moisture regime: The rate of square appearance is affected by the moisture stress factor H2OST. Bolls mature and open when their physiological age is between PAR(4) and PAR(5), and the distribution of boll opening within this period is simulated as a third degree function. A period of moisture stress induces earlier boll opening, and this is simulated by reducing the value of PAR(4) and PAR(5).

Moisture stress also affects the shedding of fruiting forms. If there is a moisture stress below a certain value, potential shedding may occur in response to this stress. The probabilities of abscission are calculated as a function of the physiological age of the fruits. It is assumed that shedding of squares is caused by carbohydrate and nitrogen stresses; shedding of young bolls (up to three days after flowering) is also caused by moisture stress, but the effect of nitrogen stress is smaller; shedding of medium aged bolls (3 to 11 days

after flowering) is caused by carbohydrate and moisture stresses; and shedding of older bolls (11 to 19 days) is caused by moisture stress only. Bolls older than that are not liable to be shed by physiological causes.

2. An example of simulating different moisture regimes.

To illustrate the simulation of different moisture regimes, data from a single line source experiment that has been conducted at Hazor (in the coastal plain of Israel) in 1984. The soil is an alluvial deep clay-loam. Cotton was planted on 31 March and germinated on 8 April. The rows were spaced 97 cm, and there were on the average 11 plants per m of row. An application of 150 kg of nitrogen per ha was made just before planting. Irrigation was applied by a single line of sprinklers, so that the amount of water received by the plants was a function of their distance from the line.

Alternate plant rows, from row 3 to row 15, were defined as seven 'treatments', and designated KB1 to KB7. Each treatment was divided into five plots that served as replicates. The effective water reaching each plot was measured by rain gauges on each irrigation. The plots were sampled regularly, once a week, to provide the validation data for the model. All the plants of 1 m samples, taken from each of the five replicates, were separated to the different organs, fruiting forms counted, and dry weight determined by oven-drying. After the beginning of boll opening, 2 m segments were marked in each replicate, and all the opened bolls harvested at weekly intervals. Cumulative data of open boll number and yield of seedcotton were thus determined.

Four of the treatments are described here. There were five irrigations during the season, on 22 June, 12 and 26 July and 8 and 22 August. The effective amounts of irrigation water were 90, 110, 110, 90 and 80 mm for treatment KB1, 30, 55, 45, 35 and 30 mm for KB3, 20, 20, 15, 15, and 15 mm for KB5, whereas KB7 did not receive any irrigation at all. The moisture content of these treatments throughout the season, as simulated by the model, is given in Fig. 32.

The results of the effect of moisture stress on photosynthesis are reflected in the simulated daily added dry matter (net carbon exchange rate), given in Fig. 33. The maximum rates were 25, 20, 15 and 12 g m⁻² day⁻¹ in KB1, KB3, KB5 and KB7, respectively.

The simulated plant height was very close to the observed data, although the model predicted in some cases a higher rate of stem growth (Fig. 34). The effect of moisture stress on vegetative growth is also evident in the leaf and stem dry weight data (Fig. 35 and Fig. 36). The model slightly underestimated leaf and stem dry weight in treatment KB1, but it overestimated leaf weight during the beginning of the season in KB7, and stem weight in KB3.

The number of open bolls was very markedly affected by moisture stress (Fig. 37). The simulation results were very near the observed data, but in KB1 and KB5 the model overestimated the number of bolls.

The observed number of open bolls was 76, 66, 31 and 30 per m^2 , whereas the simulated number was 83, 63, 46 and 60 in KB1, KB3, KB5 and KB7, respectively.

The dry weight produced in the bolls of the plants was also very markedly affected by moisture stress, and this was simulated quite accurately by the model (Fig. 38). These are the total weights of the bolls (including the burs). The final simulation results were 850, 700, 390 and 260 $g\ m^{-2}$ in KB1, KB3, KB5 and KB7, respectively.

The yield of seedcotton, however, was overestimated by the model in the dry treatments (Fig. 39). The observed yields of seedcotton were 455, 393, 151 and 133 $g\ m^{-2}$, whereas the simulated yields were 549, 434, 263 and 175 in KB1, KB3, KB5 and KB7, respectively. It seems that some environmental effects, such as insect damage, that were not simulated in the model, caused the final yield to be less than the potential yield. This was more prominent in the drier treatments.

An analysis of the simulated stress factors throughout the season may highlight some processes affected by the moisture regime. Carbohydrate stress (Fig. 40) appeared earlier in the well irrigated treatments than in the drier ones, and also lasted for a much longer period. The reason for this phenomenon is that moisture stress affects vegetative growth rates more severely than photosynthesis (Marani et al., 1985). The well irrigated plants have larger sinks for carbohydrates in their organs than the dry ones, and they are therefore more liable to be stressed for carbohydrates.

