IRRIGATION EFFICIENCY AND CONTROLLED ROOT-ZONE WETTING IN DEEP SANDS

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ABSTRACT

Ten field water management experiments were conducted with corn, soybeans and peanuts during 1977, 1978, and 1979 on well-drained sandy soils at Gainesville and Live Oak. Irrigation scheduling treatments varied from one to eight per experiment.

A simple computer simulation model provided an estimate of seasonal evapotranspiration (ET), drainage, and change in soil storage. These data and calculated water use efficiencies served as a test of the effectiveness of various irrigation scheduling strategies, and provided information on crop response to water stress.

Yields increased linearly with estimated ET. Regression of corn yields on estimated ET gave the following 3-year average results for Gainesville and Live Oak, respectively:

$$Y = 661X - 22{,}895 \quad (R^2 = 0.90)$$

$$Y = 471X - 12{,}964 \quad (R^2 = 0.73)$$

where Y is grain yield, kg/ha-cm, and X is ET, cm.

These findings were interpreted to mean that the most efficient crop production use of water is obtained when water is supplied to meet the full easonal ET needs imposed by the atmosphere. In addition, a strategy of light, frequent irrigation of only the top 30 cm of sandy soils will produce high yields with minimum deep seepage loss of water and nutrients.

CHAPTER I. INTRODUCTION

Although the Florida climate is characterized by relatively high rainfall, two factors create a need for irrigation of crops for efficient production: (1) inconsistent and often unfavorable rainfall distribution patterns, and (2) the predominance of sandy soils with low water and plant nutrient storage capacities. The annual rainfall distribution is highly nonuniform with approximately 80-90% of the total occurring during the summer. Even during years with average rainfall distribution, irrigation is commonly required during spring and late autumn. Reasonably successful irrigation and other management practices have evolved over the years from farmer experience and scientific findings; nevertheless, recent population growth has accelerated the demand on our large but finite water resource, and have made it necessary that all users--agriculture, municipalities, and industry--develop more efficient water-use systems. Favorable factors in the Florida climate such as long growing season, warm temperatures, and high total rainfall justify the continued development of more efficient irrigation practices through application of present knowledge and the discovery of new knowledge through research.

In fact, the need for new information exists for most of the humid southeastern United States where there has been a major increase in irrigated agriculture during the past five years (Bruce et al., 1980). In particular, it has been found that crop production practices associated with irrigated agriculture in arid regions are not applicable to humid regions without considerable modification and adaptation. Humid region agriculture depends mostly upon rainfall for crop production, and irrigation is needed during relatively short but numerous droughts. Consequently, when uneven rainfall distribution patterns are coupled with soils which have characteristically restricted root zones and thus limited water storage capacities, there is created a major problem in the scheduling of irrigation. Timing, application intensity, method of application, and amounts of water applied affect the fraction of added water used by the plant, the leaching losses of pesticides and fertilizers, and in many cases the aeration condition in the root zone. These problems have not yet received research attention commensurate with the high return potential for solution to them. Of considerable current interest and research attention, is a water management system based on high-frequency irrigation with shallow wetting of the root zone (Rawlings and Raats, 1979). In this system, small quantities of water are applied frequently to meet crop needs in a manner such that a closely following rainfall replenishes water depleted from deeper portions of the root zone without excessive loss to deep seepage.

In Florida, most well-drained sandy soils temporarily store less than one inch of water per foot of soil depth, so that the growing crop can develop water stress within 3 to 7 days (depending on rooting depth) following a rainfall or irrigation. When the soil deficit is replenished with irrigation , the possibility always exists that unexpected rainfall will displace the infiltrated irrigation water so that it will be lost from the root zone as deep seepage. The severity of deep seepage loss of irrigation water increases as the water retaining capacity of the soil decreases. Deep seepage is also more severe if the soil is relatively wet at the time irrigation water is applied. And for a given soil, deep seepage of water increases as depth of rooting decreases. In the final analysis, careful water management of crops in humid regions can be used to minimize deep seepage loss of water applied as irrigation. It is neither desirable or practical to completely eliminate deep seepage in agricultural soils. However, farmers should attempt to minimize the deep seepage loss of irrigation water. Farmers can minimize such losses by careful irrigation scheduling based on crop growth stage and rooting depth, soil water status and water retaining capacity, evaporative demand of the atmosphere, and rainfall forecasts.

The objectives of the current study were:

1. To test the hypothesis that, for humid regions characterized by short duration droughts, improved water-use efficiency can be attained by replenishing a part rather than the full soil water deficit in the root zone without adverse effects on crop yield.

2. To determine, under field conditions on deep sands, the influence of sprinkler irrigation management on the partition of total water input between evapotranspiration and deep seepage, and on the water-use efficiency of corn, soybeans, and peanuts.

3. To develop and validate mathematical models incorporating total water input amounts and distribution patterns and soil physical properties for the purpose of describing water infiltration, redistribution, deep seepage and uptake by plants.

4. To develop, from the field data and the mathematical models, efficient water management systems which can be implemented readily by growers and utilized by water planners and policy-makers.

CHAPTER II. FIELD EXPERIMENTS, GAINESVILLE

Ten water management field experiments were conducted during the growing seasons of 1977,'78, and'79. Crops included corn, peanuts and soybeans. Three soil series were involved: Lake, Arredondo, and Kendrick fine sands. Lake fine sand is a member of the hyperthermic, coated family of Typic Quartzipsamments. In the test sites, this soil has sandy A and B horizons that extend to a depth of 210 cm or more with a sandy clay B2t horizon underneath. Arredondo and Kendrick fine sands are members of the loamy, siliceous, hyperthermic families of Grossarenic and Arenic Paleudults, respectively. In the experimental area, Arredondo fine sand is similar to the Lake fine sand except that a sandy clay loam B2t horizon begins at depths ranging from 120 to 200 cm. The Kendrick fine sand profile consists of fine sand material over a fine sandy loam B2t horizon which begins at depths of 100 to 150 cm.

Irrigation was carried out by three overhead sprinkler systems: (1) hand-operated fan spray nozzle on garden hose, (2) low pressure "Micro-jet" sprinklers, and (3) impact sprinklers. Water management treatment variables included timing of irrigation events and quantities per event. Irrigation intensities were 2.55 cm per hour or less so that no surface runoff occurred.

Other soil and crop management practices were approximately equal to or better than those currently recommended for farmers. The soil water status was monitored periodically with tensiometer readings of water suction and neutron and gravimetric measurements of volumetric water content. Rainfall distribution was nonuniform with time over the three years of the study. Crop damaging droughts of varying durations occurred during each year.

Crop response to water management was determined as yield of marketable grain. Response to irrigation was analyzed using a simple water balance model (Rao et al. 1976, 1981) which incorporates estimated daily evapotranspiration (ET) rates (from monthly averages), measured soil water characteristics (field capacity, permanent wilting percentage, and water redistribution time), estimated root depth with time, and a water extraction rate which equals the ET rate until 80% of the available water has been depleted. At that point, the extraction rate was decreased linearly with decreasing available water to zero at the wilting point.

Water balance simulations used in the Gainesville and Live Oak experiments were based on potential ET rates calculated for Jacksonville (Table 1). These ET rates were calculated using the Penman method from longterm weather records and from handbook tables of extraterrestial radiation. In most of the simulations, a 10% downward adjustment of the ET rate was made for an incomplete crop canopy (0-25 days) during the early part of the season, and a 10% upward adjustment was made for later in the season (after 40 days). The latter adjustment was made in consideration of the non-average weather conditions associated with prolonged droughts.

Table 1. Calculated daily potential evapotranspiration rates by months for three locations.

	Potential evapotranspiration		
	Jacksonville	Tampa	Miami
	cm/day		
January	0.112	0.152	0.191
February	0.163	0.206	0.252
March	0.234	0.277	0.323
April	0.343	0.371	0.391
May	0.411	0.432	0.424
June	0.422	0.432	0.422
July	0.429	0.414	0.432
August	0.391	0.399	0.417
September	0.312	0.348	0.356
October	0.226	0.279	0.287
November	0.150	0.191	0.216
December	0.104	0.142	0.180
Annual Total, Jan-Dec (cm)	100.5	111.0	118.4

A. Corn, 1977, Experiment I

Experiment I was designed to test the yield response of three corn hybrids under irrigation to subsoiling and to multiple sidedressings at a fixed total nitrogen level.

1. Methods

This experiment was located on Kendrick fine sand soil and a solid set overhead sprinkler irrigation system delivered water at the rate of 0.51 cm/hour. All plots received irrigation averaging 1.9 cm per application when the soil water suction at 15 cm depth reached 500 cm. Treatments were arranged in a factorial statistical design of three corn hybrids, two soil conditions, and four nitrogen application schemes.

The 5.5 x 7.6 m plots were arranged in a randomized block with four replications (Table 2). Prior to planting, subsoiling was performed with chisel plow 30 cm on center and to a depth of 35 cm. Corn was planted by hand in 45 cm rows with 30 cm spacing (71,760 plants/ha) on March 29, 1977 and harvested July 27 to Aug. 7 (soon after maturity).

Values of various parameters used in the water balance simulation are given in the Appendix Table. The time dependence of root growth and water redistribution are shown in Figures 1 and 2.

2. Results and Discussion

The rainfall distribution pattern shown in Figure 3 indicates that the corn growing season of 1977 was extremely deficient in water. Only 12.7 cm of rainfall occurred, and 42.2 cm of water was used as irrigation (Table 3). The simulated and measured seasonal water balance data are given in Table 4. Actual ET and water drainage (deep seepage) losses may be higher or lower than these estimates. Nevertheless, the simulated data provide useful information for evaluating results and planning further studies.

Table 2. Nitrogen application treatments (sub-subplots) for corn Experiment I, Gainesville, 1977.[1/]

Number of applications	Date	Nitrogen[2/] kg/ha
1	May 6	224
2	April 29	112
	May 13	112
3	April 29	56
	May 13	112
	May 27	56
4	April 22	56
	May 6	56
	May 20	56
	June 6	56

[1/] Main plot treatments: Funk 4810, Pioneer 3369A, and McNair 508 corn hybrids; subplot treatments: non-subsoiled and subsoiled.

[2/] As NH_4NO_3, additional nitrogen applied at planting as part of mixed fertilizer (45-39-149-45 kg/ha N-P-K-Mg).

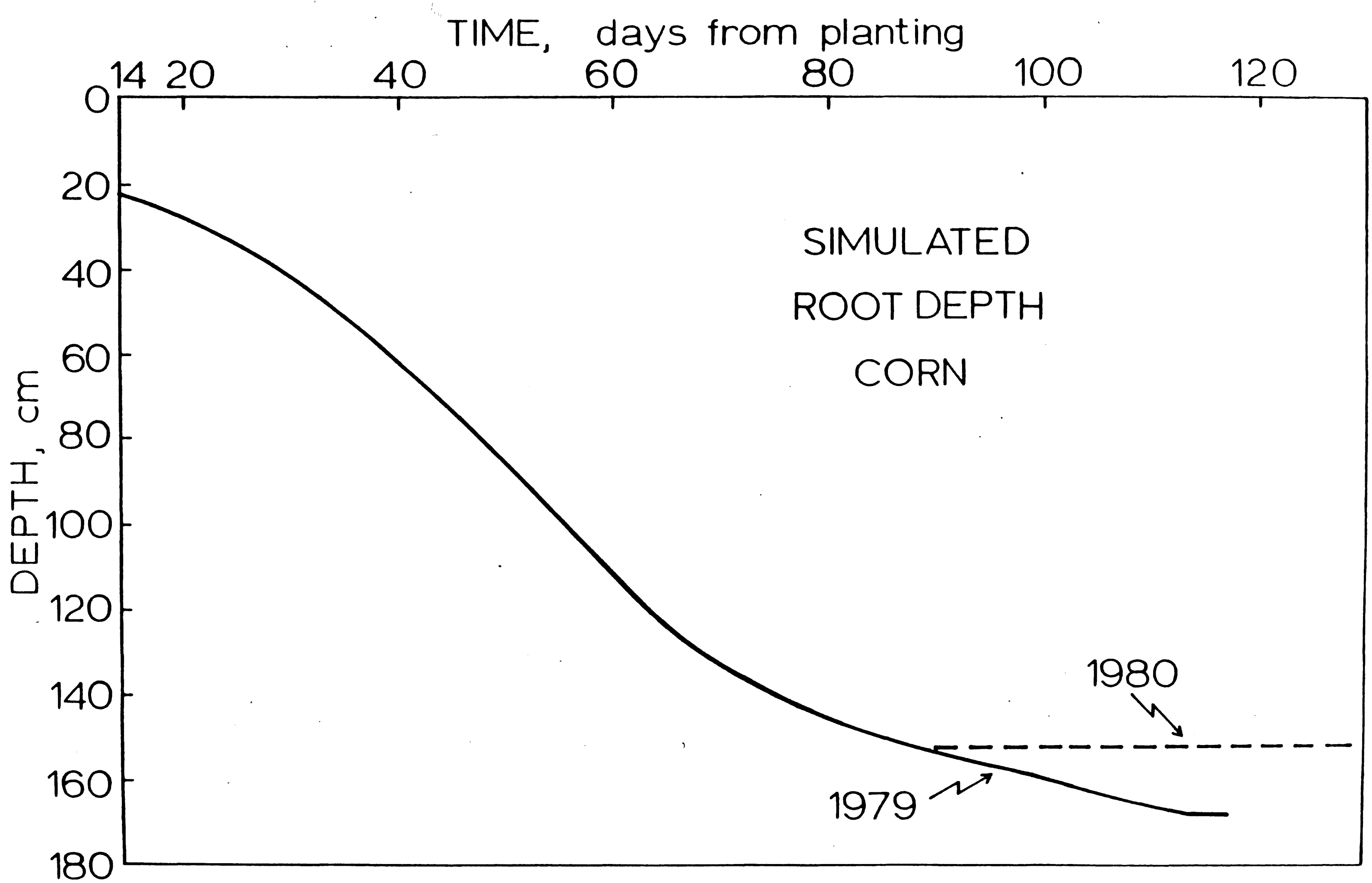

Figure 1. Estimated depth of corn root zone with time after planting.

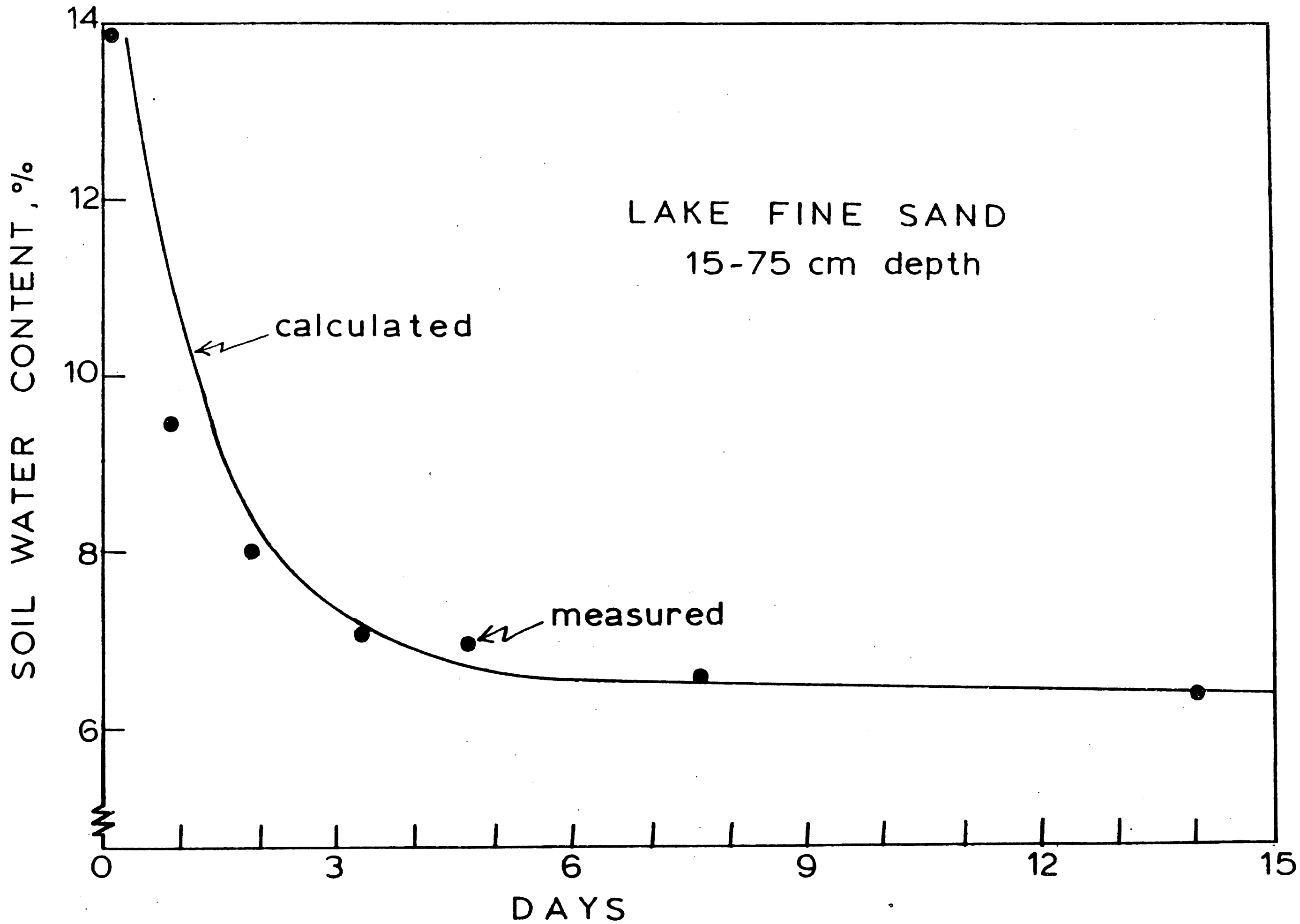

Figure 2. Water redistribution time in a Lake fine sand.

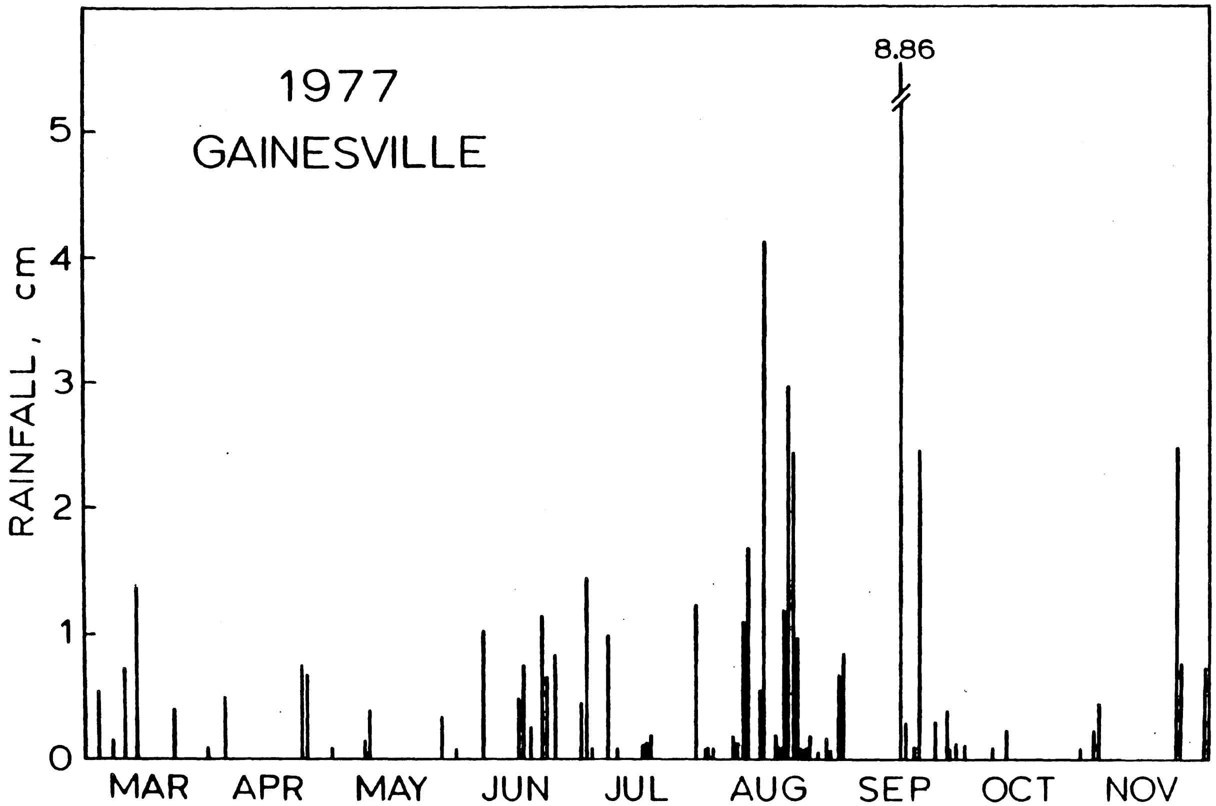

Figure 3. Rainfall distribution at Gainesville, 1977.

Table 3. Schedule for water application to corn, Gainesville, 1977, Experiment I.

Date	Irrigation amount[1/]	Date	Irrigation amount
	cm		cm
May 1	1.07	June 9	2.03
4	1.52	11	2.54
8	1.52	14	2.29
12	1.52	20	2.11
15	1.78	27	2.79
18	1.96	30	2.36
21	2.18	July 6	1.78
25	2.54	12	2.16
29	1.91	15	1.78
June 2	0.64	22	1.78
4	2.16	26	1.78
	Total		42.20

[1/] Rainfall, 12.7 cm.

Table 4. Corn grain yields and estimated water balances for Experiments I and II, Gainesville 1977.

Treatment[1/]	ET	Irrig.[2/]	Profile water depletion[3/]	Drainage	Grain yield
	cm				kg/ha
			Experiment I		
Irrigated	48.21	42.20	2.13	9.03	8911
			Experiment II		
No irrigation (1)	20.85	-	8.02	-	282 b
Irrigated (2)	47.33	47.59	5.44	18.55	7991 a
Irrigated (3)	47.64	51.12	2.24	18.57	9000 a

[1/] See text for details.

[2/] Rainfall amounts of 12.92 and 12.85 cm occurred for Experiments I and II, respectively.

[3/] Net seasonal loss from the soil profile.

Grain yields (Table 5) for the three hybrids were in the range expected for corn growing in sandy soils under good water management. The Pioneer hybrid gave significantly higher grain yields than did the Funk and McNair hybrids. Subsoiling generally improves root density distribution in this sandy soil by mechanically disrupting soil zones which have become compacted due to tillage; however, this improvement would not be expected to provide increased corn yield during dry years (1977) when irrigation is used extensively.

Three and four split applications of N gave higher corn yields than a single application. This result could be attributed to a larger volatilization loss from the single application.

Table 5. Yield of corn grain as affected by hybrid, subsoiling, and number of nitrogen sidedressings.

Treatment	Grain yield[1/] kg/ha
Hybrid:	
Funk 4810	8671 b
McNair 508	8770 b
Pioneer 3369A	9293 a
Soil condition:	
Non-subsoiled	8857 a
Subsoiled	8965 a
Nitrogen sidedressings:[2/]	
1	8501 b
2	8733 ab
3	9283 a
4	9128 a

[1/] Yield values followed by the same letter are not different at the 0.05 level.