The moisture stress factor affecting vegetative growth (HFAC) is given in Fig. 41. There was a moisture stress in all treatments during the first two weeks after germination, when the root system was very small. There also was a period of severe moisture stress before the first irrigation. This may explain why yields of KB1 were lower than the potential yields (of up to 700 $g\ m^{-2}$ of seedcotton) that are obtainable under optimal conditions. After the first irrigation the levels of stress were different in all treatments. KB7 was continuously stressed from the beginning of June until the end of the season.

There were short periods of nitrogen stress (Fig. 42) in the very young plants, probably because of the undeveloped root system. After that there was no apparent nitrogen deficiency until the end of July. In August and September nitrogen stress appeared earlier and it was more severe in the two extreme treatments, KB1 and KB7, than in KB3 and KB5. This may have been caused in KB1 by leaching of nitrates by excessive irrigation and by increased nitrogen uptake by the strongly vegetative plants. In KB7 this was probably due to reduced nitrogen uptake by the plants caused by low soil water content and reduced transpiration.

Figure 32. The simulated soil moisture content (per cent v/v, average 0-90 cm) throughout the season in four irrigation treatments, single source line experiment HAZOR 1984.

Figure 33. The simulated daily added dry weight, $\text{g m}^{-2} \text{ day}^{-1}$, throughout the season in four irrigation treatments, single source line experiment Hazor 1984.

Figure 34. The simulated (____) and observed (+) plant height, cm, throughout the season in four irrigation treatments, single source line experiment Hazor 1984.

Figure 35. The simulated (____) and observed (+) leaf dry weight, g m⁻², throughout the season in four irrigation treatments, single source line experiment HAZOR 1984.

Figure 36. The simulated (____) and observed (+) stem dry weight, g m⁻², throughout the season in four irrigation treatments, single source line experiment HAZOR 1984.

Figure 37. The simulated (____) and observed (+) number of open bolls, per m², throughout the season in four irrigation treatments, single source line experiment Hazor 1984.

Figure 38. The simulated (____) and observed (+) total boll dry weight, g m⁻², throughout the season in four irrigation treatments, single source line experiment HAZOR 1984.

Figure 39. The simulated (____) and observed (+) cumulative weight of seedcotton in the open bolls, g m⁻², throughout the season in four irrigation treatments, single source line experiment HAZOR 1984.

Figure 40. The simulated carbohydrate stress factor (F) throughout the season in four irrigation treatments, single source line experiment Hazor 1984.

Figure 41. The simulated moisture stress factor (HFAC) throughout the season in four irrigation treatments, single source line experiment Hazor 1984.

Figure 42. The simulated nitrogen stress factor (STRESN) throughout the season in four irrigation treatments, single source line experiment Hazor 1984.

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D.

THE SIMULATION OF NITROGEN FERTILIZER APPLICATION AND THE EFFECTS OF NITROGEN STRESS IN THE COTTON MODEL.

A. MARANI and Yael REKAH

1. The main nitrogen-related processes in the system.

The main processes in the COTMOD model, which are related to the nitrogen content in the plant and in the soil, will be briefly described in this section. A more complete description of these processes, and some general information about the model, may be obtained (see the appendix).

When irrigation or rain water moves down to the next soil layer, the dissolved nitrates are also moved downwards. The movement of nitrates with the water, between soil layers, is also simulated for the diffusion process.

The program checks if a date of fertilizer application has been reached. If so, the fertilizer is uniformly mixed in the three uppermost soil layers (to a depth of 15 cm), and the content of ammonium and nitrate nitrogen in these layers is updated.

The depth of each layer is used to modify the rates of mineralization and of nitrification, because the microorganisms are assumed to be less prevalent and less active in the deeper soil layers. After calculating the average daily soil temperature in each layer, the temperature-factor for the mineralization process is calculated. The amount mineralized is proportional to the organic N, modified by a soil moisture factor. The amount of mineralized nitrogen is added to the NH_4 nitrogen and subtracted from the organic nitrogen.

The process of nitrification of NH_4 nitrogen is treated in a similar manner, but the soil moisture factor is calculated in a different way and so is the temperature factor.

The nitrogen requirement for plant growth is allocated to soil layers in the same proportions as the allocation of water uptake. The actual uptake of nitrate-N from each layer is calculated by a Michaelis-Menten type function of the concentration of nitrate-N in the soil solution.

To simulate the uptake of ammonium, a thermodynamic approach is used to estimate the concentration of $\text{NH}_4\text{-N}$ dissolved in the soil

solution (i.e., not adsorbed on the soil particles). This is based on the approach described by McLaren and Peterson (1965). The actual uptake of dissolved $\text{NH}_4\text{-N}$ from each layer is also calculated as a Michaelis-Menten function.

The amounts of nitrate and NH_4 nitrogen in the soil are updated and adjusted from a per plant basis to a per soil volume basis. The total nitrogen uptake is then calculated.

The subroutine that simulates the rate of denitrification is a preliminary attempt to include this process in the model. Much more work is needed to develop and validate it. The effects of soil temperature, and soil moisture (a 3rd degree function of the soil water potential) on the rate of denitrification are calculated. It is assumed, however, that denitrification may occur only in the presence in the soil of organic matter, or when young actively growing roots are present. The nitrate content in the soil layer is decreased, by denitrification in proportion to these factors.

The effect of nitrogen stress on the rate of photosynthesis is expressed as a function of the nitrogen content of the leaves. The actual growth, i.e., the allocation of available carbohydrates for the growth of plant parts, is affected by several factors, including a nitrogen stress function. The growth of the fruits, leaves and stems is reduced by nitrogen stress, to an extent computed by empirical functions of STRESN (the computed nitrogen stress factor in the plant).

The formation of new main stem nodes is delayed by nitrogen stress. The daily growth in plant height is also modified by nitrogen stress.

The subroutine NITR computes the nitrogen requirements of the plant, the actual nitrogen added to plant parts, the nitrogen concentration in each plant part, and the nitrogen stress factor. It is based on the results of Jones et al. (1974), Thompson et al. (1976), Marani and Aharonov (1964), and Halevy et al. (1987).

Minimum and maximum nitrogen content values in the plant parts are assumed. The plant parts are numbered as follows: 1 - leaves; 2 - seeds; 3 - burs; 4 - stems; 5 - roots. When leaves are shed, the amount of nitrogen in the leaves is updated. Also, when fruits are shed, the amount of nitrogen in the seeds and in the burs is updated.

The "nitrogen requirement" (RQ) of a plant part is defined as the product of its added dry weight and its maximum nitrogen content NMAX. When the total content of nitrogen in the active tissue of this part is less than NMAX, RQ is increased by a certain proportion of the difference. REQ is the sum of the amount of nitrogen required by all plant parts, in g per plant.

AVAILN, the available nitrogen for the plant, is equal to the amount taken up from the soil on that day, UPTN. However, if UPTN is less than REQ, a process of reallocation of nitrogen from the vegetative tissues is simulated. The amount of nitrogen exceeding the minimum concentration in the leaves, stems and roots is defined as "nitrogen reserves". A fixed proportion of these reserves is

subtracted from them and added to AVAILN.

When AVAILN is sufficient for all the nitrogen requirements, the amount of nitrogen in each part is updated by RQ, and AVAILN is reduced accordingly. Otherwise, a series of priorities is simulated, and the nitrogen stress factor STRESN is calculated as the ratio of AVAILN to REQ. It is assumed that the first priority is to the seeds, then to the leaves, then on an equal basis to the burs and stems, and the last priority is to the roots. In each case, not more than a certain proportion of the available nitrogen may be used by each part, and AVAILN is updated accordingly.

RESN is the total amount of reserve nitrogen before reallocation. If there is some unused AVAILN, it is returned to the vegetative plant parts in proportion to the reserves that were in them before reallocation. The concentration of nitrogen in the dry matter is now recalculated for each part.

The rate of square appearance is affected by the nitrogen stress factor STRESN. If there is a nitrogen stress below a certain value, potential shedding may occur in response to this stress. It is assumed that shedding of squares is caused by carbohydrate and nitrogen stresses; shedding of young bolls (up to three days after flowering) is caused by all three stresses, but there is a smaller effect of nitrogen stress; but shedding of older bolls is not affected by nitrogen stress.

2. An example of simulating nitrogen application.

To illustrate the simulation of different nitrogen regimes, data from two experiments are given here. Data were taken from the "permanent plot" experiment at Bet-Dagan (in the coastal plain of Israel) in 1984. Cotton has been continuously grown since 1978, and the same fertilizer treatments have been applied to all plots from 1981. The soil is an alluvial deep clay-loam. Cotton was planted on 22 April and germinated on 29 April. The rows were spaced 97 cm, and there were on the average 10 plants per m of row. Two extreme treatments are described here: BDNO with no nitrogen application; and BDN4 with an application of 240 kg of nitrogen per ha (as ammonium sulfate) made just before planting. Before planting there were 7 and 21 g m⁻² in the upper 30 cm of soil, in BDNO and BDN4, respectively. Irrigation was applied by sprinklers. There were four irrigations on 1 May (50 mm), 26 June (80 mm), 20 July (100 mm) and 9 August (100 mm).