[2/] See Table 2 for rates at each application.

B. Corn, 1977, Experiment II

The purpose of this experiment was to determine the response of corn to irrigation regimes having small quantities of water applied frequently (small frequent applications) versus medium quantities applied less frequently (medium infrequent applications).

1. Methods

Replicated (4 each) treatments were: (1) no irrigation, (2) irrigation frequently in small amounts, and (3) irrigation less frequently in medium amounts. Plots 7 x 7 m were located on Lake fine sand. During irrigation events overhead sprinklers delivered water at the rate of 1.7 cm/hr. Irrigation times and amount are shown in Table 6 and rainfall in Figure 3. Water was applied when the soil water suction at 15 cm depth reached approximately 200 cm. DeKalb XL-80 corn hybrid was planted in 45 cm rows at a population of 95,000 plants/ha on March 24, 1977. Corn reached maturity on July 27 and was harvested on August 15. Simulated and measured water data were obtained in the same way as for Experiment I. See the Appendix Table for input data.

Table 6. Schedule of water application to corn, Gainesville, 1977, Experiment II.

Date	Irrigation amount[1/] Treat. 2 cm	Irrigation amount[1/] Treat. 3 cm	Date	Irrigation amount Treat. 2 cm	Irrigation amount Treat. 3 cm
May 2	--	1.70	June 12	3.68	--
3	1.70	--	13	--	3.60
8	1.30	1.70	15	4.80	1.70
14	1.70	2.55	20	--	4.38
18	3.12	--	27	3.82	--
19	--	3.40	29	--	--
22	3.40	--	30	3.68	--
23	--	--	July 6	--	4.38
25	3.40	--	10	5.38	--
26	--	4.25	15	--	4.24
June 1	3.83	--	17	4.24	--
3	--	4.39	24	--	3.82
5	3.54	--			
8	--	3.40	Total	47.59	51.12

[1/] Rainfall, 12.85 cm.

2. Results and Discussion

Seasonal rainfall for Experiment II was approximately the same as for Experiment I (Figure 3). Irrigation amounts and distribution patterns for treatment 2 and 3 did not differ as much as anticipated because of the extremely dry growing season (Table 6). The amounts may be overestimated as much as 10%.

Water balance and grain yield data are given in Table 4 along with data from Experiment I. Yields from the irrigation treatments in both experiments are comparable even though the calculated amount of water applied was larger in Experiment II. The simulation model indicated excessive irrigation quantities in the latter experiment with a consequent drainage loss of water from the root zone. It is possible that the actual ET was greater than calculated since the plots were small enough for a marked oasis effect and the climatic conditions during the long drought were far from the average conditions assumed in the calculation of expected ET (Table 1).

C. Peanuts, 1977

The objective of this study was to determine the yield response of peanuts on a deep, well-drained sandy soil to four irrigation treatments.

1. Methods

Small field plots 5.5 x 5.5 m located on Lake fine sand, were planted with 'Florunner' peanuts in 91 cm rows on April 22, 1977. Four treatments were replicated four times: (1) no irrigation, (2) frequent irrigation, small amount, (3) infrequent irrigation, medium amount, and (4) infrequent irrigation, small amount. Water was applied by hand with a calibrated fan spray nozzle on a garden hose. Repeated passes along each row provided a rate of application of nearly 42 cm/hr. Irrigation was scheduled for treatments 2 and 3 when soil water suction at 15 cm reached 500 cm or more. In treatment 4, plant water stress symptoms were allowed to develop before irrigation was scheduled. Simulated water balance data were obtained as before (Appendix Table).

Soil water content and suction were monitored with a neutron meter and tensiometers, respectively. Data are in a thesis by Nafis (1979).

2. Results and Discussion

Rainfall and irrigation distribution data are shown in Figures 3 and 4. The first three irrigations were also applied initially to the

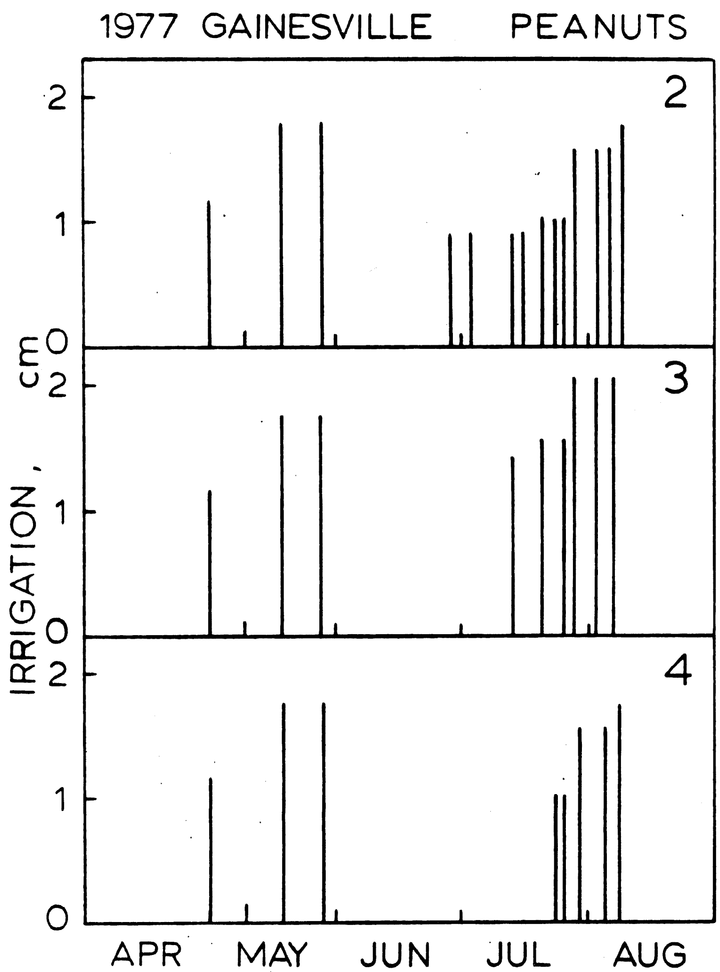

Figure 4. Irrigation schedules for three water management treatments on peanuts, Gainesville, 1977.

no-irrigation treatment in order to get the plants up and established during a very dry period. Irrigation input, simulated ET, drainage from the root zone, and pod yields are given in Table 7. Roots were assumed to increase in depths linearly with time from 4 cm on day 1 to a maximum of 200 cm by day 90. The simulated ET values may be lower than actual since there was additional apparent drainage water under irrigation. Nevertheless, most of the added irrigation was allocated to ET and the measured pod yields increased linearly with the calculated values of ET (Figure 5).

Table 7. Water balance and peanut yields, Gainesville, 1977.

Treatment	ET	Irrig.[1/]	Profile water depletion[2/]	Drainage	Yield
	cm				kg/ha
Non-irrigated	36.95	4.8	2.45	0.53	2261 c
Irrig., frequent	46.91	12.9	1.88	2.89	3817 a
Irrig., infrequent	44.76	10.4	1.96	2.67	3622 a
Irrig., plant stress	41.78	6.7	1.92	1.89	2999 b

[1/] Rainfall, 30.2 cm.

[2/] Net seasonal loss from the soil profile.

In 1975 studies, peanut pod yields were 4500 kg/ha when the amount of seasonal water depletion was 57 cm, and irrigation of 8 cm did not cause a yield increase (Varnell, et al. 1976). However, when water input was decreased by covering the plot during midseason rainfalls the yields were decreased to 3900 kg/ha with a water depletion of 48 cm. The latter yield is similar to that predicted from the 1977 results in Figure 5 if we assume that water depletion is a fair estimate of evapotranspiration.

The peanut plant is often considered to be drought tolerant due to its characteristic deep rooting and reinitiation of blooming and fruiting after drought stress. Nevertheless, these data indicate that peanuts do respond to water management and that yields can be severely reduced by an overall seasonal water deficit.

D. Corn, 1978

This study involved two crops - corn and peanuts - grown in adjacent plots on the same Lake fine sand site as the 1977 peanut experiment.

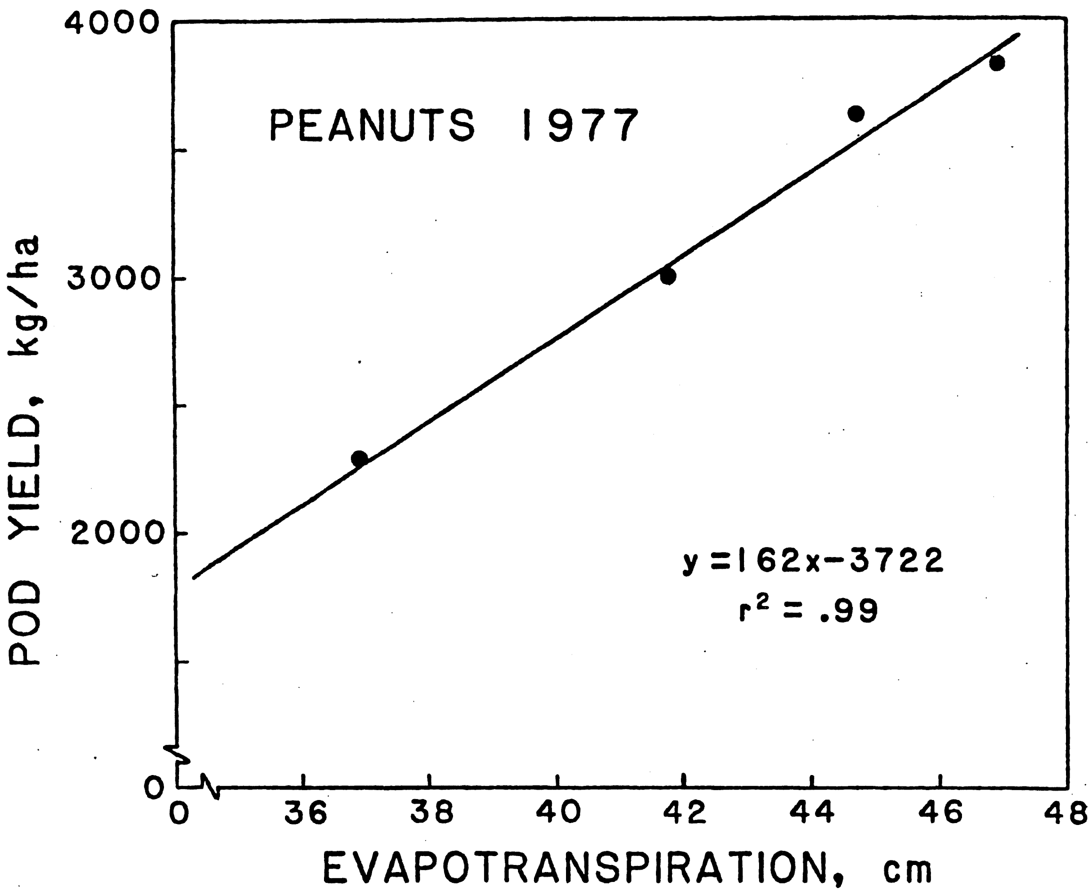

Figure 5. The relationship of peanut pod yield to estimated evapotranspiration, Gainesville, 1977.

The objective was to determine the effect of irrigation strategy (frequency and quantity) on periodic water depletion rates and on irrigation water-use efficiency.

1. Methods

De Kalb XL-80 field corn was planted in plots 5.54 m x 5.54 m on March 17, 1978. Plant spacing was 39.48 cm in north-south rows spaced at 45.72 cm and the plant population was 72,000 plants/ha.

Four treatments were assigned in a four-replicate, randomized block design: (1) no irrigation, (2) light, frequent irrigation - irrigate with just enough water to wet the soil to 30 cm depth when soil water suction at 15 cm was between 150 and 500 cm of water, (3) medium, infrequent irrigation - irrigate as in 2 except to 45 cm depth, and (4) light, infrequent irrigation same schedule and rate as 2 except irrigation frequency was decreased during periods of grain filling.

The irrigation system consisted of "Microjet" sprinklers fastened to black polyethylene tubing which was placed on the soil surface between rows. The system delivered 1.7 cm/hr at 25 PSI.

2. Results and Discussion

The seasonal rainfall and irrigation distributions in 1978 are shown in Fig. 6. The irrigation treatment numbers 1, 2, and 3 in the figure correspond to treatments 2, 3 and 4, respectively. Water balance and yield data are given in Table 8. Yields were lower than obtained in either of the 1977 experiments (Table 4) even though more total water input occurred in 1978. The predicted drainage shows that the input water could not be used as efficiently in meeting ET demand as apparently was the case on a dif-ferent soil type and under different water input conditions in 1977.

The simulated data (ET, net profile depletion, and water drainage), though unverified by direct means in the experiment, reveal interesting facts. The particular rainfall distribution pattern resulted in deep seepage losses of water from irrigated treatments. The magnitude of the losses was influenced by the evapotranspiration model used. Higher actual ET values would be balanced by less deep seepage loss and/or more net depletion of the soil profile. However, the latter quantity is simply the difference between the storage at the beginning and end of the season and does not indicate the level of depletion which may have occurred during the season. In the unirrigated treatment, rainfall and an adequately depleted profile must have occurred concurrently throughout the season in order to produce the low level of predicted outflow.

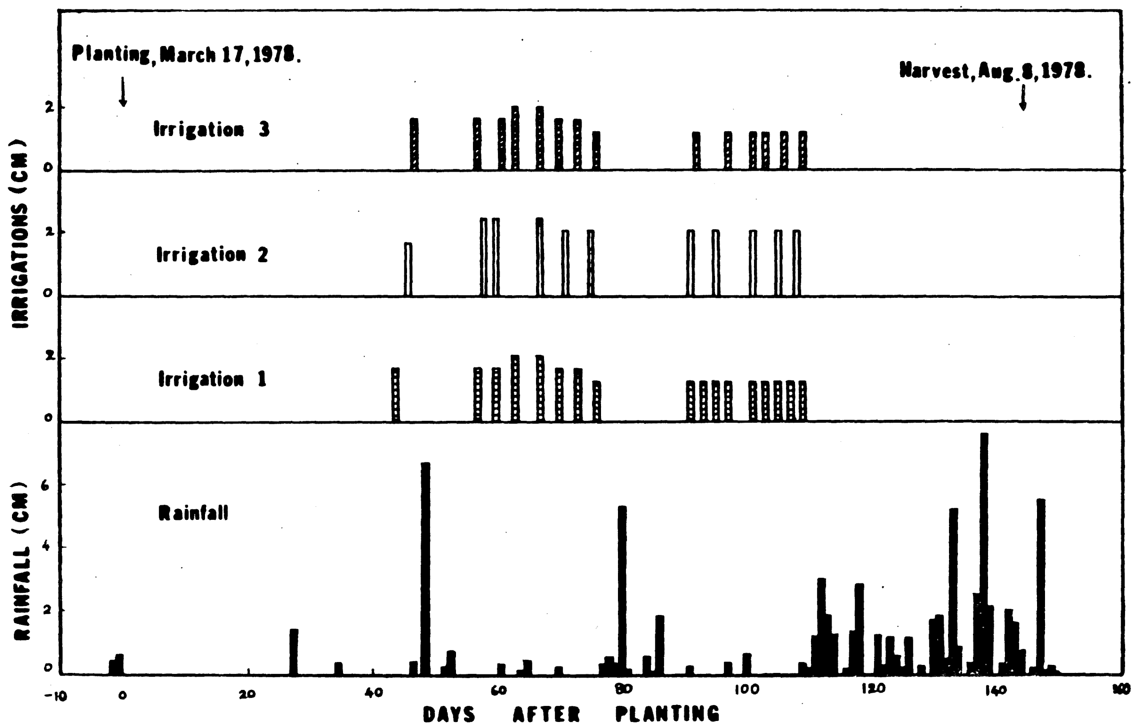

Figure 6. Rainfall distribution and irrigation schedules for three water management treatments on corn, Gainesville, 1978.

Nevertheless, without irrigation, the total water available to the corn crop over the season and during critical periods was less than that needed to produce grain yields which would offset the costs of production.

Table 8. Effect of water management on yields of corn and peanuts and simulated water balance, Gainesville, 1978.

Treatment[1/]	ET	Irrig.[2/]	Profile water depletion[3/]	Drainage	Yield[4/]
	- - -	- - -	cm	- - -	kg/ha
			Corn		
Non-irrigated (1)	35.77	--	1.37	1.80	2110 b
Irrigated (2)	44.92	25.46	0.44	17.19	7720 a
Irrigated (3)	44.36	24.23	0.47	16.55	7080 a
Irrigated (4)	44.04	21.65	0.50	14.31	7070 a
			Peanuts		
Non-irrigated (1)	44.03	--	8.72	26.40	3780 a
Irrigated (2)	50.68	15.44	1.75	28.32	4190 a
Irrigated (3)	48.64	13.29	2.43	28.78	4390 a

[1/] See text for details.

[2/] Rainfall, 36.2 cm on corn and 61.7 cm on peanuts.

[3/] Net seasonal loss from the soil profile.

[4/] Grain for corn and pods for peanuts.

From the standpoint of irrigation water-use efficiency in a humid climate with sandy soils, these data are not very encouraging. On the other hand, a non-irrigated crop production system would have been an economic disaster. The irrigation scheduling strategy was designed to minimize leaching losses s and at the same time minimize crop damage from drought. The degree of success actually achieved with the water management strategy used is not easy to measure, but a brief analysis of tensiometer and water content data is instructional.

It is evident from hydraulic head values during the dry period from 53 to 75 days (Fig. 7) that irrigation in treatment 2 was producing a net downward water flow below 45 cm depth. In contrast, the hydraulic head distribution with depth in the non-irrigated treatment (Fig. 8) showed a net flow gradient upward, reaching increasing depths with time

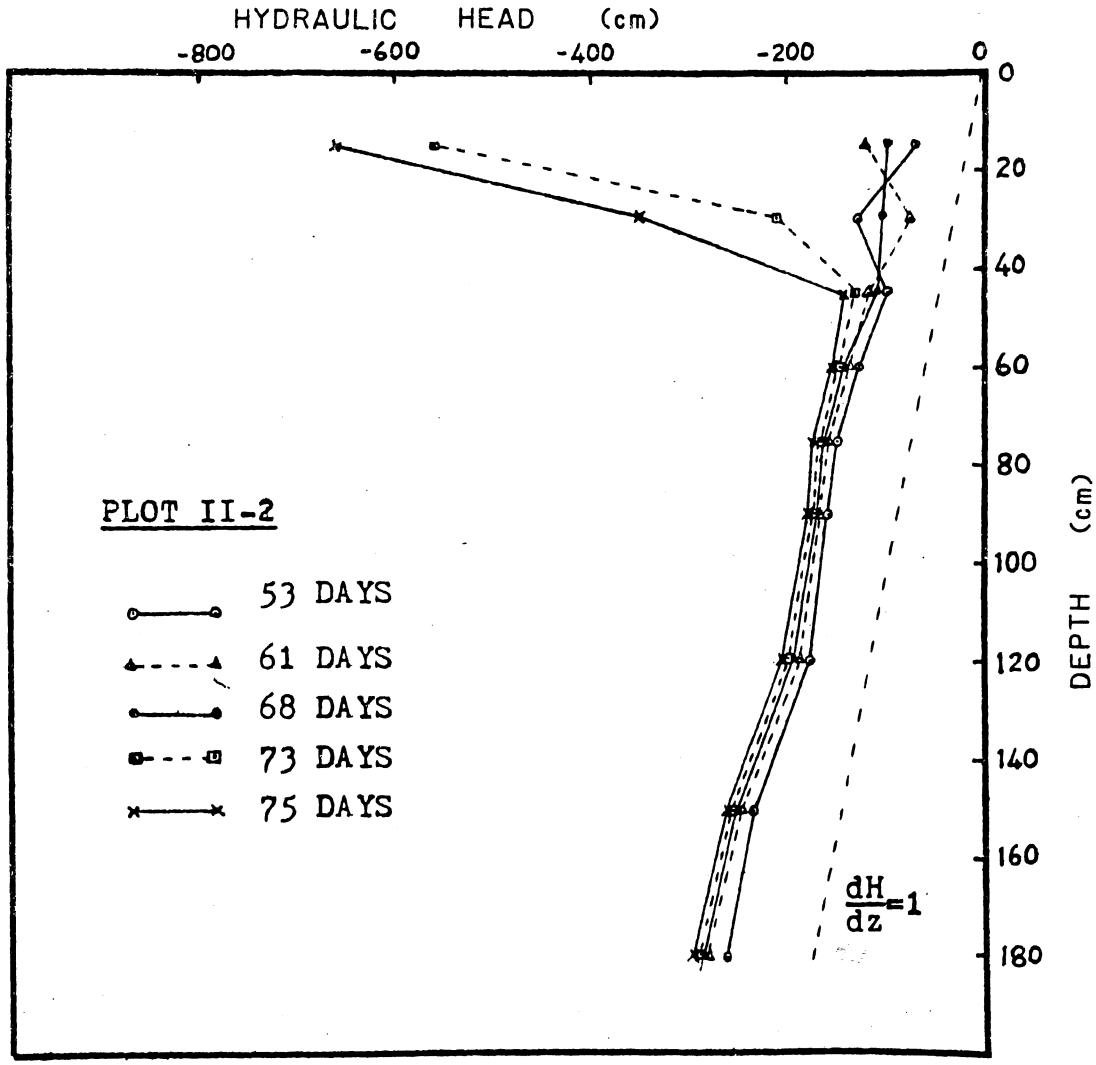

Figure 7. Hydraulic head distribution with soil depth under irrigated corn during a dry period 53 to 75 days after planting, Gainesville, 1978.

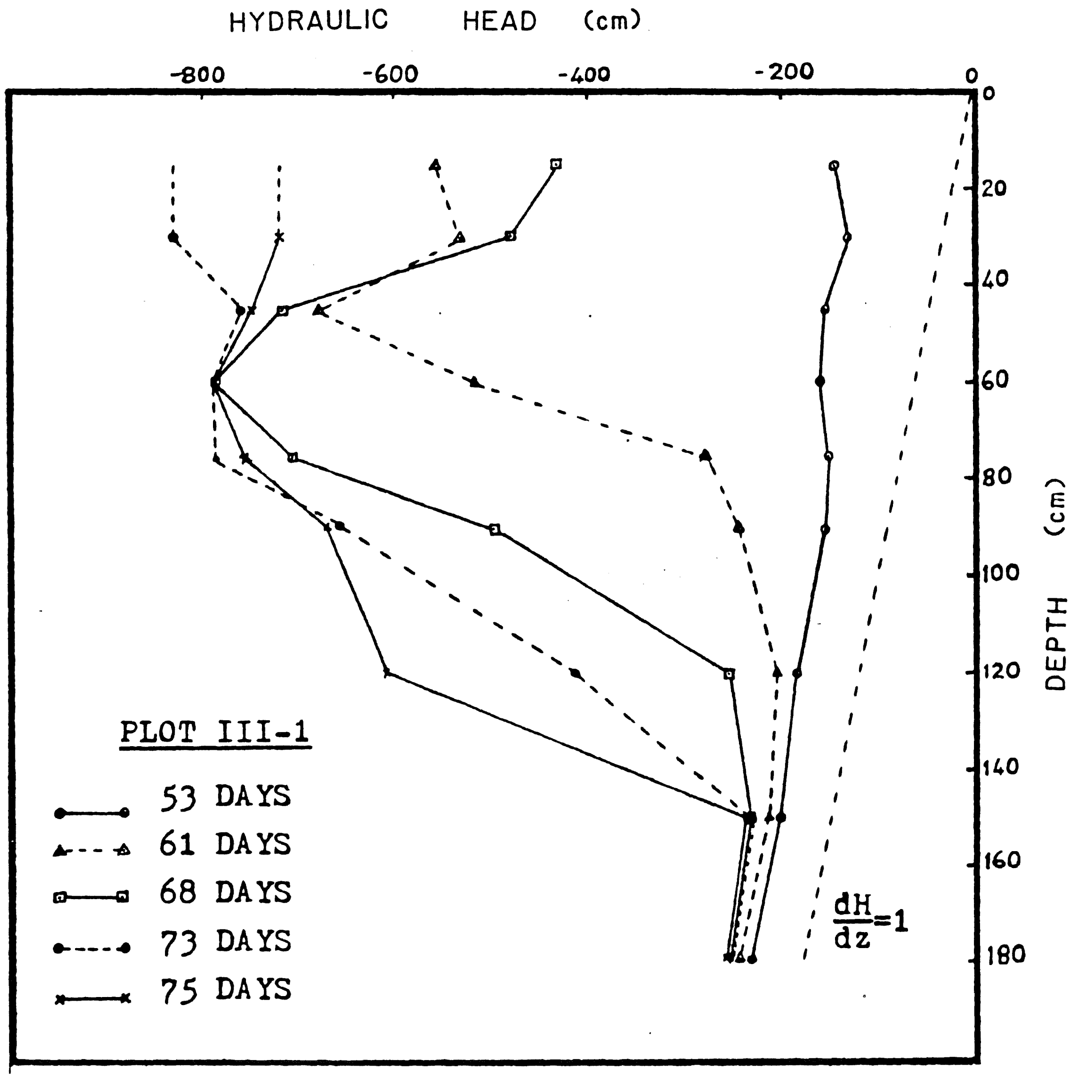

Figure 8. Hydraulic head distribution with soil depth under non-irrigated corn during a dry period 53 to 75 days after planting, Gainesville, 1978.

to 150 cm. Changes in the neutron measured water content distribution with depth and time for the non-irrigated treatment are shown in Fig. 9.

The water flux condition in the 150-180 cm zone throughout the season for the same two treatments is shown in Fig. 10. Since flow occurs from higher to lower hydraulic head values, the net flow direction was downward for nearly the whole season in treatment 2 (irrigated). In treatment 1 (non-irrigated) the soil dried out more than in treatment 2 and there was an 18-day period (112-120 days) when the net flow direction was upward. The water flux through the 150-180 cm zone could be calculated from the Darcy flow equation using the hydraulic head gradient and the water content dependent hydraulic conductivity.

Table 9. Effect of water management on periodic water depletion rates of corn and peanuts, Gainesville, 1978.

Days[1/]	Water depletion rate on treatments[2/]			
	1	2	3	4
	mm/day			
		Corn		
4-11	3.66	2.92	3.64	--
12-26	2.29	2.57	1.70	--
27-40	2.08	1.79	2.52	--
41-68	3.71	4.02	5.88	6.69
69-77	3.65	9.86	7.34	8.93
78-89	6.19	6.66	5.56	6.60
90-102	3.31	9.62	7.77	8.01
103-138	5.62	8.05	8.27	8.27
		Peanuts		
25-33	5.11	4.39	5.09	--
34-47	5.24	6.92	5.30	--
48-57	1.92	3.21	4.43	--
58-68	4.75	6.02	5.77	--
69-103	11.06	11.20	11.48	--
104-117	4.18	7.43	5.28	--
118-130	1.28	4.73	4.52	--

[1/] Days from planting: corn, March 17, 1978, and peanuts, May 10, 1978.

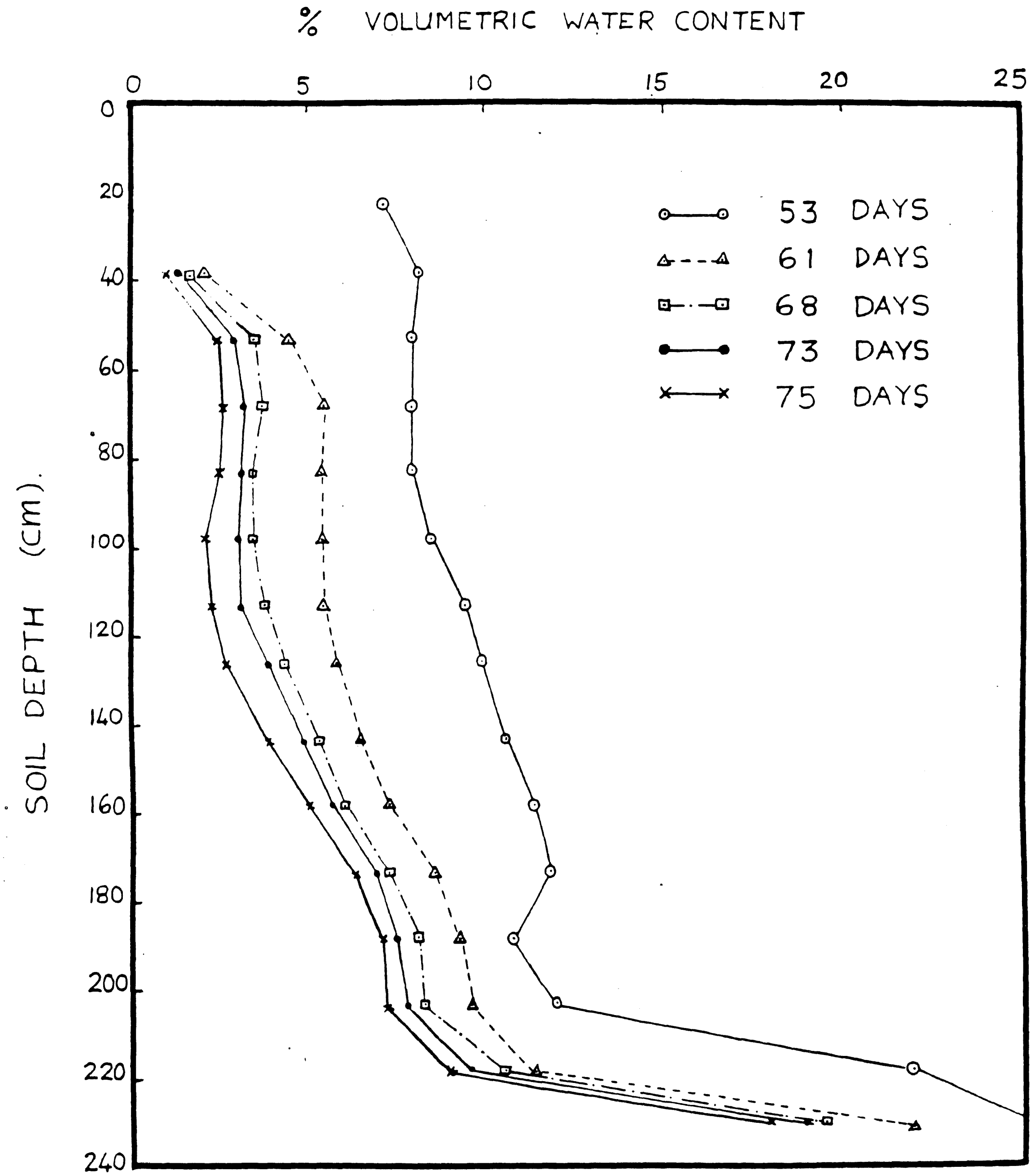

Figure 9. Soil water content distribution with depth under non-irrigated corn during a dry period 53 to 75 days after planting, Gainesville, 1978.

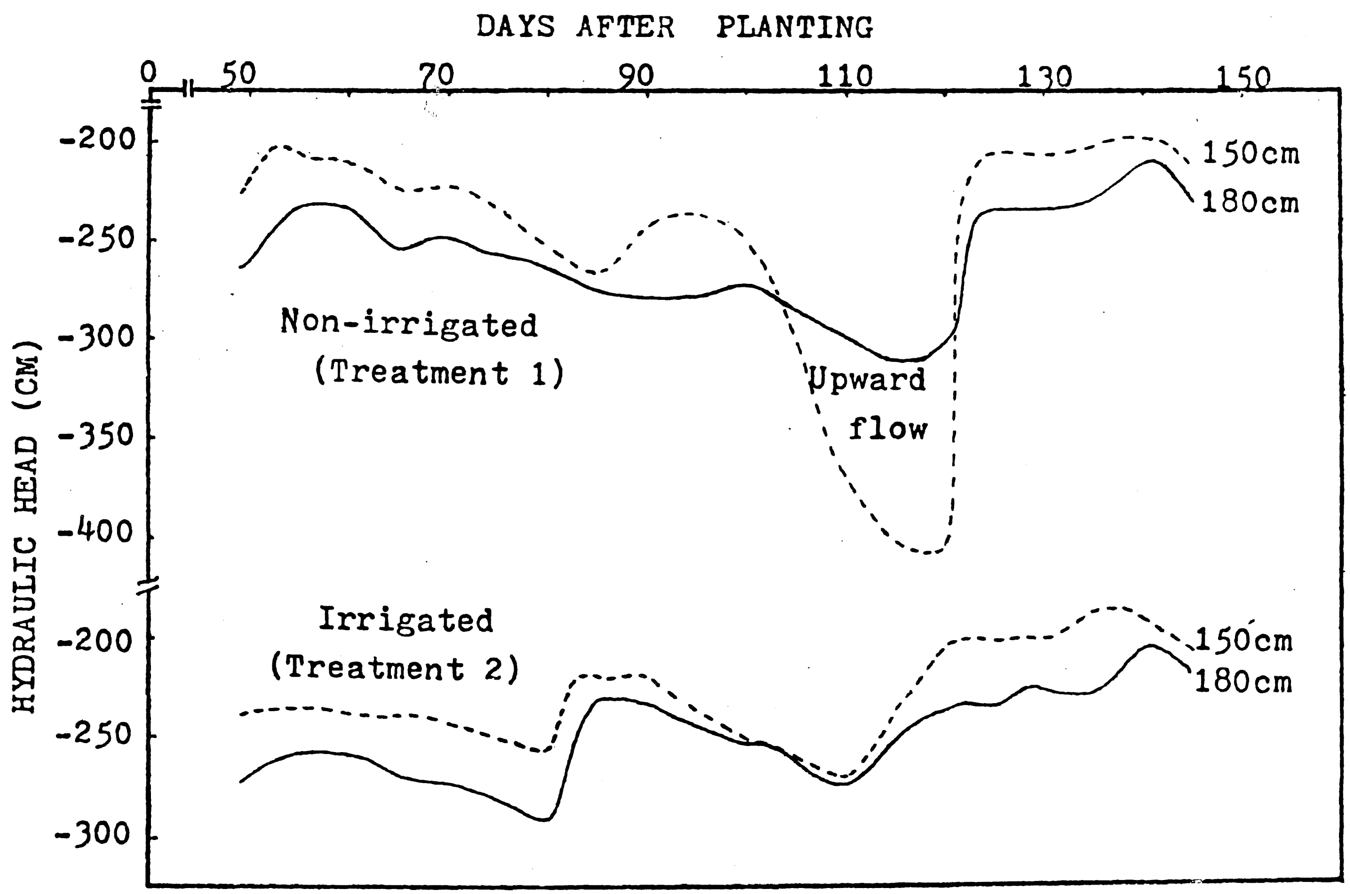

Figure 10. Change in hydraulic head at two depths with time as affected by irrigation management of corn, Gainesville, 1978.

Further information on the water balance resulting from the irrigation strategies in this experiment is provided by the measured daily water depletion data of Table 9. Water input data and periodic neutron measured soil water contents were used to make the calculations. It is likely that plants were under water stress during these periods when daily depletion was less than expected ET (Table 1). This condition existed in all treatments from days 12-40, and in treatment 1 for days 41-77 and 90-102. During the 12-40 day period, water depletion was low due to incomplete ground cover rather than plant water stress. Periods of potential drainage loss from the soil profile were indicated by water depletion rates in excess of the expected ET rates. This was the situation for all periods other than the potential drought stress periods indicated above. These depletion data, like the simulated water balance and tensiometer data do not reveal the true success of the irrigation strategy, because measured water input and soil water contents are subject to sampling error.

E. Peanuts, 1978

The objective of this experiment was to determine the effect of irrigation strategy on periodic water depletion rates and on irrigation water-use efficiency. The peanut experimental plots were located adjacent to the above corn plots which were a part of the overall study.

1. Methods

'Florunner' peanuts were planted in north-south rows on May 10, 1978. The distance between rows was 0.92 meter. The field plot design was a randomized block with three water management treatments and four replica-tions. Plot size was 6.15 m x 5.54 m. The three treatments were (1) control (rainfall only) (2) light, frequent irrigation - irrigate to 30 cm soil depth when soil water suction at 15 cm was greater than 200 cm and (3) medium, infrequent irrigation - irrigate to 45 cm soil depth when suction at 15 cm was greater than 200 cm.

As in the corn experiment "Microjet" sprinklers were used but the system was redesigned to apply water over the peanut canopy. The black polyethylene tubing was fastened to narrow wooden slats mounted about 0.6 m above the ground. Water was applied at 1.36 cm/hr at 25 PSI.

2. Results and Discussion

Seasonal rainfall and irrigation distributions are shown in Fig. 11. Irrigation treatment numbers in the figure correspond to treatment numbers 2 and 3 respectively. Yield and water balance data are given in Tables 8 and 9.

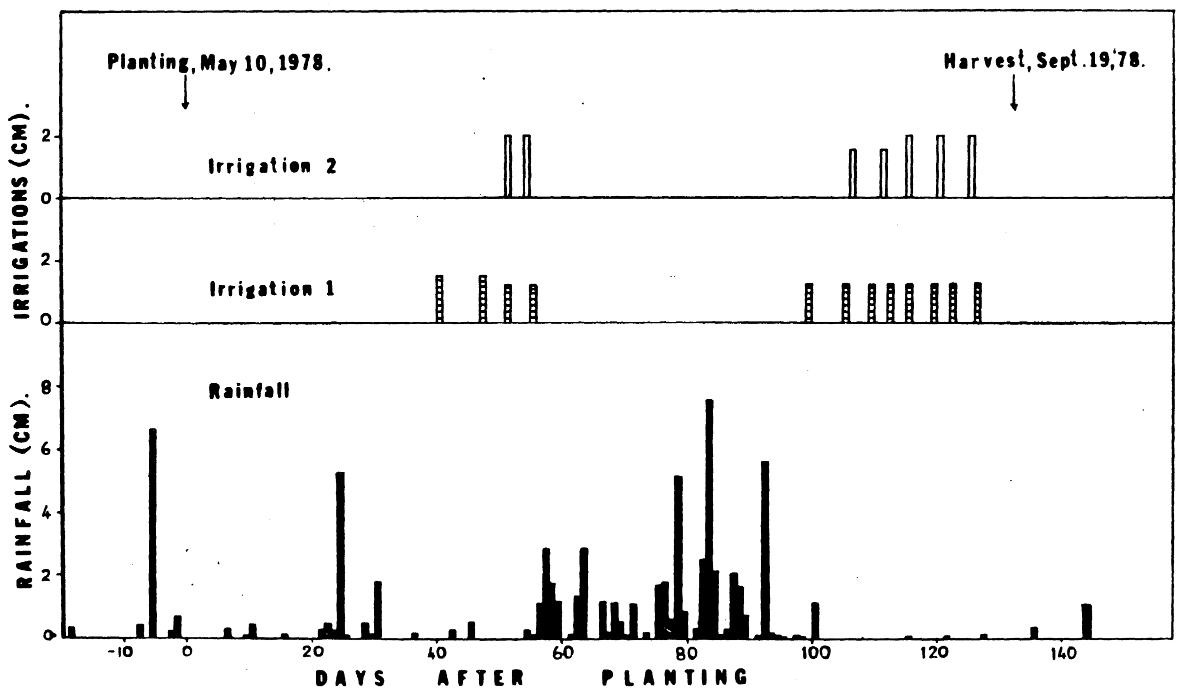

Figure 11. Rainfall distribution and irrigation schedules for two water management treatments on peanuts, Gainesville, 1978.

Much more total water was available in 1978 than in 1977, and the yields were slightly higher. Yield increases due to irrigation were not significant. However, late season leaf spot damage contributed to a large variability between plots. The unirrigated treatment was wilted for the last 12-15 days of the season. Apparently the plants had already produced a near normal pod load before the drought became severe.

Excessive rainfall in the 60-90 day period contributed to a large simulated drainage from the profile in all treatments. Note that in contrast to the corn experiment the irrigation schedule interacted with the rainfall distribution in such a way as to minimize the increased water outflow over the unirrigated treatment. However, the nonirrigated soil profile was left in a more depleted state at the end of the season. The predicted net profile depletion level at the end of the season was lower than the neutron measured level (4.65 cm vs. 5.98 cm). This is not a great difference, but when coupled with differences in the opposite direction for the irrigated treatments (treatment 2, 11.53 cm vs. 7.16 cm; treatment 3, 10.85 cm vs. 7.51 cm) it means that the differences between the nonirrigated and irrigated treatments in simulated ET values were not as large as they were in reality. Adjustments on the basis of the measured profile water contents would be in the direction of lowering the simulated ET for the nonirrigated treatment and increasing these values on the irrigated treatments. On the other hand, the discrepancy could be due to uncertainties in the amounts of irrigation input. An overestimate of the input would result in a calculated water content higher than measured.

These and earlier data support the not-so- obvious fact that irrigation water must increase ET over non-irrigated ET in order to avoid an increase in profile outflow equal to the amount of irrigation water applied. In a humid climate with sandy soils it will not be possible to manage the irrigation of crops for an economical production without some additional contribution to the water drained below the root zone. The estimated ET values obtained in the corn and peanut experiments in 1978 appear to be reasonable (Table 8).

Daily water depletion rates (Table 9) were calculated for periods of varying length from measured water input and neutron measured changes in soil profile water content. These depletion rates, when compared with the appropriate expected ET rates of Table 1, show the periods of potential drought stress (depletion < expected ET) and of potential drainage outflow (depletion > expected ET). For an irrigation treatment, a depletion rate less than expected ET would indicate that irrigation quantities were not adequate to prevent plant water stress. Treatment 2 in the 48-57 day period is an example. In reality errors in measurement of the soil water content or of the amount and uniformity of water input could result in inaccurate water depletion estimates.

Root density distributions were measured in treatments 1 and 2 on September 11, 1978 (Fig. 12). Sampling was not extensive enough to measure any treatment differences, but the results are typical of those found by Robertson et al. (1979, 1980). In this experiment, roots were observed at 225 cm depth.

F. Soybeans, 1978

A newly installed irrigation field plot area with solid set impact sprinklers was used to study the response of soybeans to irrigation scheduling strategies.

1. Methods

The experimental area was located on Arredondo fine sand and consisted of twenty-four 13.7 m x 13.7 m water management plots arranged as a randomized block in four replications. Impact sprinklers on the corners of each plot delivered water at the rate of 2.54 cm/hr in a quarter circle pattern with a radius of 14.3 m. Five of the six-treatments available were chosen for this study. Water management treatments (main) were: (1) no irrigation, (2) irrigation, light rate and frequent, (3) irrigation, medium rate and infrequent, (4) irrigation, light rate and infrequent, and (5) irrigation, mixed light and medium rates. Irrigation scheduling for treatments 2 and 3 was based on a tensiometer reading of approximately 150 cm at a depth of 15 cm. Treatment 4 was irrigated at a suction of 300 cm at a depth of 30 cm. The light rate of irrigation in treatment 5 was scheduled in the same way as for treatment 2, but when the suction at 30 cm reached 300 cm a medium rate of irrigation was scheduled. Soybean response was measured in terms of yield of mature beans.

Subplot treatments were cultivars of soybeans - Bragg and Cobb. Planting was on June 15, 1978 in 76 cm rows with a population of about 258,000 plants/ha. Field dry beans were harvested November 7, 1978.

2. Results and Discussion

Rainfall distribution can be seen in Fig. 11. No rainfall occurred between Oct. 1 (day 144, peanuts) and the end of the soybean season (November 28). Irrigation distribution for the various irrigation treatments are given in Table 10. Soybean yields increased linearly with the amount of water applied (Figure 13). Apparently quantity was more important for this season than the strategies of application.

Yields are given in Table 11 along with simulated water balance results. Simulated ET was nearly the same for all irrigated treatments indicating that the model was not sensitive enough to detect the expected real ET decrease for treatment 4 where there was a measured decrease in

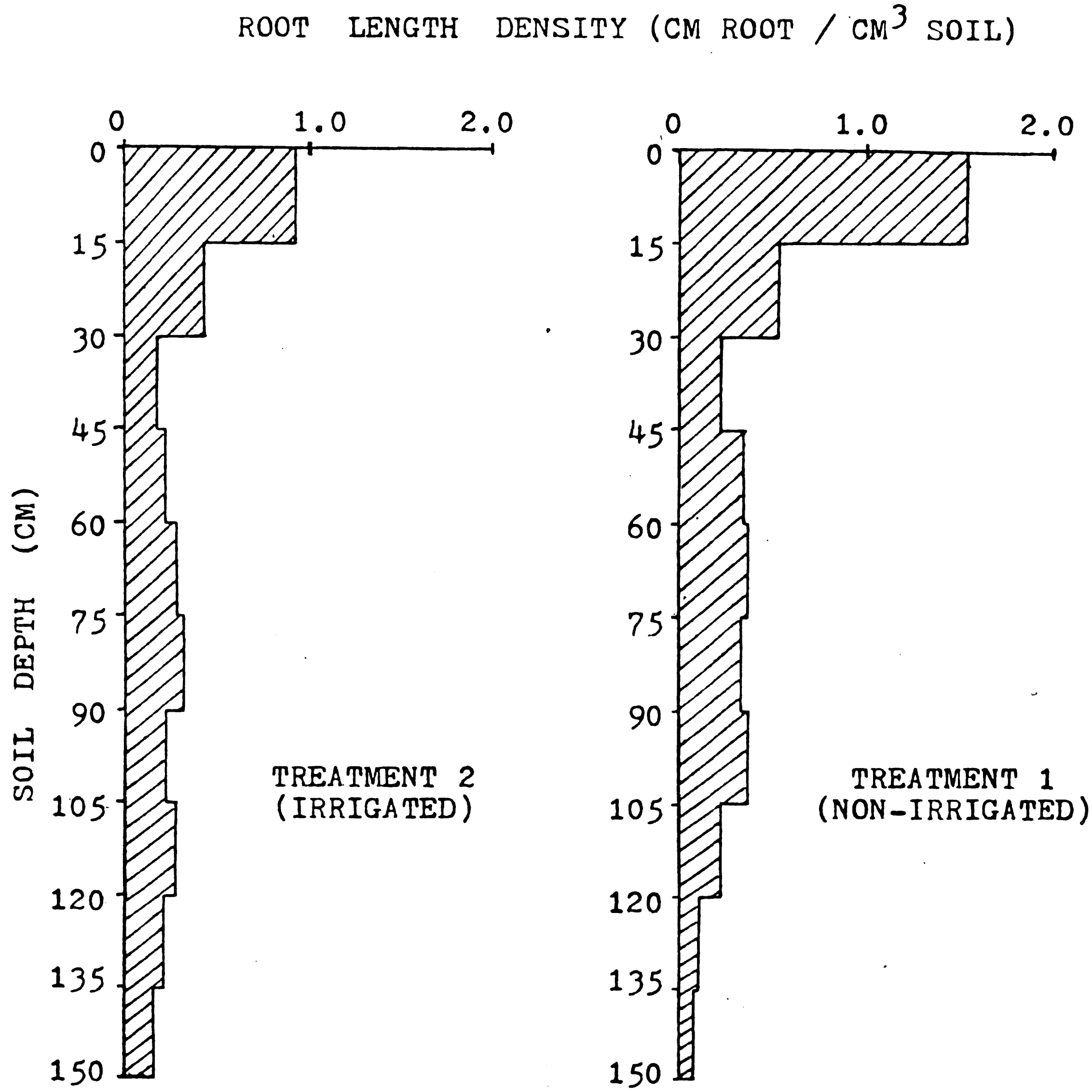

Figure 12. Peanut root density distribution with depth in irrigated and non-irrigated treatments, Gainesville, 1978.