A series of four experiments, on four different farms, was conducted in 1984. In each experiment, an area of 18 by 200 m was left unfertilized with nitrogen, while the rest of the field was fertilized according to the usual practices in the area. Data from one of these experiments, at Hulda (in the coastal plain of Israel) are given here. Cotton was planted on 3 April and germinated on 12 April. The rows were spaced 97 cm, and there were on the average 10 plants per m of row. HULDNO did not receive any nitrogen, whereas HULDNI was fertilized with 150 kg of nitrogen per ha (as aqueous ammonia) just after planting. Before planting there were 8 g m⁻² of nitrate-nitrogen in the upper 30

cm of soil, in both treatments. Irrigation was applied by sprinklers. There were five irrigations on 29 May (50 mm), 21 June (60 mm), 1 July (50 mm), 16 July (50 mm) and 2 August (30 mm).

The plots were sampled regularly, once a week, to provide the validation data for the model. All the plants of 1 m samples, replicated six times in Bet-Dagan and five times in Hulda, were separated to the different organs, fruiting forms counted, and dry weight determined by oven-drying. After the beginning of boll opening, 2 m segments were marked in each replicate, and all the opened bolls harvested at weekly intervals. Cumulative data of open boll number and yield of seedcotton were thus determined.

The soil moisture content in these treatments throughout the season, as simulated by the model, is given in Fig. 43. The nitrogen regime had a slight effect on the rate of water use, because of less vegetative plants in the treatments with no nitrogen.

The results of the effect of nitrogen deficiency on photosynthesis are reflected in the simulated daily added dry matter (net carbon exchange rate), given in Fig. 44. The maximum rates were 22 and 24 g m⁻² day⁻¹ in BDN0 and BDN4, respectively, and 22 and 24 g m⁻² day⁻¹ in HULDNO and HULDNI, respectively.

The simulated plant height was very close to the observed data, although the model predicted in the high N treatments slightly lower rates of stem growth (Fig. 45). The effect of nitrogen stress on vegetative growth is also evident in the leaf and stem dry weight data (Figs. 46, 47). The model slightly underestimated leaf and stem dry weights in the high nitrogen treatments in both locations.

The number of open bolls was slightly affected by nitrogen deficiency (Fig. 48). The simulation results were very near the observed data in Bet-Dagan, but in Hulda the model overestimated the number of bolls. The observed number of open bolls were 77, 97, 71 and 87 per m², whereas the simulated numbers were 72, 83, 99, and 128 in BDN0, BDN4, HULDNO and HULDNI, respectively.

The dry weight produced in the bolls of the plants was affected by nitrogen deficiency in Bet-Dagan more than in Hulda (Fig. 49), and this was simulated quite accurately by the model, although overestimated in many cases. These are the total weights of the bolls (including the burs).

The yield of seedcotton was slightly underestimated in Bet-Dagan, but it was overestimated by the model in Hulda (Fig. 50). The observed yields of seedcotton were 483, 702, 386 and 502 g m⁻², whereas the simulated yields were 448, 549, 462, and 526 in BDN0, BDN4, HULDNO and HULDNI, respectively. It seems that some environmental effects, such as insect damage, that were not simulated in the model, caused the final yield to be less than the potential yield in Hulda.

Figure 43. The simulated soil moisture content (per cent v/v, average 0-90 cm) throughout the season in two nitrogen treatments, Bet-Dagan and Hulda 1984.

Figure 44. The simulated daily added dry weight, g m⁻² day⁻¹, throughout the season in two nitrogen treatments, Bet-Dagan and Hulda 1984.

Figure 45. The simulated (____) and observed (+) plant height, cm, throughout the season in two nitrogen treatments, Bet-Dagan and Hulda 1984.

Figure 46. The simulated (____) and observed (+) leaf dry weight, g m⁻², throughout the season in two nitrogen treatments, Bet-Dagan and Hulda 1984.

Figure 47. The simulated (____) and observed (+) stem dry weight, g m⁻², throughout the season in two nitrogen treatments, Bet-Dagan and Hulda 1984.

Figure 48. The simulated (____) and observed (+) number of open bolls, per m², throughout the season in two nitrogen treatments, Bet-Dagan and Hulda 1984.

Figure 49. The simulated (____) and observed (+) total boll dry weight, g m⁻², throughout the season in two nitrogen treatments, Bet-Dagan and Hulda 1984.