Table 10. Irrigation schedule, soybeans, Gainesville, 1978.

Date	Irrigation Amount on Treatment Numbers[1/] 2	3	4	5
	cm			
June 30	1.27	1.27	1.27	1.27
Aug. 18	1.27	1.91	--	1.27
23	1.27	1.91	--	1.27
25	1.27	--	--	1.27
26	--	1.27	--	--
28	1.07	1.07	1.07	--
30	1.07	1.47	1.07	1.07
Sept. 1	1.07	--	--	1.70
3	1.07	1.47	1.47	--
5	--	--	--	1.19
7	1.07	1.52	--	--
8	--	--	1.47	1.47
10	1.07	1.07	--	--
13	0.84	1.27	0.84	1.27
16	0.84	--	1.14	--
17	--	1.07	--	1.07
19	0.84	--	--	--
20	--	1.07	--	1.07
21	--	--	1.27	--
22	0.84	--	--	--
23	--	1.27	--	0.84
26	0.69	--	1.27	--
27	--	1.07	--	0.69
29	0.84	--	--	--
Oct. 4	--	0.84	--	0.84
6	0.69	--	1.07	--
10	0.84	0.97	--	1.19
11	--	--	1.27	--
12	--	1.07	--	1.27
21	0.97	0.97	--	0.97
Total	18.89	22.56	13.21	19.72

[1/] There were two irrigations (June 16 and 19) of 0.84 cm each on all five treatments, but this was included as rainfall, making it a season total of 55.1 cm.

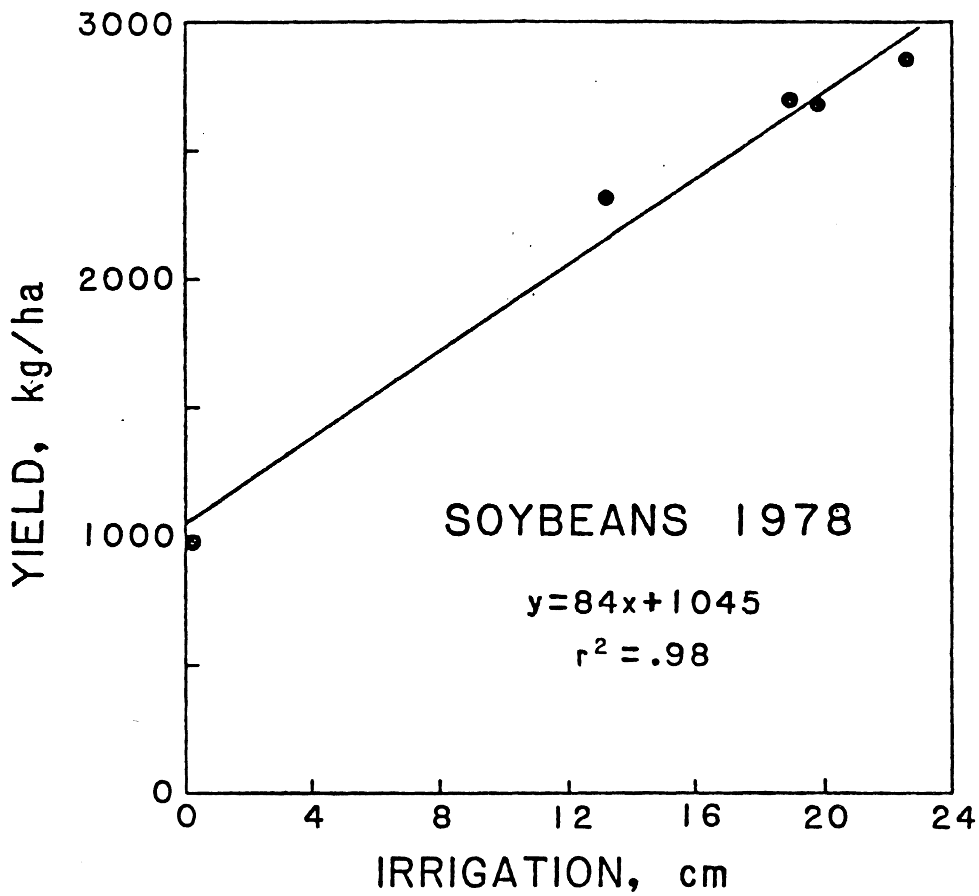

Figure 13. Soybean yields as influenced by irrigation amounts, Gainesville, 1978.

Table 11. Effect of water management on yield of soybeans and simulated water balance, Gainesville, 1978.

Treatment[1/]	ET	Irrig.[2/]	Profile water depletion[3/]	Drainage	Yield
	- - -	- - -	-cm-	- - -	kg/ha
Non-irrigated (1)	35.42	--	11.24	30.91	976 c
Irrigated (2)	46.76	18.89	4.10	31.32	2690 a
Irrigated (3)	47.01	22.56	2.39	33.03	2832 a
Irrigated (4)	46.86	13.21	9.88	31.32	2311 b
Irrigated (5)	47.01	19.72	3.15	30.94	2668 a

1/ See text for details.

2/ Rainfall, 55.1 cm.

3/ Net seasonal loss from the soil profile.

yield. The discrepancy could result from any one or a combination of the following input parameter deficiencies: an underestimate of ET, an overestimate of field capacity, and an overestimate of the time needed for water redistribution in the soil profile.

In contrast to other water balance data presented thus far, these data predict very little influence of irrigation on drainage loss of water. Nearly all of the irrigation input was used for ET and storage in the soil profile. This is the desired objective of the irrigation management in humid regions. However, in this case all of the irrigation was applied during a prolonged drought so that a few small rainfalls did not cause an overfilling of the soil reservoir. The relatively large drainage outflow for all treatments was due to high rainfall during the period June 12 through August 11.

The neutron-measured soil water profile status, the approximate field capacity profile, and the soybean root density distribution are given in Fig. 14. On October 27 the non-irrigated plot was essentially at the permanent wilting point to a depth of about 135 cm. The irrigation regime for treatment 2 (light, frequent) allowed the lower part of the profile to become water-depleted as planned. Root densities were a little larger for soybeans than for peanuts (Fig. 12). The decrease in root density in the 30-60 cm soil depth zone was evident in both the soybean and peanut data and was attributed to a compact soil zone created by tillage.

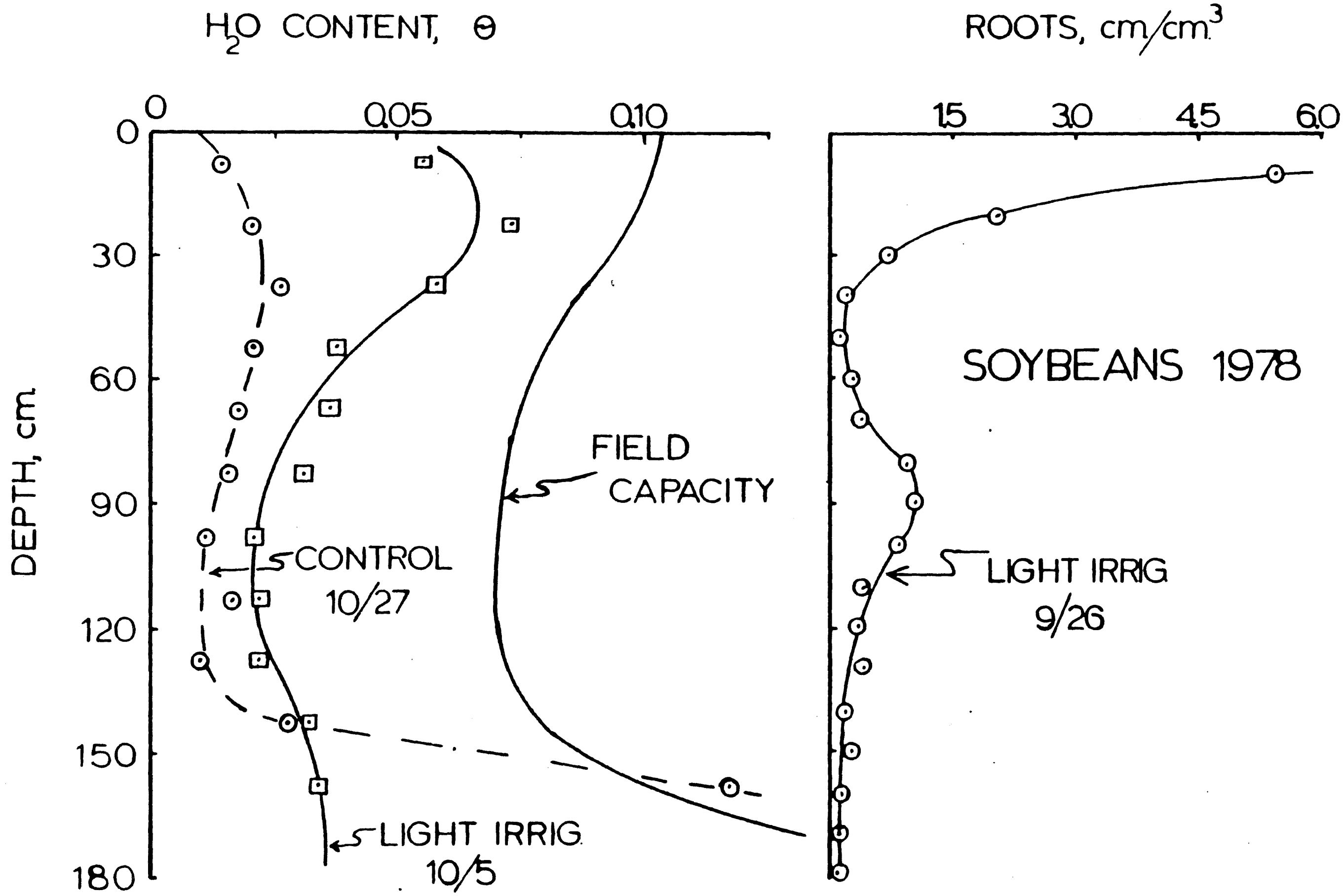

Figure 14. Soil water content and soybean root density distribution with depth, Gainesville, 1978.

G. Corn, 1979

The purpose of this study was to determine the effect of drought on grain yield of corn for different stages of plant growth and for two irrigation scheduling practices.

1. Methods

The field experiment was established on Lake fine sand with a solid set, impact sprinkler irrigation system delivering 2.54 cm of water per hour. The plots were 13.7 x 13.7 m in size and arranged in a randomized block statistical design in four replications. Water management treatments were: (1) no irrigation, (2) irrigation, light rate and frequent, (3) irrigation, medium rate and infrequent, (4) irrigation, same as treatment number 2 except beginning at tassel, and (5) irrigation, same as treatment number 2 except no irrigation during tasseling and silking. Irrigation was scheduled when readings from tensiometers at 15 cm depths exceeded 150-250 cm of water suction. Funk G-4507 corn hybrid seed were planted on March 13, 1979 in 90 cm rows at a population of 71,000 plants/ha.

2. Results and Discussion

Rainfall distribution and irrigation schedule data are shown in Fig. 15 and Table 12. Yields and simulated water balance data are given in Table 13. Due to previous experiments in the field plot area, yields were highly variable. Irrigated treatment differences were not significant. Nevertheless, the omission of irrigation during tasseling and silking (treatment 5) resulted in a yield not significantly larger than the non-irrigated treatment.

The water balance data shows the effect of poor rainfall distribution in relation to the water retaining properties of the soil. Had the 11 cm outflow from the non-irrigated treatment been available for ET, the expected yield would have been near the maximum obtained in the experiment.

A summary of results from the four Gainesville corn experiments is presented in Fig. 16 and 17. In 1977, the very low yield for nonirrigated corn did not fall in the region of linear response and was omitted. The reasonably good regression between yield and irrigation (Fig. 16) indicates a remarkable similarity of drought factors for the three years, although a much better linear fit of the data would be obtained if the 1977 data were excluded. On the other hand, the response may be curvilinear as found by (Skogerboe, 1979). It is apparent that total water input was more important to grain yield than scheduling strategy during these years. The regression coefficient of 143 kg/ha-cm (5.79 bu/acre-in) is a 3-year average measure of irrigation water-use efficiency.

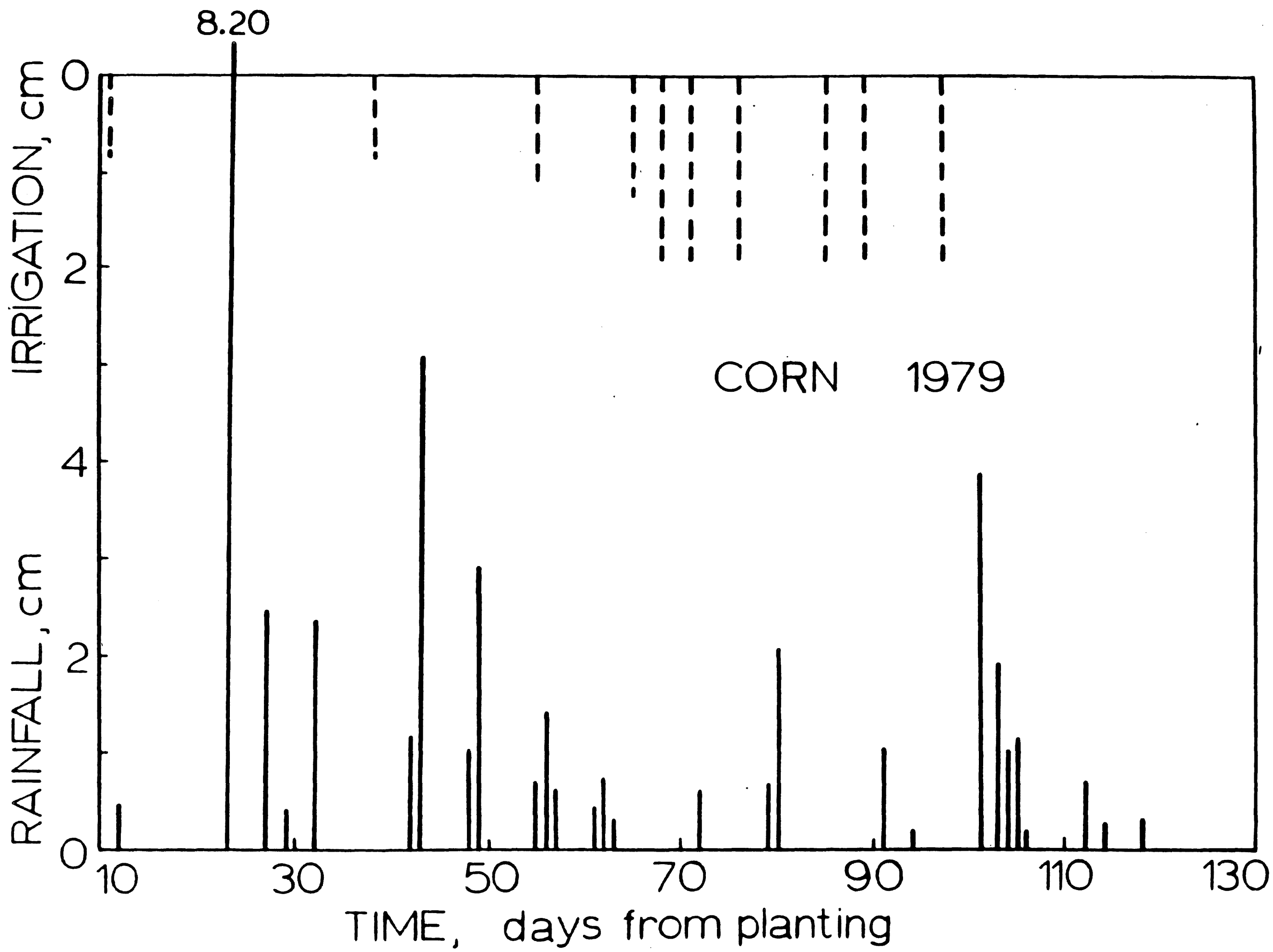

Figure 15. Rainfall distribution and irrigation schedule for treatment 2 of corn experiment, Gainesville, 1979.

Note that coefficients would be higher if data for each year were taken separately.

The regression of grain yield on simulated ET(Fig. 17) yields a slightly higher R^2-value and a larger regression coefficient(661 kg/ ha-cm). Again, the data suggest that seasonal ET was more important than irrigation scheduling strategy. The regression coefficient is much larger than the 147 kg/ha-cm value found in Colorado (Skogerboe, 1979). However, calculated values from corn grain data of Hillel and Guron (1973) in Israel were 540, 440, and 450, respectively for 1968, '69, and '70. Our ET simulations may be forcing the range of values within unrealistically small bounds, especially for the higher levels of irrigation where the model allocated a considerable amount of the water input to drainage outflow.

Table 12. Irrigation schedule, corn, Gainesville, 1979.

Date	Irrigation amount on treatment numbers[1/]			
	2	3	4	5
	cm			
March 22	0.84	0.84	0.84	0.84
April 20	0.84	1.65	--	1.06
May 7	1.07	1.65	--	1.07
17	1.27	1.91	1.27	--
20	1.91	2.54	1.91	--
23	1.91	--	1.91	--
26	--	2.67	--	--
28	1.91	--	1.91	--
30	--	2.54	--	--
June 6	1.91	2.54	1.91	1.91
10	1.91	--	1.91	--
13	--	2.54	--	--
18	1.91	2.54	1.91	--
Total	15.48	21.42	13.65	4.88

[1/] Treatment number 1 also was irrigated with 0.84 cm on 3/22; rainfall, 42.47 cm.

Table 13. Effect of water management on yield of corn and simulated water balance, Gainesville, 1979.

Treatment[1/]	ET	Irrig.[2/]	Profile water depletion[3/]	Drainage	Grain yield
	cm				kg/ha
Non-irrigated (1)	37.81	0.84	5.58	11.08	1434 b
Irrigated (2)	43.80	15.84	2.54	16.72	5120 a
Irrigated (3)	43.80	21.42	2.64	22.60	5187 a
Irrigated (4)	42.68	13.64	3.09	16.52	4248 a
Irrigated (5)	39.60	4.87	5.34	13.07	2690 ab

[1] See text for further details.

[2] Rainfall, 42.47 cm.

[3] Net water loss from the soil profile.

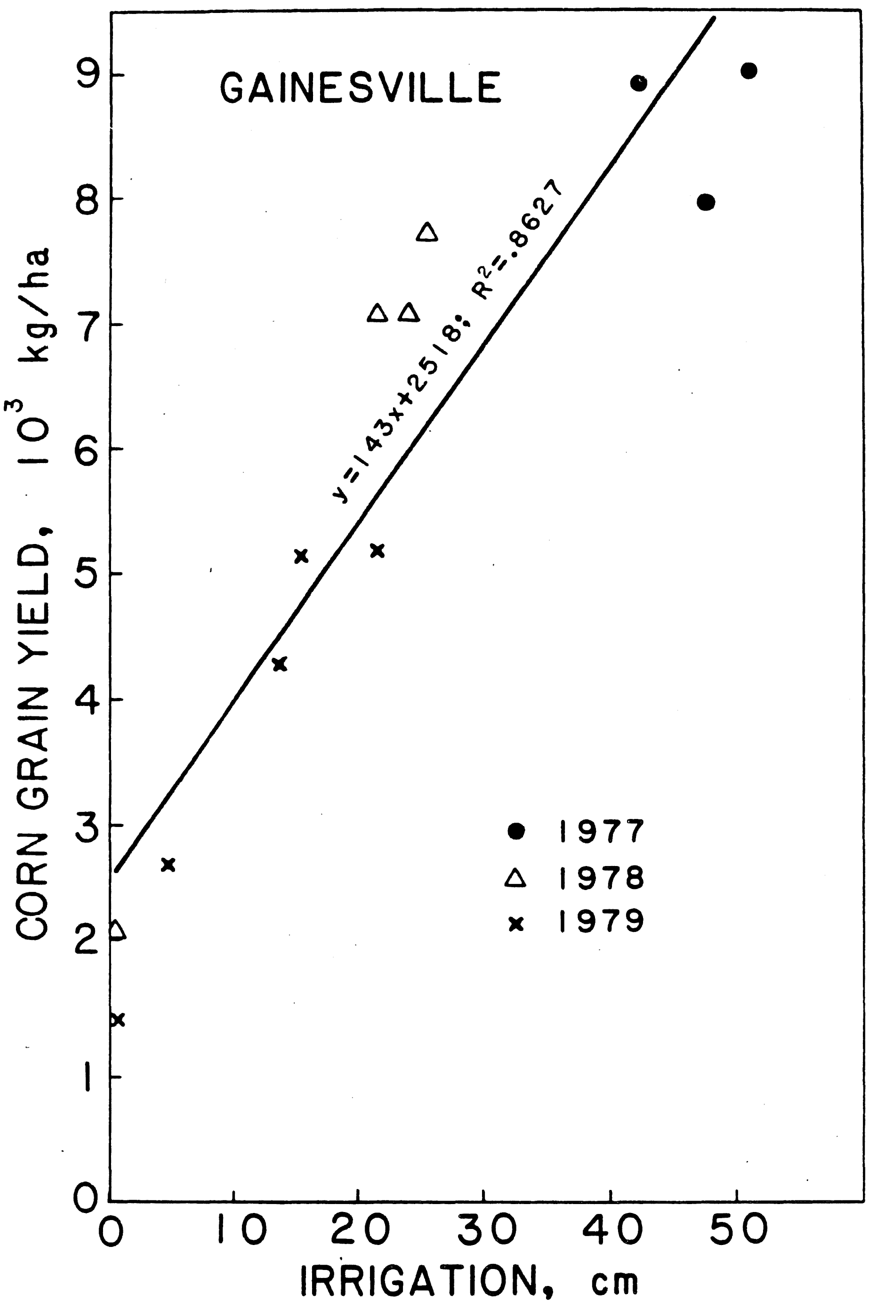

Figure 16. Yield of corn grain as affected by irrigation amounts, Gainesville, 1977, 1978, and 1979.

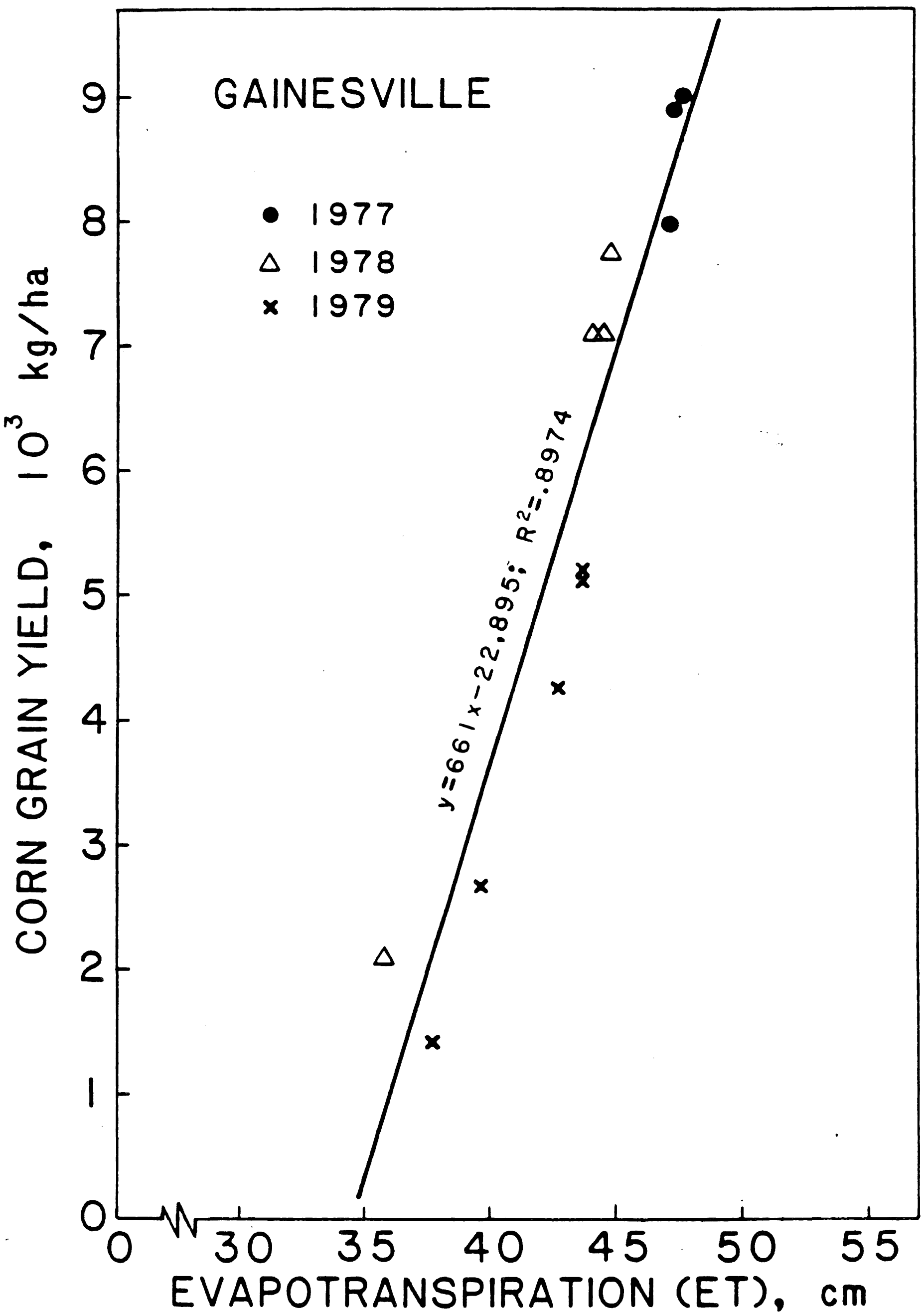

Figure 17. Yield of corn grain as affected by estimated evapotranspiration, Gainesville, 1977, 1978, and 1979.

CHAPTER III. FIELD EXPERIMENTS, LIVE OAK

Three water management field experiments were conducted on corn during 1977, 1978, and 1979. The experimental site of three hectares consisted of predominantly Lakeland fine sand, a member of the thermic, coated family of Typic Quartzipsamments. A subsurface asphalt layer (soil moisture barrier) was previously (1967 and 1970) installed in one of two-treatment main plots (0.37 ha) in four replications (Saxena, et al., 1973). The barrier to water and nutrient flow was placed in a continuous strip (0.3 cm thick) at a depth of approximately 65 cm with overlapping passes of a special sweep plow. However, the process did not result in a complete seal at the lines of overlap; consequently, perching of a water table on the barrier occurred only for very short times and only during large and intense rainfalls. Nevertheless, a uniquely modified soil profile was created--one in which water was retained in larger amounts and for longer time periods in soil located above the barrier than for the case of naturally rapid drainage in the untreated soil. With a life expectancy of more than 25 years, the barrier system has the potential for increasing the proportion of rainfall utilized by plants. Moreover, the field facility provides an unusual opportunity to study selected strategies for irrigation management and their influence upon crop yield and water and nutrient balance in sandy soils of humid regions.

Four water management subplots (24 x 24 m) were maintained in the same location over the three seasons. One of the subplots was non-irrigated and the other three were irrigated overhead from impact sprinklers mounted on portable aluminum pipe.

Water balance simulations were performed similarly to that described for the Gainesville Experiments (Chapter II). Also, the basic irrigation management strategy was to irrigate frequently at light rates (small quantities of water per event) leaving part of the water-depleted soil profile unfilled and available to store rainfall.

A. Corn Experiment, 1977

The purpose of this experiment was to determine interrelationships between moisture barrier, irrigation strategy, plant population, nitrogen fertilizer level, and grain yield for two corn hybrids. A second purpose was to measure downward flux of water below the root zone under different water management treatments.

1. Methods

The four water management subplots described above were split into eighteen sub-subplots to which factorial treatments (two corn hybrids, three plant populations, and three nitrogen rates) were assigned randomly. Water management treatments were: (1) no irrigation, (2) frequent irrigation with light rate (small quantities per event) when the soil water suction at 15 cm depth exceeded 120 cm of water, (3) same as 2 except infrequently with medium rate, and (4) same as 2 except irrigation was applied when soil water suction exceeded 600 cm. Water management treatments on the asphalt barrier plots were designated by adding the letter "A" to the above numbers. Corn hybrids DeKalb XL-80 and Funk G-4507, were planted March 22, 1977 and harvested July 25. Nitrogen fertilizer was applied only as a sidedressing, 30% at 16 days after planting 70% at 45 days. Nitrogen levels were 134, 202, and 269 kg/ha. Plant populations were 39, 59, and 79 thousand plants/ha in rows 76 cm apart. Irrigation was by overhead impact sprinklers at 1.9 cm per hour. Soil water data used in water balance simulations are given in the Appendix Table. An extensive network of mercury manometer tensiometers was installed in only sub-subplots planted with Funk G-4507 corn at the highest plant population and nitrogen levels of all water management subplots of two replications. Tensiometers were placed in depth intervals varying from 5 to 30 cm with maximum depths of 45 and 300 cm, respectively for the barrier and non-barrier treatments. Readings were taken once-daily on Monday through Friday of each week. Evaluation of these data will be reported elsewhere. However, calculations of downward flux of water at 240 cm depths were obtained by multiplying gradients of hydraulic head from tensiometer readings with hydraulic conductivities obtained in an earlier study (Parra, 1971).

2. Results and Discussion

Rainfall and distribution and irrigation scheduling data are shown in Figs. 18 and 19. Drought conditions were serious in most of May and for shorter periods in April, June, and July. These water input distributions are reflected in the soil water status as measured by tensiometers (Figs. 20-24). Tensiometer data were shown as hydraulic heads at various depths and in two to four-day intervals. Thus, one can obtain a qualitative view of both water content and vertical water flux directions. Moreover, during dry periods the hydraulic head readings revealed the presence or absence of water absorption by roots.

At a given depth, water content decreases as the hydraulic head becomes more negative. Water flows vertically in the direction of

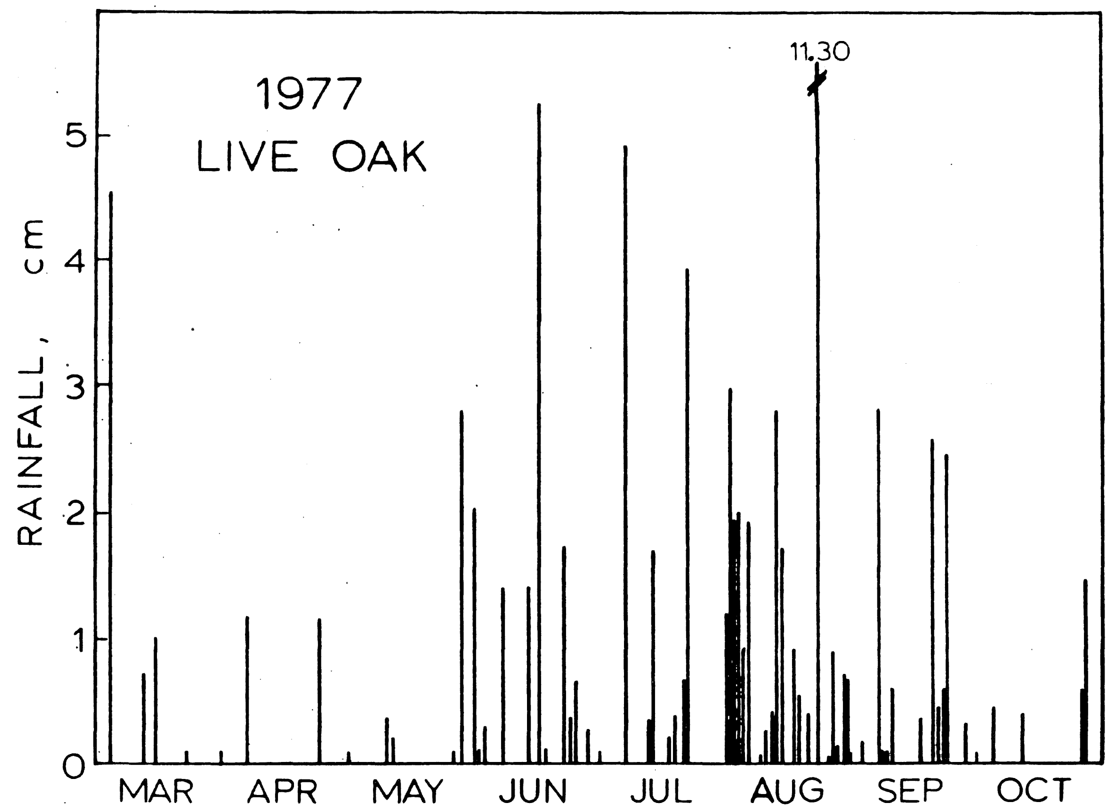

Figure 18. Rainfall distribution, Live Oak, 1977.

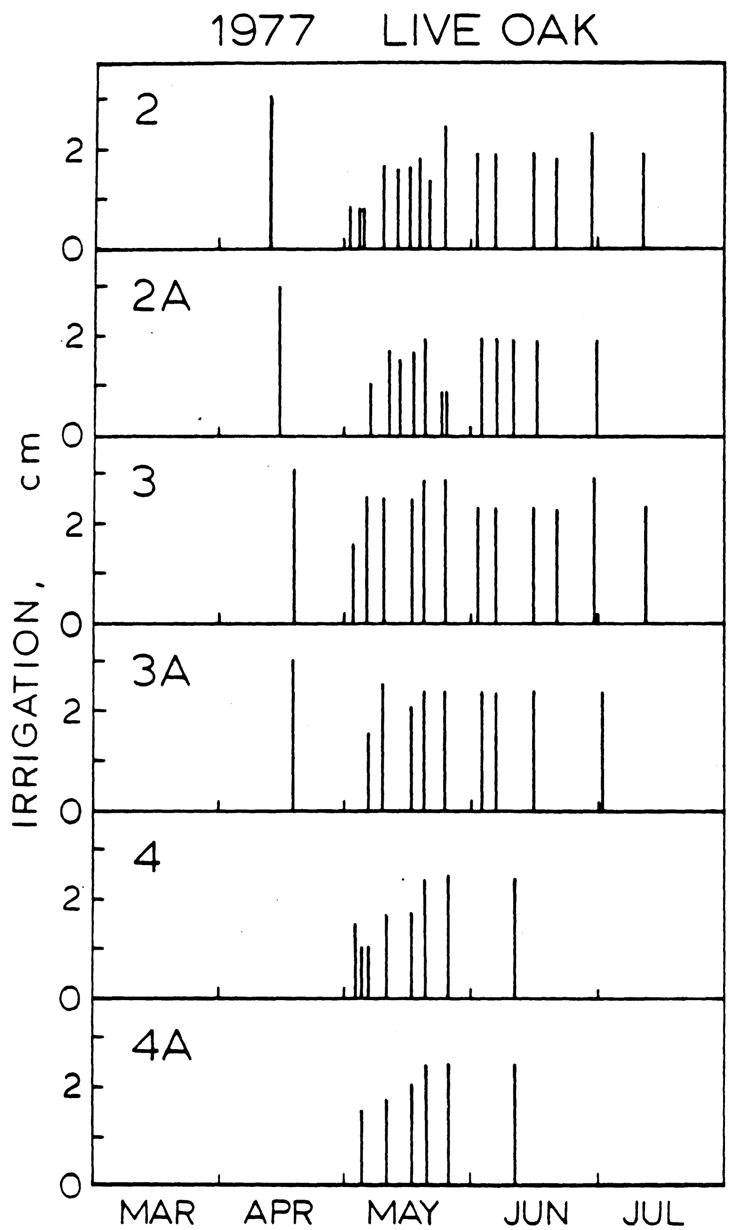

Figure 19. Irrigation distribution for six irrigation treatments on corn, Live Oak, 1977. Treatments with the letter "A" included a subsurface asphalt barrier treatment.

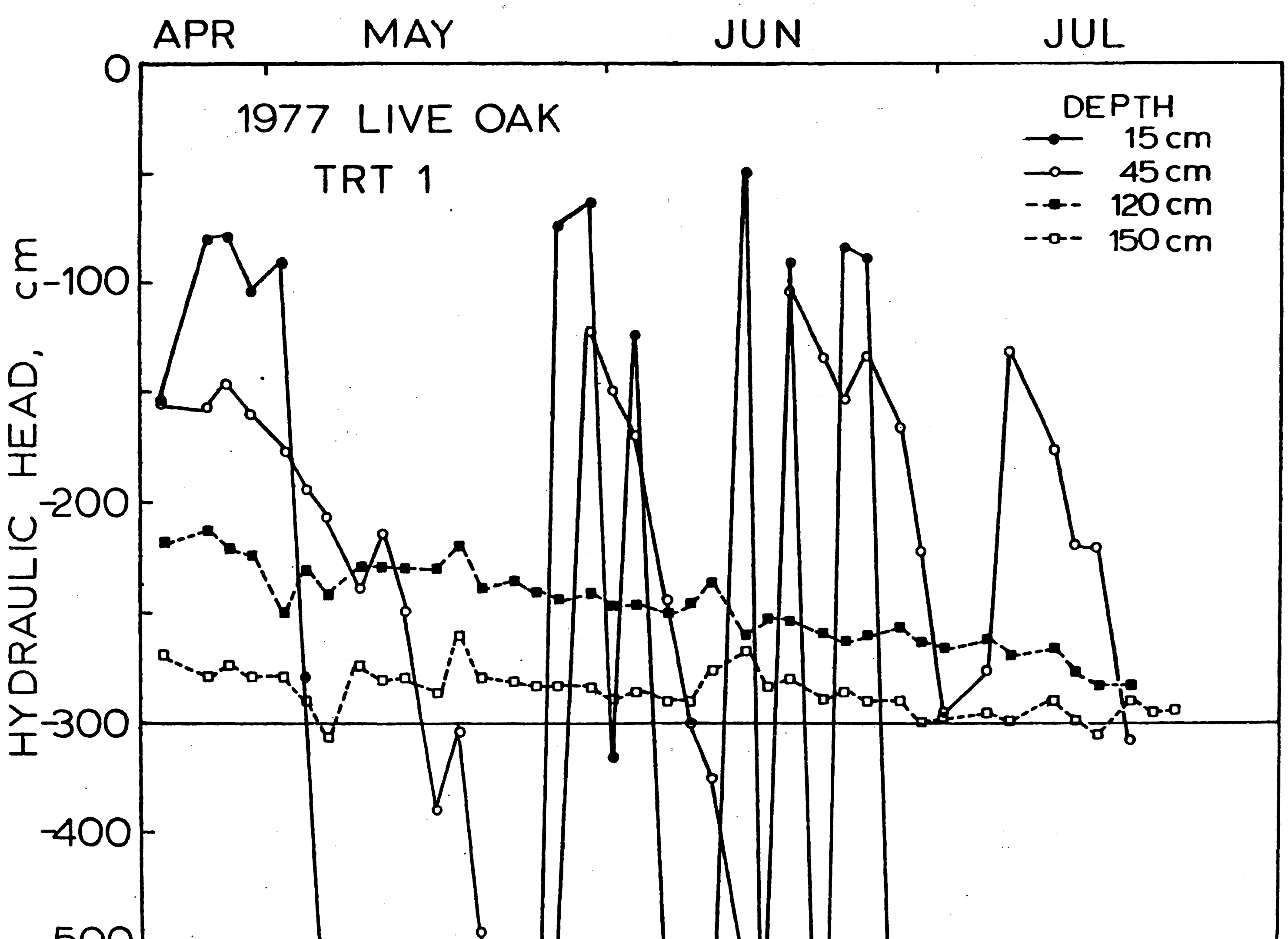

Figure 20. Hydraulic head distribution with depth and time under non-irrigated corn, Live Oak, 1977. Soil surface was the datum.

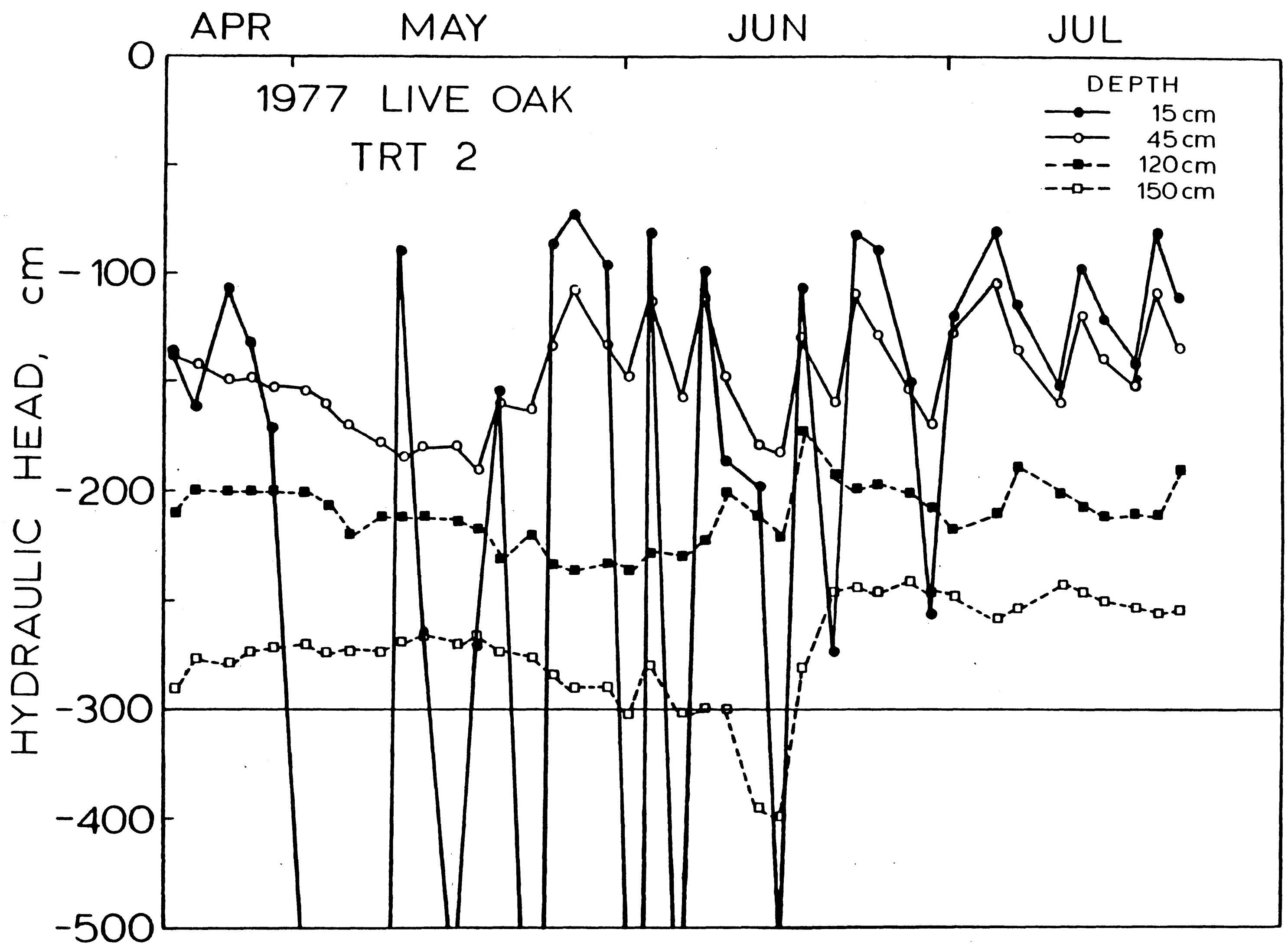

Figure 21. Hydraulic head distribution with depth and time under irrigated corn, treatment 2, Live Oak, 1977. Soil surface was the datum.