Figure 50. The simulated (____) and observed (+) cumulative weight of seedcotton in the open bolls, g m⁻², throughout the season in two nitrogen treatments, Bet-Dagan and Hulda 1984.

An analysis of the simulated stress factors throughout the season may highlight some processes affected by the nitrogen regime. Carbohydrate stress (Figs. 51, 52) appeared earlier in the well fertilized treatments than in the nitrogen deficient ones, and also lasted for a slightly longer period. The reason for this phenomenon is that nitrogen stress, similarly to moisture stress, affects vegetative growth rates more severely than photosynthesis.

The moisture stress factor (HFAC) is presented in Figs. 53, 54. There was a less severe moisture stress in the nitrogen deficient treatments, probably because they had a smaller leaf area and therefore transpired less (see also Fig. 43).

The nitrogen stress factor (Figs. 55, 56) indicated, as might be expected, a less severe nitrogen stress in the fertilized treatments. However, a severe stress developed during boll development even in the fertilized plots. This appeared earlier in Hulda than in Bet-Dagan. This phenomenon may be explained by the very large sink for nitrogen which is created mainly by the developing seeds. This sink is much larger than the rate of nitrogen uptake from the soil. The maximum possible uptake rate of nitrogen by cotton plants was found to be not more than 0.5 g m^{-2} (Marani and Aharonov, 1964; Halevy et al., 1987). Some time after the seeds start growing, the nitrogen reserves in the vegetative organs are depleted, and a nitrogen stress develops. After the last irrigation, when soil water is depleted, nitrogen uptake is reduced and the nitrogen stress becomes more severe.

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Figure 51. The simulated carbohydrate stress factor (F) throughout the season in two nitrogen treatments, Bet-Dagan 1984.

Figure 52. The simulated carbohydrate stress factor (F) throughout the season in two nitrogen treatments, Hulda 1984.

Figure 53. The simulated moisture stress factor (HFAC) throughout the season in two nitrogen treatments, Bet-Dagan 1984.

Figure 54. The simulated moisture stress factor (HFAC) throughout the season in two nitrogen treatments, Hulda 1984.

Figure 55. The simulated nitrogen stress factor (STRESN) throughout the season in two nitrogen treatments, Bet-Dagan 1984.

Figure 56. The simulated nitrogen stress factor (STRESN) throughout the season in two nitrogen treatments, Hulda 1984.

Evaluation of research achievements.

(a) Scientific.

- The effects of moisture stress on photosynthesis, dry matter allocation and yield formation in cotton have been evaluated.

- The necessary modifications of existing process-oriented cotton simulation models, in order to enable them to simulate water and nitrogen management inputs, have been defined and recoded.

- The effects of carbohydrate, moisture and nitrogen stresses on cotton fruiting and yield have been evaluated.

(b) Agricultural and economical.

- The COTMOD model can now be used by farmers and extension workers to evaluate different irrigation and nitrogen practices, to predict the results of changing such practices, and thus help decision making by farm managers.

Description of cooperation.

All research activities have been jointly planned, and their implementation in both countries has been coordinated. The results have been jointly evaluated and discussed, and the report has been jointly written. Visits have been made by Dr. A. Marani to the U.S.A., and by Dr. D.N. Baker to Israel to achieve this cooperation.

Appendix.

The model COTMOD will now be available for research and education purposes. Documentation and instructions for use are too bulky to be included in this report, but they may be obtainable on diskettes from A. Marani or from BARD office upon request.

The model is written in FORTRAN77, and can be run on any PC or AT compatible computer equipped with an 8077 or 80287 mathematical co-processor. Two 5 1/4 360K diskettes contain the following files:

(1) Programs for execution:

COTMOD.EXE	The model.
WTHRE.EXE	A program for creating climate data files.
SOILINP.EXE	A program for creating a soil data file.
COTINP.EXE	A program for creating the main input file.
OUTCOT1.EXE	A program for preparing the output or validation files for input by Lotus.
GRMACRO.WK1	A Lotus macro for preparing graphs from the output of the model.
GRVMACRO.WK1	A Lotus macro for preparing graphs from the output of the model and validation data.
PARAM.INP	Parameter file for Acala SJ2.

(2) Source and documentation :

COTPC1.FOR to COTPC10.FOR and COTMOD.INC	files with the source code for the model (FORTRAN77).
COTMOD.CMT	Comments to the program.
COTMOD.DIC	Dictionary of variables.
COTMOD.PAR	Definition of the parameters in PARAM.INP.
COTMOD.INP	Definition of the input files required for running the model.
VALFILE	Definition of the format of the file with the validation data to be used by OUTCOT1.

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