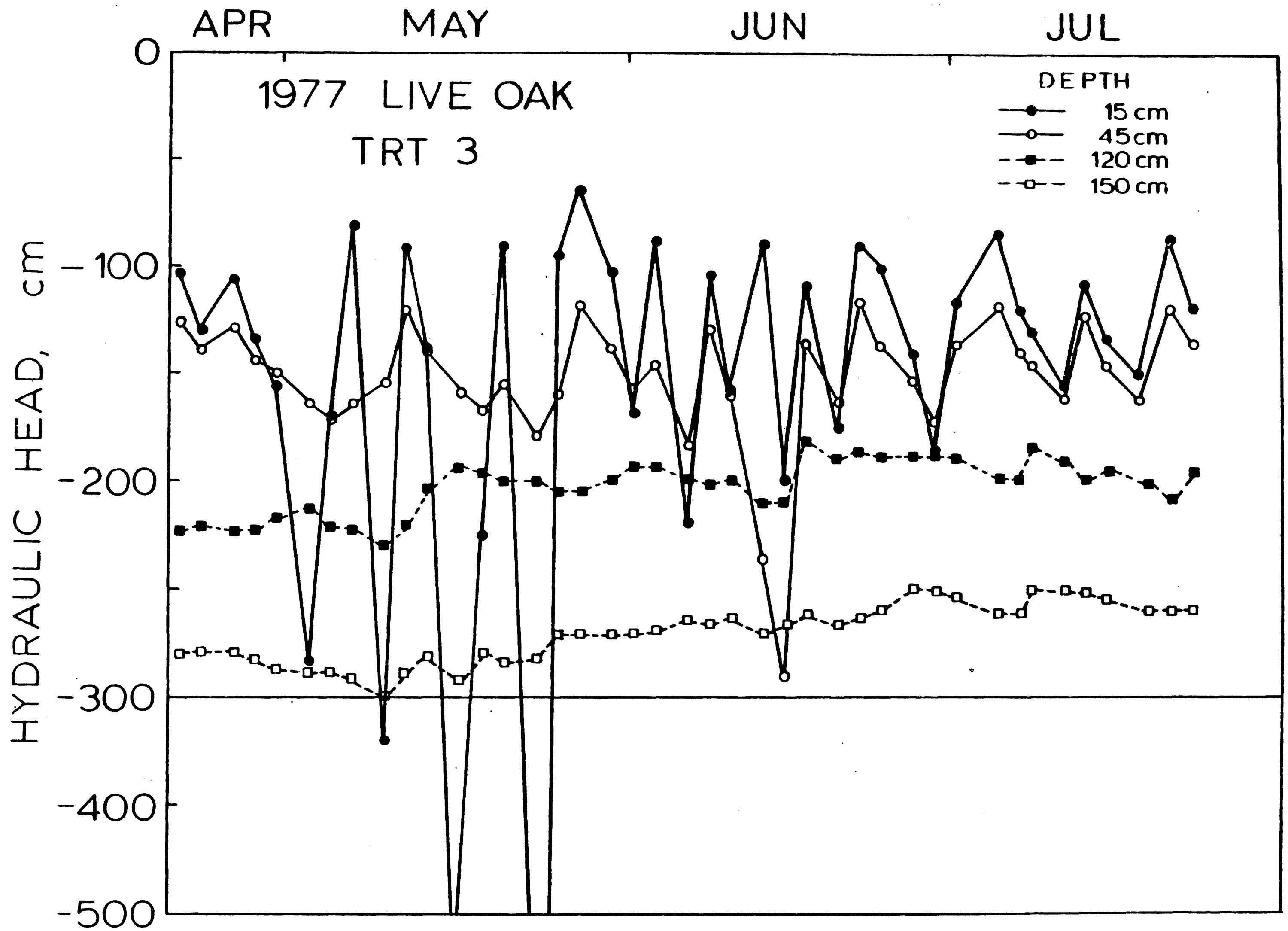

Figure 22. Hydraulic head distribution with depth and time under irrigated corn, treatment 3, Live Oak, 1977. Soil surface was the datum.

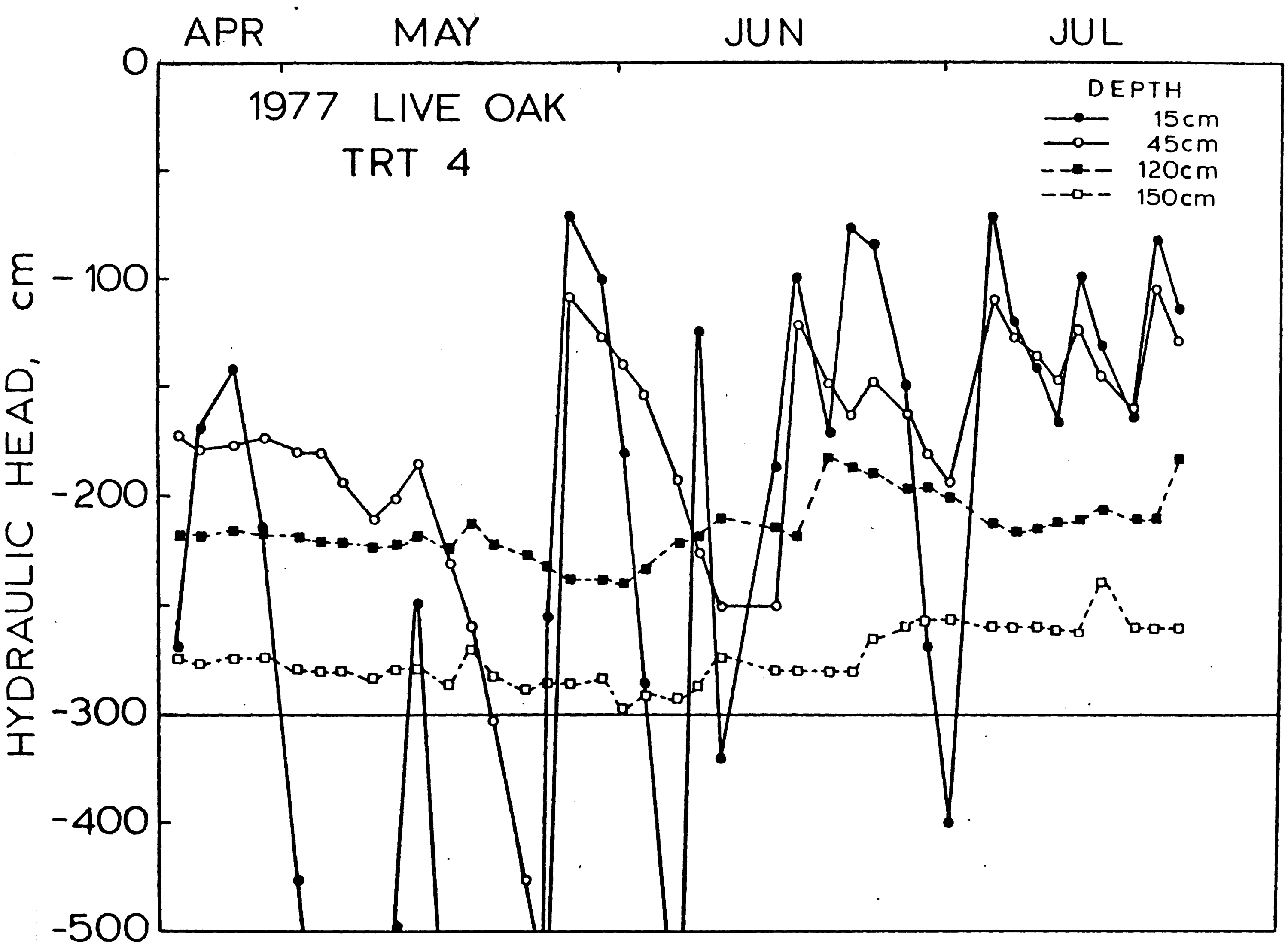

Figure 23. Hydraulic head distribution with depth and time under irrigated corn, treatment 4, Live Oak, 1977. Soil surface was the datum.

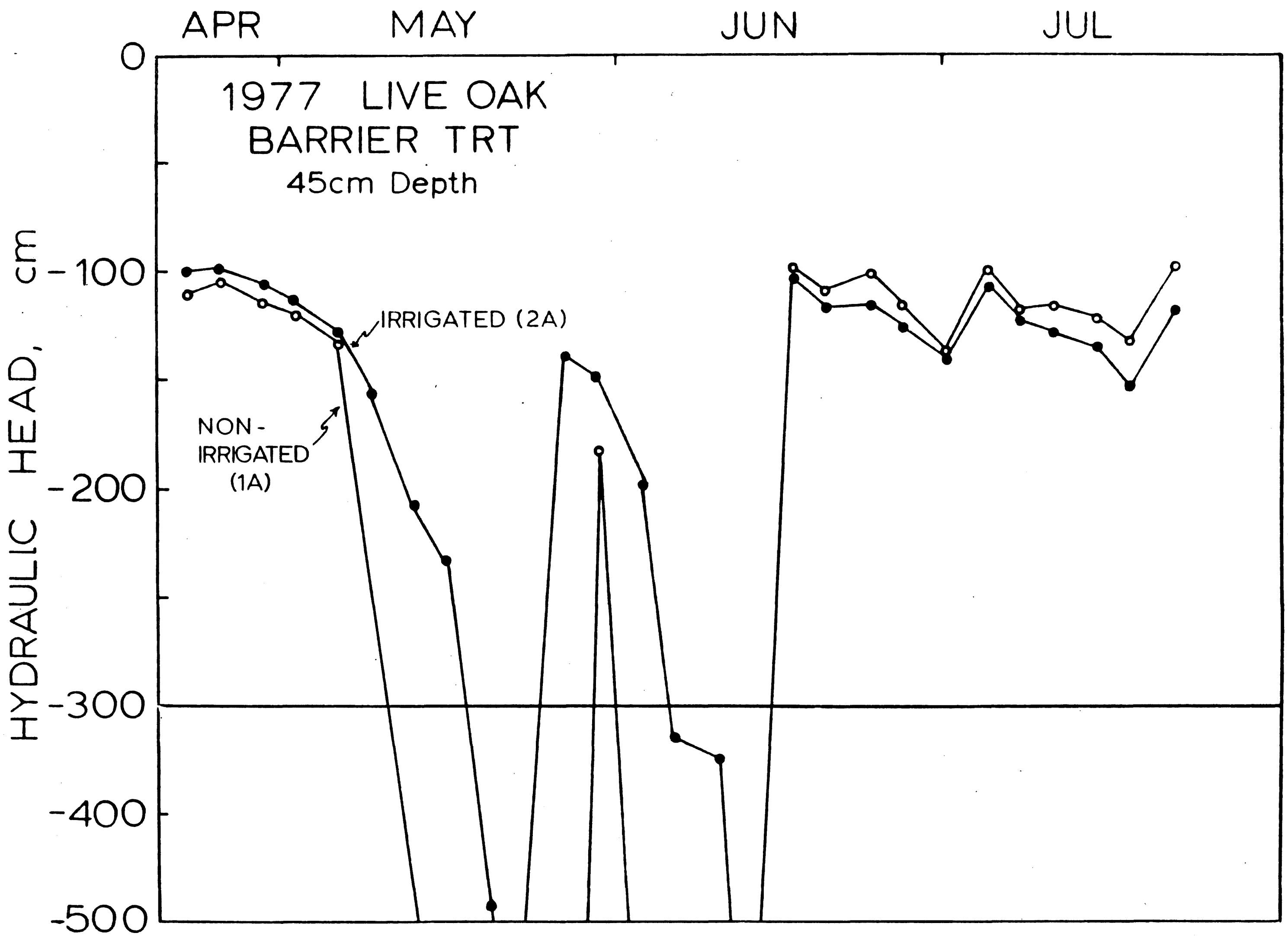

Figure 24. Hydraulic head distribution with time at a depth of 45 cm under non-irrigated and irrigated corn grown on soil modified by a subsurface asphalt barrier, Live Oak, 1977.

decreasing (more negative) hydraulic head. For example in treatment 1, non-irrigated (Fig. 20) water flow in April was downward between all depths shown. In May, as the soil became dry, net water movement became upward, first in the 15 to 45 cm zone and next in the 45 to 120 cm zone. Wide temporal swings in hydraulic heads at the two upper tensiometers resulted from alternate periods of droughts and rainfall. However, in the 120 and 150 cm zone net water flow was downward throughout the season. At the 120 cm soil depth soil water content decreased with not much evidence of water withdrawal by roots until late season. Likely, plants stunted in "above-ground" growth by the May droughts were also limited in root growth.

Irrigation (Figs. 21, 22, and 23) attenuated temporal variability in hydraulic head readings at 15 and 45 cm. Water flow throughout the season was vertically downward at depths below 45 cm in treatments 2 and 3. In contrast, the less frequently irrigated treatment 4 exhibited three periods of upward movement in the 45 to 120 cm zone. Root activity as indicated by tensiometer readings was not easily discernable in the 120 to 150 cm data of the irrigated treatments because the soil profiles were maintained in a moist state.

The influence of the asphalt barrier on hydraulic head at 45 cm depth in non-irrigated and irrigated treatments is shown in Fig. 24. Irrigation essentially eliminated drying of the soil at 45 cm since the strategy was to restore to field capacity (Appendix Table) only the top 30 cm of the soil profile. Comparing the early and late season hydraulic head values in Fig. 24 with those at the same depth in Figs. 20 to 23 reveals the higher soil water retention in soil above barrier. In addition, the fluctuation of hydraulic head was less over the barrier.

Simulated (model) water balance data and corn yields are given in Table 14. Yields will be discussed later. In the non-irrigated treatments all input water and a considerable soil profile depletion was used for evapotranspiration. On the other hand, irrigation caused a substantial deep seepage or drainage loss in some cases. Assuming that the simulated ET was correct, it is evident that several rainfall events occurred when the soil profile was not sufficiently depleted to retain the amount which fell. The more water-conserving treatments 4 and 4A reduced drainage loss but also resulted in reduction in yield. One of the more striking results in Table 14 is the effect of the increased soil water retention by the moisture barrier in producing larger yields with less irrigation. The results are unique in demonstrating improved productivity of droughty sandy soils from an alteration of a purely physical soil property. Finally, these data call attention to the need, in humid regions to utilize irrigation strategies which maximize use-efficiency of water, fertilizers, and pesticides. It's unlikely that one can

Table 14. Effect of water management on yield of corn and simulated water balance, Live Oak, 1977.

Treatment[1/]	ET	Irrig.[2/]	Profile water depletion[3/]	Drainage	Grain Yield
	cm				kg/ha
			Non-barrier		
Non-irrigated (1)	33.58	--	6.58	0.54	3015
Irrigated (2)	42.18	28.61	1.24	15.22	7741
Irrigated (3)	42.85	32.65	1.25	18.60	8081
Irrigated (4)	40.62	14.09	3.35	4.37	6217
			Barrier		
Non-irrigated (1A)	34.89	--	7.80	0.46	3367
Irrigated (2A)	42.55	21.98	1.87	8.85	9363
Irrigated (3A)	43.06	23.43	1.87	9.79	9266
Irrigated (4A)	41.40	12.39	3.13	1.67	8349

1/ See text for details.

2/ Rainfall, 27.55 cm.

3/ Net seasonal water loss from soil profile.

Table 15. Estimates of seasonal drainage in relation to water management treatments, Live Oak, 1977.

Treatment[2/]	Seasonal deep seepage at 240 cm depth[1/]		
		Tensiometer	
	Model[3/]	Rep. I	Rep. III
	cm	cm	cm
Non-irrigated (1)	0.54	0.23	2.47
Irrigated (2)	15.22	5.27	0.73
Irrigated (3)	18.60	1.38	7.93
Irrigated (4)	4.37	1.00	2.77
Fallow	-	-	12.33

1/ During 121 days.

2/ See text for details.

3/ From Table 14.

always win the water balance game without losing crop yield. The implications for agricultural production, economics, resource-use efficiency, and pollution control have not been fully appreciated or explored.

In an attempt to obtain a measure of the real water balance (non-barrier treatments) we calculated seasonal downward water flux at 240 cm depths from hydraulic head readings at 210 and 240 cm. The results along with simulated values from Table 14 are given in Table 15. Obviously, there is a need for more replication, and one might question whether the frequency of readings were sufficient for such calculations. Other problems include spatial variability in soil and in irrigation water application. Treatment differences were not clearly delineated from the tensiometer data, but the range of values is less than that simulated by the model and possibly indicates that the model has underestimated ET and overestimated water outflow by deep seepage.

Yield data (Tables 16 and 17) were organized to show the following significant two-way interactions: barrier x population, irrigation x population, variety x population, variety x fertilizer, and irrigation x fertilizer. Tukey's honestly significant difference (THSD) values were calculated as an aid in making comparisons among the various average yields. In Table 16, THSD values for comparison of barrier, water management, and variety treatment means at the same population were 943, 1289, and 294, respectively. And THSD values for comparison of population means at the same barrier, water management, and variety treatments were 353, 499, and 353, respectively. In Table 17 THSD values for comparison of water management and variety treatment means at the same fertilizer level were 1289, and 294, respectively. And THSD values for comparison of fertilizer means at the same water management and variety treatments were 499 and 353, respectively. The results of these comparisons will be stated in general terms only.

The barrier improved yields at all populations, and yield increases with population were greater on the barrier treatmeent. All irrigation treatment yields were higher than the non-irrigated treatment at each population. In addition, at the highest population, treatment 2 and 3 yields were signficantly higher than treatment 4. Considering population effects at the same irrigation treatment, there was no response for treatment 1. Response to population in treatment 4 leveled off at 59,000 plants/ha. In contrast, for irrigation treatments 2 and 3, there was an increase in yield with each increase in plant population. Funk G-4507 corn hybrid yields increased with increasing population while DeKalb XL-80 leveled off at the intermediate population. There was no difference in corn hybrids at the smallest population level, but highest yields were obtained from Funk G-4507 at the intermediate and high plant populations.

Table 16. Corn grain yields as affected by plant population, moisture barrier, water management, and corn hybrid, Live Oak, 1977.

Treatment[1]	Grain yield		
	39,000[2] kg/ha	59,000 kg/ha	79,000 kg/ha
Non-barrier	5593	6559	6640
Barrier	6554	7928	8278
Non-irrigated (1)	3105	3371	3098
Irrigated (2)	7313	8918	9426
Irrigated (3)	7340	8981	9702
Irrigated (4)	6535	7705	7609
DeKalb XL-80	6182	7062	7102
Funk G-4507	5964	7424	7816

1/ See text for details.

2/ Plants/ha.

Table 17. Corn grain yields as affected by nitrogen fertilizer level, water management and corn hybrid, Live Oak, 1977.

Treatment[1]	Grain yield		
	134[2] kg/ha	202 kg/ha	269 kg/ha
Non-irrigated (1)	3322	3186	3066
Irrigated (2)	8285	8723	8648
Irrigated (3)	8240	8701	9081
Irrigated (4)	7166	7246	7437
DeKalb XL-80	6447	6916	6984
Funk G-4507	7060	7013	7132

1/ See text for details.

2/ Fertilizer N, kg/ha.

Corn response to irrigation interacted with fertilizer level. Grain yields increased with increasing fertilizer level only for irrigation treatment 3 and only at the highest nitrogen level. For each level of nitrogen applied, all irrigation treatments gave higher corn yields than non-irrigation treatments. However, at the intermediate and high nitrogen levels, yields were lower in irrigation treatment 4 than in the other irrigation treatments. In relation to variety and fertilizer level, Funk G-4507 corn was higher yielding than DeKalb XL-80 only at the low nitrogen level and did not respond to nitrogen levels. Grain yield of DeKalb XL-80 increased with increasing nitrogen application only up to the intermediate level.

B. Corn Experiment, 1978

The overall objective was the same as for the 1977 experiments except that corn hybrid was not included as a variable.

1. Methods

The four water management subplots described earlier were split into six sub-subplots (3 x 12 m) to accomodate factorial treatments of three nitrogen fertilizer levels (134, 268, and 336 kg of N/ha) and two plant populations (59 and 90 thousand plants/ha). Corn hybrid DeKalb XL-80 was planted in 76 cm rows on March 16, 1978 and harvested on July 18. Water management treatments and irrigation methods were the same as in the 1977 experiment. Soil water was monitored in the highest nitrogen plots in replicates 1 and 3 using tensiometric and neutron techniques. Input data used in the water balance simulations are given in the Appendix Table.

2. Results and Discussion

Rainfall and irrigation schedule data are shown in Figs. 25 and 26. In Fig. 26, the late July through October data are from a soybean experiment not reported here. Note that the drought period for the corn experiment extended from early May through June.

Simulated water balance data and corn yields are given in Table 18. Grain yields were less than in 1977. Yields for treatments 2A and 3A (barrier) were more than 1.3 times those for treatments 2 and 3. All of the irrigation treatments resulted in a maximum ET of around 42 cm while the ET of both non-irrigated treatments were nearly the same at 36 cm. These values are very close to those obtained in 1977 (Table 14). One third or more of the irrigation water applied was allocated to drainage. However, as in 1977, irrigation water was used more efficiently with the barrier treatment. These results challenge us to develop water management systems which will equal the effectiveness of the barrier-irrigation

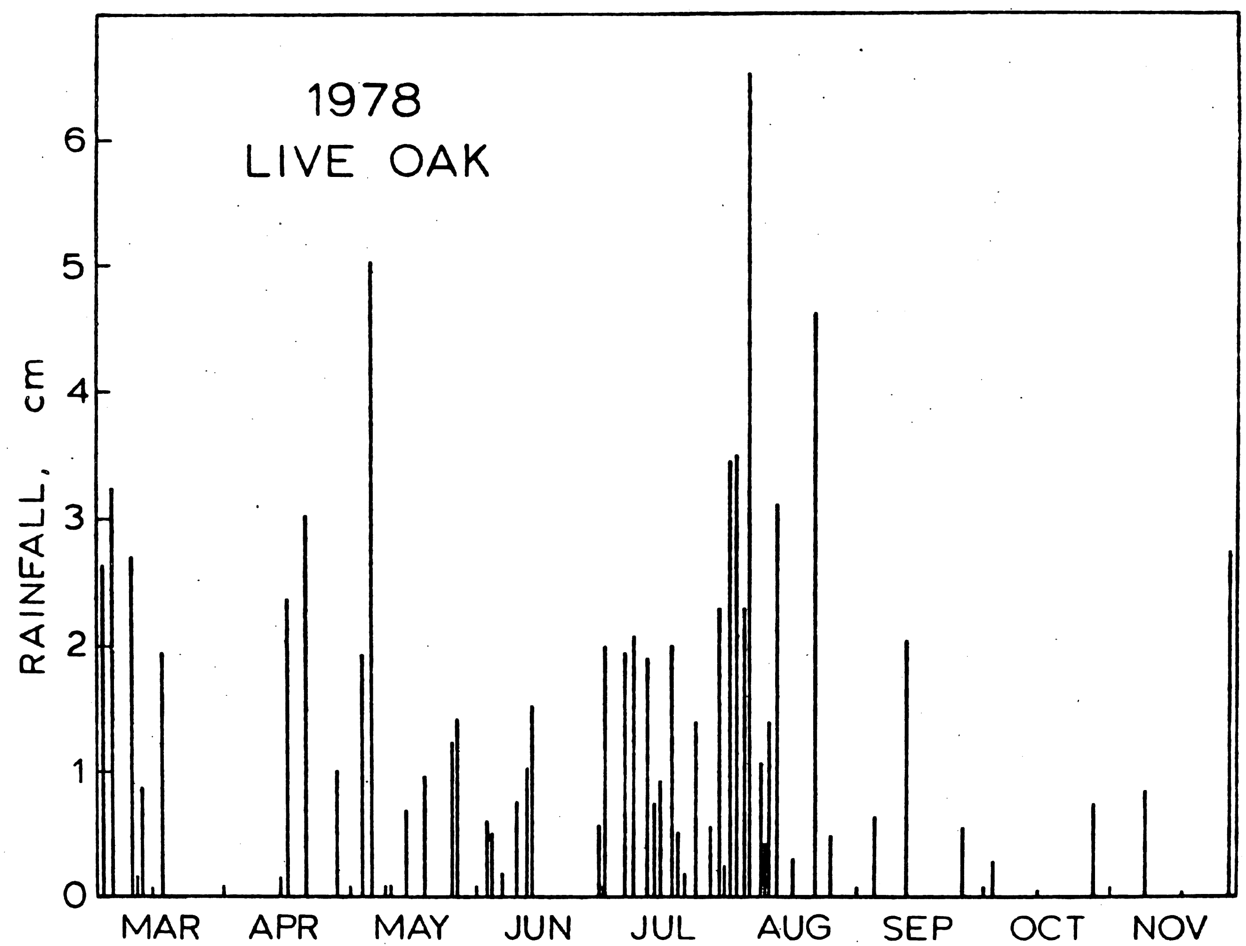

Figure 25. Rainfall distribution, Live Oak, 1978.

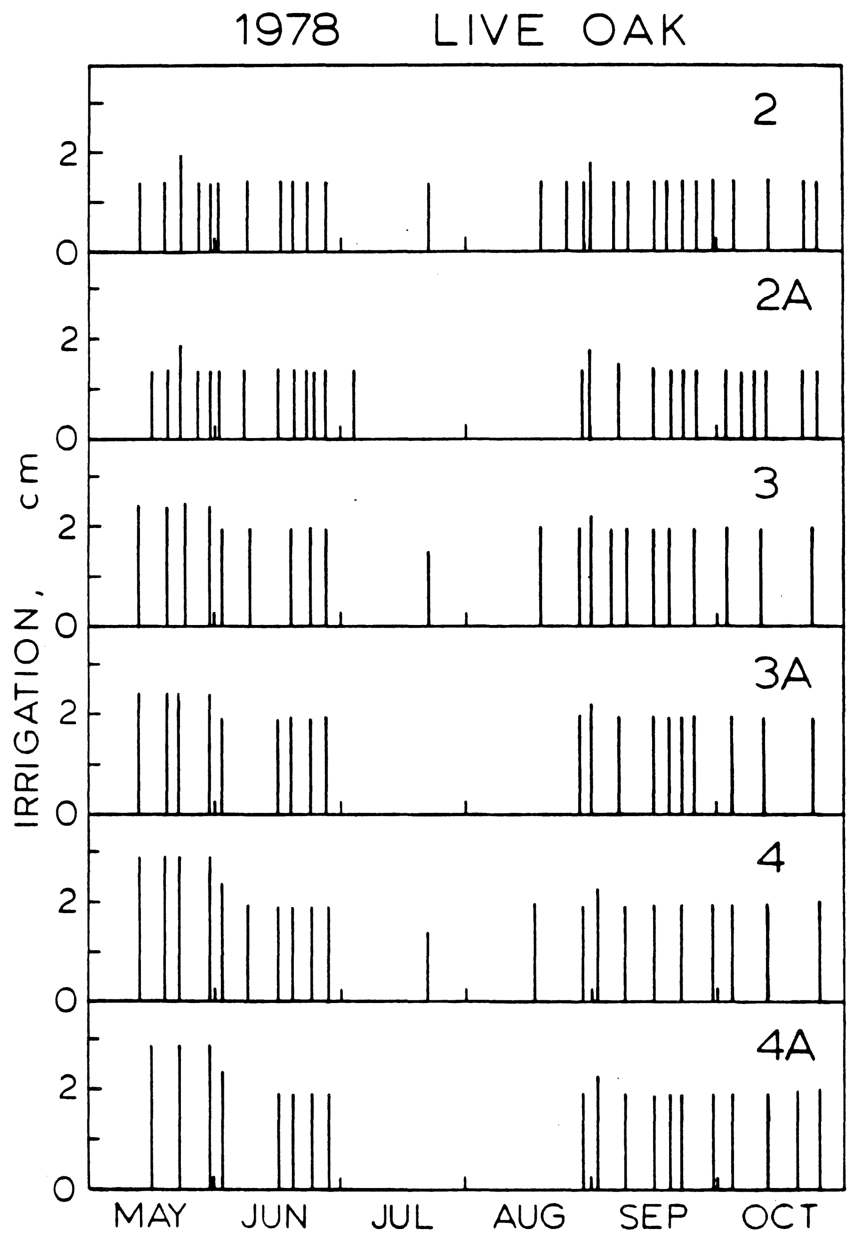

Figure 26. Irrigation distribution for six irrigation treatments on corn, Live Oak, 1978. Treatments with the letter "A" included a subsurface asphalt barrier treatment.

system. There was more drainage loss from the non-irrigated treatment in 1978 than in 1977, although in both years the amount represented a small percentage of the rainfall.

In contrast to several two-way interactions obtained in 1977, only one was found in 1978--irrigation by population (Table 19). On the non-irrigated treatment, the corn yield for the high population treatment was less than that for the lower population. Population had no effect within the irrigated treatments. This result is opposite to the 1977 results where marked response to population increase was obtained for irrigation treatment 2 and 3. However, the maximum number of plants/ha was 79,000 in 1977 versus 90,000 in 1978. Considering the data for both years, it is evident that for DeKalb XL-80, 90,000 plants/ha was larger than required for optimum grain yield. At the same population, treatment 1 means were smaller than all the irrigated treatment means (THSD = 1295). Yields were affected by both barrier and nitrogen fertilizer level (no interaction) as shown in Table 20.

Table 18. Effect of water management on yield of corn and simulated water balance, Live Oak, 1978.

Treatment[1/]	ET	Irrig.[2/]	Profile water depletion[3/]	Drainage	Grain yield
	----------	cm	----------		kg/ha
		Non-barrier			
Non-irrigated (1)	35.77	--	8.05	3.42	2475
Irrigated (2)	41.81	16.20	1.06	6.59	6290
Irrigated (3)	41.81	19.02	1.04	9.39	6353
Irrigated (4)	41.81	23.32	1.14	13.79	6821
		Barrier			
Non-irrigated (1A)	36.53	--	8.06	2.68	3272
Irrigated (2A)	42.10	19.06	0.88	9.00	8509
Irrigated (3A)	42.10	19.02	0.91	8.98	8624
Irrigated (4A)	42.10	18.56	0.91	8.52	7942

[1/] See text for details.

[2/] Rainfall, 31.15 cm.

[3/] Net seasonal water loss from soil profile.

Table 19. Corn grain yields as affected by water management and plant population, Live Oak, 1978.

Treatment[1/]	Grain yield 59,000[2/]	90,000	Average
	- - - - - - -	kg/ha - - - - -	
Non-irrigated (1)	3324	2423	2874
Irrigated (2)	7244	7555	7400
Irrigated (3)	7578	7398	7488
Irrigated (4)	7535	7228	7382
Average	6420	6151	

[1/] See text for details.

[2/] Number of plants/ha.

Table 20. Corn grain yields as affected by subsurface moisture barrier and nitrogen fertilizer level, Live Oak, 1978.

Nitrogen added[1/]	Grain yield No barrier	Barrier	Average
kg/ha	- - - - - - - -	kg/ha - - - - -	
134	5114	6589	5852
268	5819	7606	6713
336	5521	7064	6305
Average	5485	7087	

[1/] N as NH_4NO_3.

Response to nitrogen was curvilinear. The additional 67 kg N/ha over the intermediate level was applied at tasseling and resulted in a reduction in yield in comparison with the yield at the intermediate level. We have not found an explanation for this puzzling result, although there is evidence in Table 17 (1977 data) that response to nitrogen was near maximum at the 269 kg/ha rate.

C. Corn Experiment, 1979

The overall objective was the same as for the 1977 and 1978 experiments. However, plant population was not included as a variable in 1979.

1. Methods

The four water management treatments described earlier were split into six sub-subplots (3 x 12 m) to accommodate factorial treatments of three nitrogen fertilizer levels (84, 168, and 252 kg of N/ha) and two corn hybrids (Coker 77 and McCurdy 67-14). Planting was in 76 cm rows to give a population of 59,000 plants/ha. Water management treatments were the same as in 1977 and '78, and they were assigned to the same field plot locations. The same overhead irrigation system was utilized. Soil water conditions were monitored in replicates 1 and 3 with tensiometers and a neutron moisture meter. Water balance simulations were made in the same way as in 1977 and '78 (see the Appendix Table). Corn was planted March 8, 1977 and harvested August 17.

2. Results and Discussion

Rainfall and irrigation scheduling data are shown in Figs. 27 and 28. The rainfall data in Fig. 28 after July apply to another experiment not reported here. As in 1978, drought conditions were prevalant in May and June of 1979.

Simulated water balance and corn yield data are given in Table 21. Again we have maximum ET values around 42 cm with irrigation. For the unirrigated plots, the low rainfall resulted in ET values of only 30-31 cm which were the smallest values for the three years. Yields from non-irrigated treatments were surprisingly close for the three years. The strange drainage results for the barrier treatments and treatments 1 and 4 (non-barrier) were a consequence of a single drainage-producing rainfall event in early April (Fig. 27).

In spite of a heavy seasonal irrigation for treatment 3, the yield was not comparable to treatments 2A and 3A on the barrier. Comparable yields were obtained on treatments 3 and 4A, but note that 64% less irrigation was required on the barrier. It is likely that yields were limited for treatment 3 by leaching losses of plant nutrients as well as the relatively high deep seepage loss of water.

Irrigated treatment yields in 1979 were equal to or slightly better than in 1977 with somewhat less irrigation use. There was one significant main effect (variety) and two significant two-way interactions: irrigation x fertilizer and irrigation x barrier. The short season variety, McCurdy 67-14, produced a significantly lower yield than the full season variety, Coker 77 (6074 vs 7826 kg/ha). The irrigation x fertilizer interaction is shown in Fig. 29. Yields are averaged over the barrier treatments. Corn did not respond to nitrogen applications when there was a drought condition (treatment 1). Treatment 4, both with and without the barrier, received the least amount of water of the

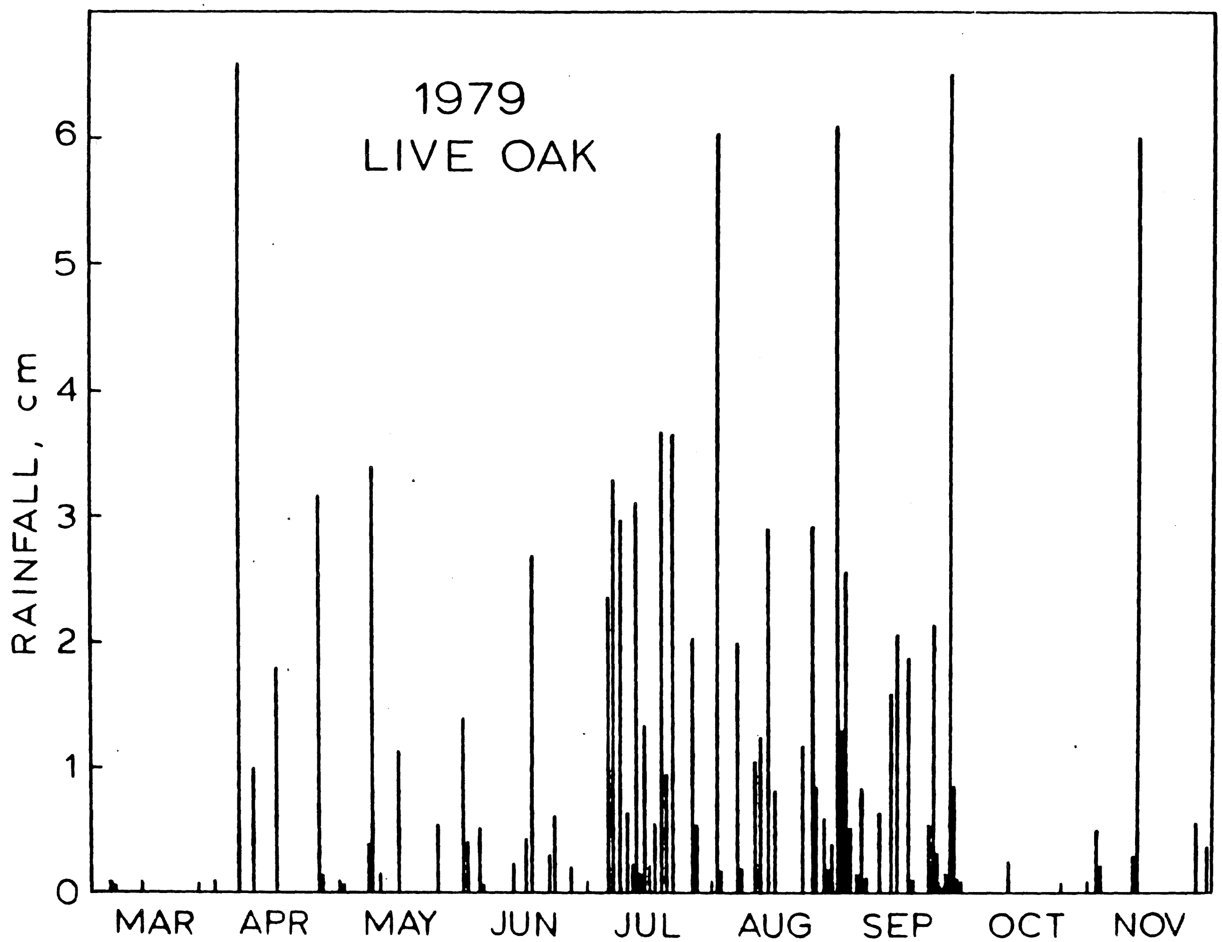

Figure 27. Rainfall distribution, Live Oak, 1979.

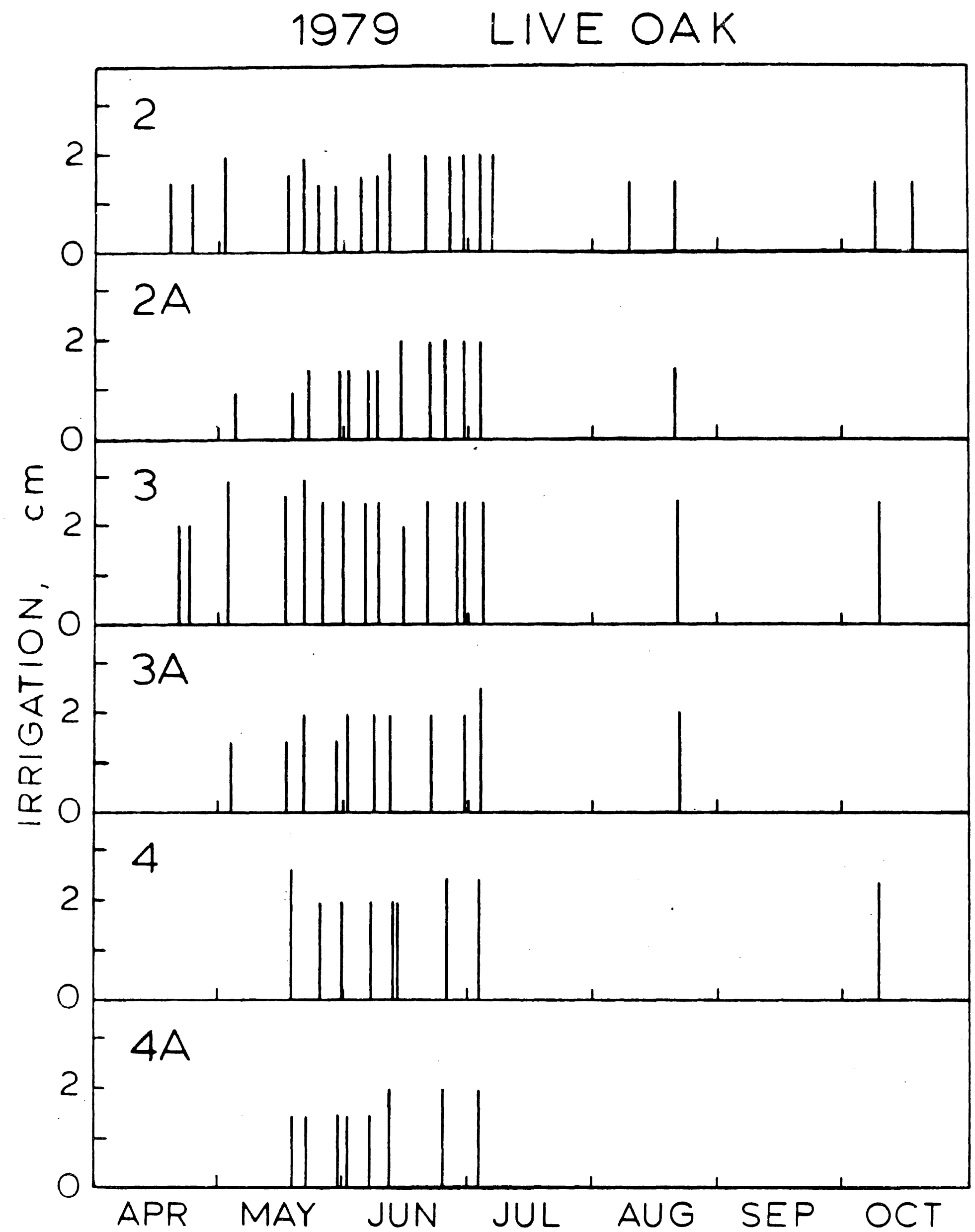

Figure 28. Irrigation distribution for six irrigation treatments on corn, Live Oak, 1979. Irrigations after July are not relevant to current study. Treatments with the letter "A" included a subsurface asphalt barrier treatment.

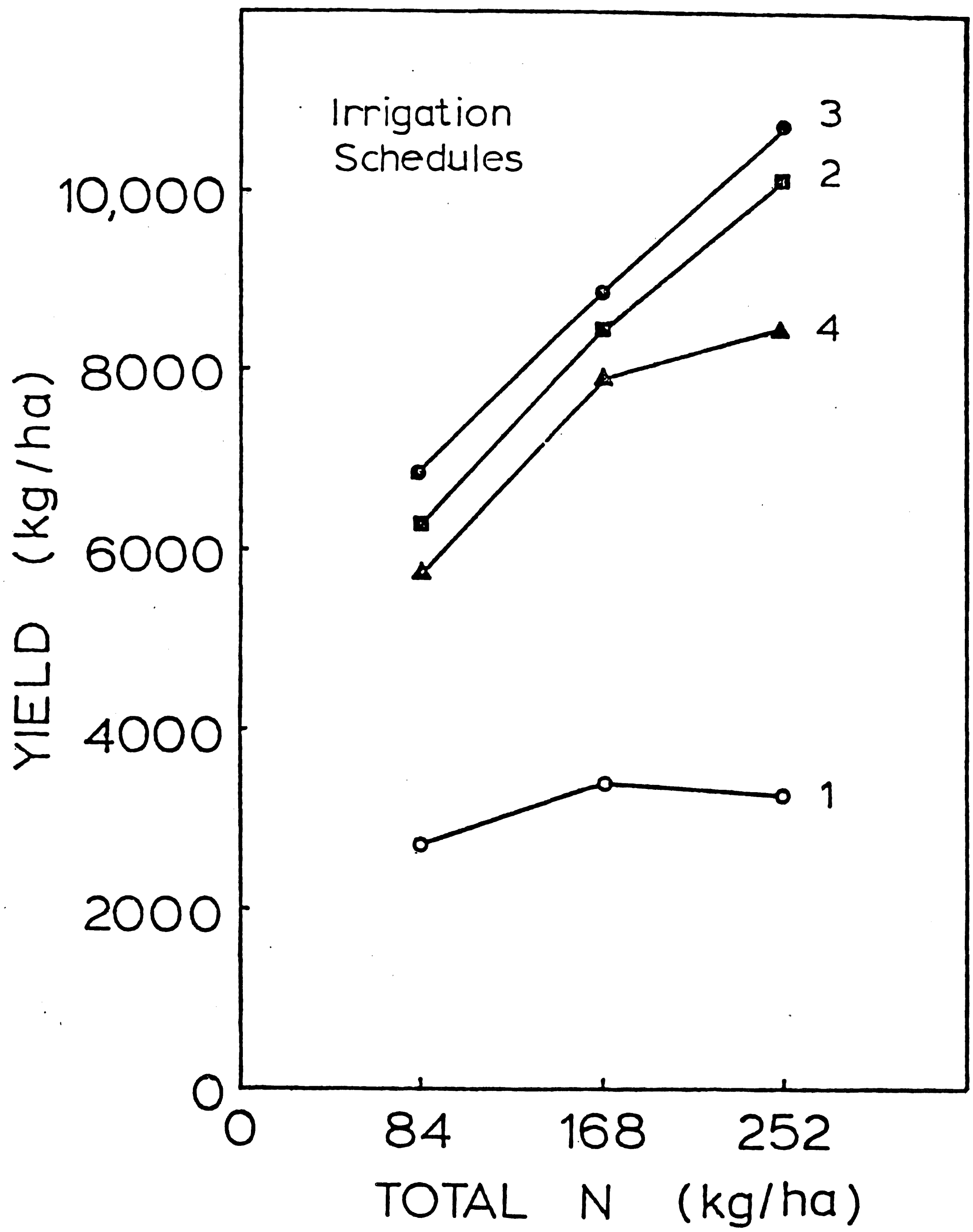

Figure 29. Influence of nitrogen sidedressing rates and water management treatments on yield of corn grain, Live Oak, 1979.

irrigated treatments, and response was limited to the intermediate level of N.

Irrigation x barrier interaction is evident in the data of Table 22. The appropriate significant difference values (THSD) for testing two means are: 1727 kg/ha for two irrigation treatments means at the same barrier treatment, and 1964 kg/ha for two barrier means at the same irrigation treatment. Barrier treatment means were different only for irrigation treatment 2 where yields were higher with the barrier. Yields on the no-barrier treatment were larger for irrigation treatments 2, 3, and 4 than for 1. On the barrier treatment, yields were higher for irrigation treatments 2 and 3, and the yield for irrigation treatment 4 was larger than for non-irrigated treatment 1.

Yield and water data for the three corn experiments at Live Oak were subjected to the same regression analysis as the Gainesville corn data (see Chapter II, C. Corn, 1979; Figures 16 and 17). The Live Oak results are given in Figs. 30 and 31. Differences in response to the barrier treatments were of sufficient magnitude to suggest separate regression lines. For irrigation and ET, the response was steeper with the subsurface barrier. The best-fitting regression equations were obtained with irrigation as a variable rather than ET. Thus, we have further evidence that the simulated ET values may not represent very well the actual ET. Analysis of the tensiometer and neutron data (beyond the scope of this report) should provide information useful in resolving this question.

However, in the Gainesville analysis, the variable ET gave a better fit than irrigation amounts. The response per unit of ET was larger at Gainesville and Live Oak than the response per unit of irrigation. And, in a further comparison of Gainesville and Live Oak data, note that the best fit was obtained for Live Oak using irrigation amounts and for Gainesville using ET amounts. The response per unit of irrigation water was larger at Live Oak than Gainesville; while the response per unit ET was larger at Gainesville. Some of the steep response at Gainesville can be attributed to the depressed yields in 1979 due to soil fertility problems associated with an earlier study in the experimental site. It is unlikely that actual ET was reduced in proportion to the yield reduction.

Finally, as noted earlier for Gainesville, the climatic factors at Live Oak during the three growing seasons must have been very similar to produce the results obtained. Further evaluation of these results and addition of 1980 data may show that Gainesville and Live Oak data can be combined for a regression relationship which will be useful for the North Florida region.

Table 21. Effect of water management on yield of corn and simulated water balance, Live Oak, 1979.

Treatment[1/]	ET	Irrig.[2/]	Profile water depletion[3/]	Drainage	Grain yield
	cm				kg/ha
			Non-barrier		
Non-irrigated (1)	31.61	--	10.11	3.79	2955
Irrigated (2)	41.50	24.01	0.26	8.05	6779
Irrigated (3)	41.50	33.45	-0.17	17.06	8021
Irrigated (4)	40.72	16.77	2.45	4.79	6814
			Barrier		
Non-irrigated (1A)	30.43	--	9.48	4.34	3442
Irrigated (2A)	41.65	17.71	2.15	4.34	9874
Irrigated (3A)	41.65	16.75	3.11	4.34	9761
Irrigated (4A)	41.63	12.01	7.84	4.34	7953

1/ See text for details.

2/ Rainfall 25.29 cm.

3/ Net seasonal water loss from soil profile.

Table 22. Effect of water management and a subsurface moisture barrier on yield of corn, Live Oak, 1979.

Treatment	Grain yield				
	1[1/]	2	3	4	Average
	kg/ha				
No barrier	2955	6779	8021	6814	97.93
Barrier	3442	9874	9761	7953	123.69
Average	3198	8327	8891	7383	

1/ Water management treatments; see text for details.

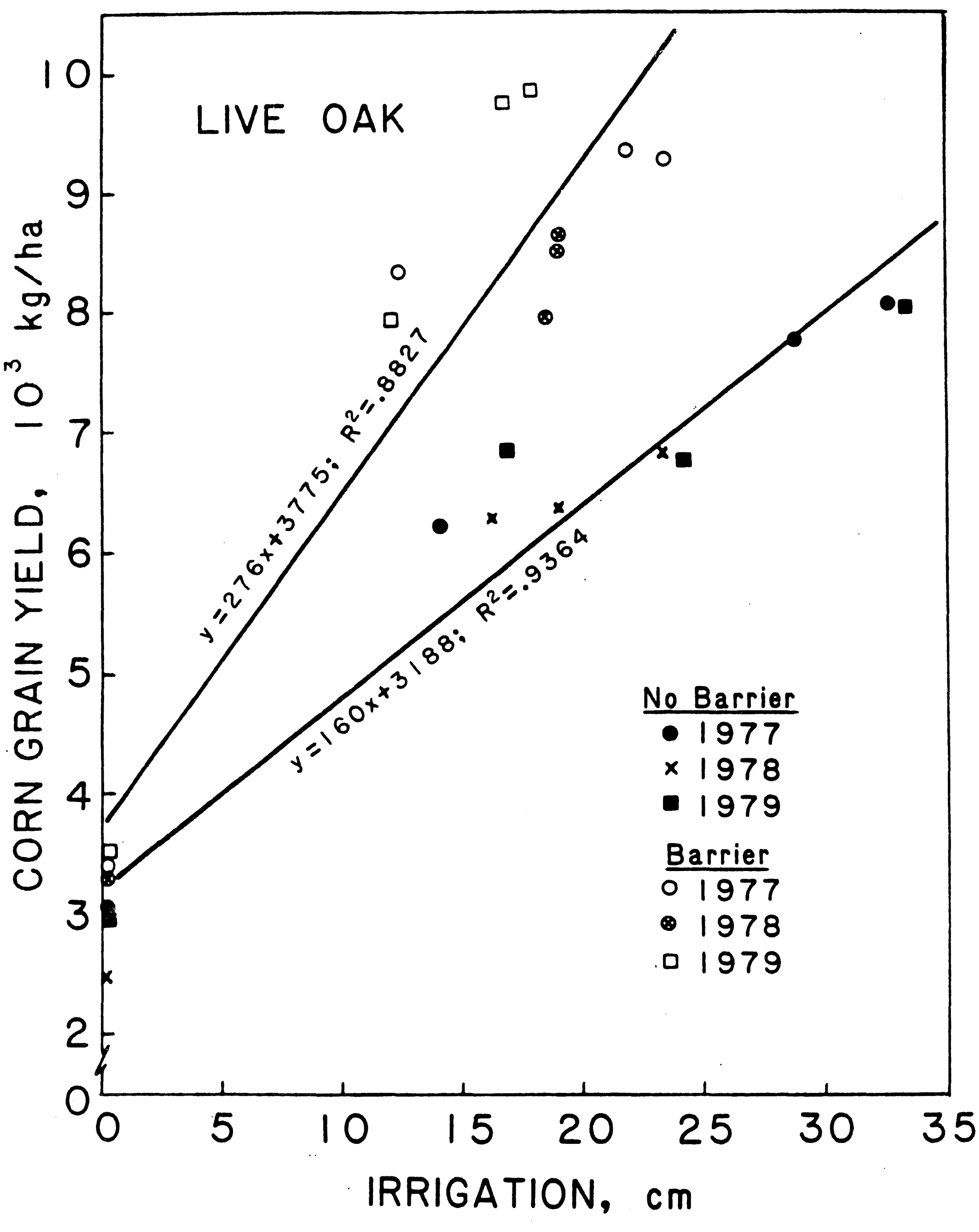

Figure 30. Influence of irrigation amounts and a subsurface asphalt barrier on yields of corn grain, Live Oak, 1977, 1978, and 1979.

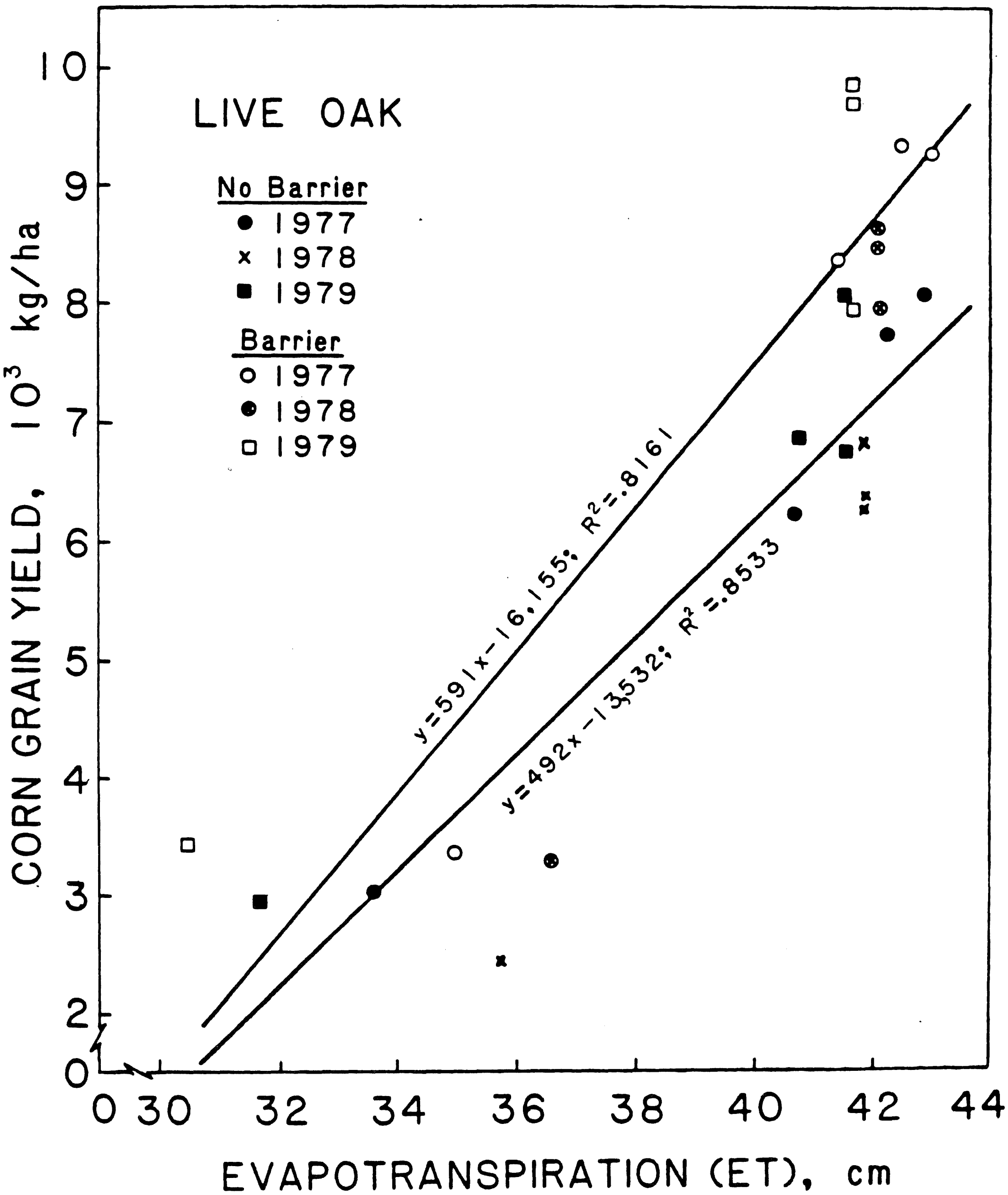

Figure 31. Influence of evapotranspiration and a subsurface asphalt barrier on yields of corn grain, Live Oak, 1977, 1978, and 1979.

CHAPTER IV. SUMMARY DISCUSSION

Results presented in Chapters II and III have important implications to Florida agriculture for scheduling strategies and agricultural water policy. These findings represent an initial effort to fulfill the need for water management information in planning and implementing the efficient use of all resources. Recognition of this need and the initiation of appropriate research programs is of relatively recent origin in Florida.

A. Water-Use Efficiency

Water-use efficiency (WUE) by plants may be expressed in several ways depending on the nature of yields and water-use data available. WUE is commonly defined simply as a yield per unit of water used per season in ET, or total depletion (ET + runoff + drainage). Total depletion is readily measurable since it is also the sum of rainfall, irrigation, and change in soil water storage. Actual ET is not easily measured, hence the common use of estimates. Crop yield, Y, may be expressed as total dry matter or some fraction of it, for example, grain. Crop yield increase (Y-Yo, where Yo is yield without irrigation) per unit of irrigation (I) provides another useful measure of water-use efficiency. In this report total grain yield, yield differences due to irrigation, irrigation amounts and estimated ET are used to calculate water use efficiencies based on irrigation [WUE(I) = (Y-Yo)/I] and on ET [WUE(ET) = Y/ET].

Calculated WUE from the corn experiments are given in Table 23 for Gainesville and Table 24 for Live Oak. Although these data are related to the regression analysis in Figs. 16, 17, 30 and 31, they permit a somewhat more detailed evaluation of the individual treatment effects in each experiment. The slope from the regression equations (irrigation-based, Figs. 16 and 30) are comparable to individual treatment WUE(I) values. However, the WUE(ET) values are based on the whole of ET and not on a threshold value as is the case in the regression analysis. Consequently, the slope of the regression equation is larger than the calculated WUE(ET) values. Also, this line of reasoning suggests that WUE(I) should usually be larger than WUE(ET) for a specific irrigation treatment. Irrigation in excess of ET needs by the crop or a large rainfall soon after irrigation will reduce WUE(I).

Large WUE(I) values may be obtained when small amounts of irrigation water are needed only at critical stages in plant growth. For example, WUE(I) values calculated from the corn data of Robertson, et al. (1973) in experiments on the asphalt barrier plots at Live Oak in 1971 were 0.28 tons of grain per ha/cm of irrigation on the non-barrier treatment and 0.49 tons/ha-cm on the barrier. Corn data of Rhoads and Stanley (1973) gave smaller WUE(I) values, 0.09 and 0.18 for 1970 and 1971. WUE(I) values calculated from corn data of Robertson et al. (1980)

ranged from 0.16 to 0.27 tons/ha-cm. In Colorado, Skogerboe, et al. (1979), found WUE(ET) values for corn ranging from 0.11 to 0.15 tons/ha-cm. The "best treatments" regression coefficient (Y/ET) was 0.18. Calculated WUE(ET) values from three years of corn grain data of Hillel and Guron (1973) in Israel ranged from 0.03 to 0.22 tons/ha-cm. Regression coefficients from their data were 0.54, 0.44, and 0.45 tons/ha-cm in 1968, '69, and'70, respectively. These coefficients are in the range of our three-year average values given in Figs. 17 and 31.

Table 23. Water-use efficiency of corn, Gainesville, 1977-79.

Treatment[1]	Water-use efficiency (WUE)[2] 1977 Exp. I	1977 Exp. II	1978	1979
	------ tons/ha-cm ------			
		Irrigation Basis		
Non-irrigated (1)	-	-	-	-
Irrigated (2)	0.20	0.16	0.22	0.24
Irrigated (3)	-	0.09	0.21	0.18
Irrigated (4)	-	-	0.23	0.21
Irrigated (5)	-	-	-	0.26
		ET Basis		
Non-irrigated (1)	-	0.01	0.06	0.04
Irrigated (2)	0.19	0.17	0.17	0.12
Irrigated (3)	-	0.19	0.16	0.12
Irrigated (4)	-	-	0.16	0.10
Irrigated (5)	-	-	-	0.07

[1] See Chapter II for details.

[2] Calculated from yield and water balance data in Tables, 4, 8, and 13. Water-use efficiency irrigation basis and ET basis abbreviated in text thusly: WUE(I) and WUE(ET).

In Tables 23 and 24, we find several treatments with WUE(I) values less than WUE(ET). In all cases, these treatments received rather large irrigation applications. For treatments 2 and 3, Gainesville 1977, the irrigation amounts were equal to or greater than ET (Table 4). Thus either ET was underestimated or irrigation amounts were greater than needed. On the other hand, irrigation amounts were not measured but calculated for the spinkler system. For treatment 3 with no barrier (Live Oak 1977 and 1979), the WUE(I) values were reasonable in magnitude, but still less than WUE(ET).

Table 24. Yield and water-use efficiency of corn, Live Oak, 1977-79.

Treatment[1]	Grain yield[2]		WUE[3], irrigation basis		WUE[3], ET basis	
	No barrier	Barrier	No barrier	Barrier	No barrier	Barrier
	kg/ha	kg/ha	-ton/ha-cm-			
			1977			
Non-irrigated (1)	2756	2889	-	-	0.08	0.08
Irrigated (2)	8487	10290	0.20	0.34	0.20	0.24
Irrigated (3)	9552	11285	0.21	0.36	0.22	0.26
Irrigated (4)	6315	9466	0.25	0.53	0.16	0.23
			1978			
Non-irrigated (1)	2603	3810	-	-	0.07	0.10
Irrigated (2)	5802	8342	0.20	0.24	0.14	0.20
Irrigated (3)	6617	8781	0.21	0.26	0.16	0.21
Irrigated (4)	6711	8279	0.18	0.24	0.16	0.20
			1979			
Non-irrigated (1)	2899	4553	-	-	0.09	0.15
Irrigated (2)	9045	13680	0.26	0.52	0.22	0.33
Irrigated (3)	11683	12422	0.26	0.47	0.28	0.30
Irrigated (4)	8764	9783	0.35	0.44	0.22	0.23

[1] See Chapter II for details. See also Tables 14, 18, and 21 for irrigation and ET data.

[2] Yields differ slightly from those given earlier since the following treatments only were selected: 1977, population and fertilizer levels of 79,000 plants/ha and 269 kg N/ha; 1978, population and fertilizer levels of 59,000 plants/ha and 252 kg N/ha.

[3] Water-use efficiency. Irrigation and ET basis designated as WUE(I) and WUE(ET) in text.

An interesting comparison of WUE(I) and WUE(ET) values is provided by treatment 5, Gainesville 1979 (Table 23). A small irrigation amount produced a large yield increase, but the WUE(ET) value was still very low. This results from the nature of the response curve; low yields give low WUE(ET) values and these measures of WUE should be used together with seasonal regression coefficients (as in Figs. 5 and 13) in evaluating irrigation treatment effects.

The advantage of the moisture barrier system over the no-barrier system is clearly evident in the differences in water-use efficiency values (Table 24). In addition, the fact that water-use efficiency was substantially increased by irrigation has important implications on resource management. When there is appreciable drought, the decision not to irrigate can be a wasteful use of water as well as of other resources!

Peanuts and soybeans gave lower water use efficiencies than corn (Table 25) as expected for high protein and oil producing crops.

Table 25. Water-use efficiency of peanuts and soybeans, Gainesville.

Treatment[1]	Water-use efficiency (WUE)[2]		
	Peanuts, 1977	Peanuts, 1978	Soybeans, 1978
	tons/ha-cm		
	Irrigation Basis		
Non-irrigated (1)	-	-	-
Irrigated (2)	0.12	0.03	0.09
Irrigated (3)	0.13	0.05	0.08
Irrigated (4)	0.11	-	0.10
Irrigated (5)	-	-	0.09
	ET Basis		
Non-irrigated	0.06	0.09	0.03
Irrigated (2)	0.08	0.08	0.06
Irrigated (3)	0.08	0.09	0.06
Irrigated (4)	0.07	-	0.05
Irrigated (5)	-	-	0.06

[1] See Chapter II for details.

[2] Calculated from yields and water balance data in Tables 7, 8, and 11. Water-use efficiency irrigation basis and ET basis abbreviated in text thusly: WUE(I) and WUE(ET).

In most cases, irrigation increased water use efficiency, and treatments 2 and 3 were the best. The 1978 peanut data show very low WUE(I) values, and they are less than WUE(ET) values. This probably indicates that too much irrigation was used in that year on a deep-rooted crop. Note that WUE(ET) values were about the same in both years, except for the non-irrigated treatments.

The 1977 peanut data in Table 25 and in Figure 5 provide an interesting contrast in data presentation and evaluation. Calculated WUE(ET) equations because there is a threshold ET value, 23 cm. This is not the case for the irrigation-based regression; the coefficient for soybeans, Figure 13, is about the same as WUE(I) values in Table 25. The excellent fit of the peanut and soybean data indicates that no significant between-treatment variations in other management factors were present. A regression coefficient of 0.138 tons/ha-cm was calculated from peanut (Florunner) data of Pallas et al. (1979) in Georgia.

Figure 5 provides another comparison in data representation - one year versus three years of data as in Figs. 17 and 31. As expected, there was a considerable year to year variation in the simulated ET for non-irrigated treatments. Since the yields were nearly the same this contributed to a much lower R^2 value than would have been obtained with annual regression equations.

Comparison of irrigation and ET annual regression equations contrasts with comparisons of WUE(ET) and WUE(I) values. Theoretically, the two regression coefficients could be nearly equal. The required conditions are: (1) ET is actual seasonal ET, and (2) accurately measured seasonal irrigation inputs contribute to ET in the same way for each treatment, i.e. the quantity of irrigation not used to increase ET (runoff and drainage losses and increase in soil storage) is the same. Even if actual ET data were available, it is not likely that the second requirement would be fulfilled in most irrigation experiments. Thus, in view of the nature of the crop-response, water-use relationship discussed earlier, it is reasonable to expect that the irrigation-based regression coefficient will be less than the ET based coefficient. This was the case for all experiments in the current study.

Regression of peanut yield on ET (Fig. 5) gives a regression coefficient of 162 kg/ha-cm, a value larger than the regression coefficient for yield on irrigation:

$$Y = 124X + 2241 \quad (R^2=0.99)$$

where Y is pod yield, kg/ha, and X is seasonal irrigation amount in cm.

Comparison of these two regression coefficients provides a very revealing test of the success attained in irrigation management. The ideal ratio of b_I/b_{ET} (where b is the regression coefficient) would be one. In this case we have 124/162 = 0.765, the highest ratio obtained in the studies reported here (Table 26). These surprising results suggest further evaluation in terms of economics of irrigation as well as of the variable irrigation effectiveness achieved.

Table 26. Water-use efficiencies from the water management experiments of this report in terms of yield versus water-use regression coefficients and their ratios.

Crop	Location of experiment	Total years	Regression coefficient Y vs. I kg/ha-cm	Regression coefficient Y vs. ET kg/ha-cm	Ratio,[1/] b_I/b_{ET}
Peanuts	Gainesville	1	124	162	0.765
Soybeans	Gainesville	1	84	144	0.583
Corn	Gainesville	3	143	661	0.216
Corn	Live Oak	3	160	471	0.340
Corn[2/]	Live Oak	3	276	591	0.467

[1/] b_I and b_{ET} are regression coefficients of yield on irrigation and evapotranspiration, respectively.

[2/] Soil profile modified with a subsurface asphalt barrier.

B. Irrigation Scheduling

Results from the present study show that an irrigation management strategy of frequent application at rates which only partially fill the ET and drainage-depleted soil profile will conserve water while meeting the water needs of crops.

An irrigation scheduling plan is presented here whereby this concept can be put into practice by farmers and other growers in Florida. Perhaps more importantly, the basic concepts of the plan can be used by industry in developing new irrigation systems and in designing new and replacement irrigation installations. Moreover, there is a current rapid development of commercial irrigation scheduling services based on a growing sophistication in communication, measurement of the physical system, computer simulation, and crop growth model development. Tools needed by the farmer to utilize this method of scheduling irrigation for crop production are a low-cost rain gauge, a radio for weather forecasts, a chart of daily potential ET estimates (Table 1), and a shovel to aid in making periodic observations of the top 30 to 45 cm of the soil profile.

The basic plan is to irrigate the top 30 cm of the soil profile often enough to prevent more than short-term (a few hours) wilting of plants. The amount of water needed can be estimated by examining the soil profile for depth of water percolation 12 to 24 hours after a measured application. A starting test irrigation amount per irrigation event for sandy soils should be in the range of 1.5 to 3.0 cm (approximately 1/2 to 1 inch).

Once irrigation has been initiated, subsequent scheduling during the drought is based upon the estimated daily ET and the amount of water added in the last irrigation. For example, assume an irrigation of 1.7 cm applied to a crop in Gainesville on May 15. The estimated ET value from Table 1 is 0.411 cm/day. Thus, dividing 1.7 by 0.411 we have four days or May 19 before the second irrigation is scheduled. A rainfall of about 0.5 cm would delay irrigation for a day.

There is an upper limit characteristic of the soil type, for the quantity of water which can be stored in the soil root zone. And, only a fraction of this amount can be transpired by the plant before temporary wilt develops. It is this fraction the usable soil water capacity, which must serve as a maximum in the above calculations. New estimates are needed throughout the season as root growth extends to increasing soil depths. To obtain the estimate, observe the growing crop over a period of rainless days following a rainfall which established a wet soil profile throughout the root zone. When the plants begin to show stress (temporary wilting) by mid afternoon or earlier in the day, it is time for the initial irrigation. Add up the days since rainfall and multiply by the expected ET for that period to obtain the estimated usable water storage. To continue the above example, assume an elapse of 7 days without rainfall prior to the May 15 irrigation. Seven days times 0.411 cm equals 2.88 cm of maximum usable storage for the particular soil and plant root depth.

Use of the maximum usable storage value in irrigation scheduling can be seen in a further step of the example above. First of all, the value is not needed as long as irrigation or rainfall does not completely restore to capacity the partially depleted soil profile. Assume, a rainfall of 1.6 cm one day after the May 15 irrigation (1.7 cm). The maximum usable storage has been restored since rainfall plus irrigation minus one day of ET equals 2.89 cm. Dividing 2.88 by 0.411 predicts an irrigation date (May 23) 7 days after the rainfall on the 16th. If the rainfall had been larger than 1.6 cm, the maximum usable storage value of 2.88 would still be used in the calculations. On the other hand, in both cases, the soil root zone would be restored to capacity, and one could begin anew to determine an initial irrigation by observation. There is a second point in the illustration just given - a justification for an irrigation amount which leaves some storage for rainfall. The rainfall of 1.6 cm did not produce deep seepage loss of water and nutrients.

In actual practice, the irrigation scheduling plan can be altered in line with keen and experienced observation of weather conditions, crop appearance and growth stage, and the soil water status. A probability of rain may justify a decision to delay a scheduled irrigation or to apply a smaller quantity if the irrigation system will permit. On the other hand, unusally hot days with low relative humidity will cause the actual ET to be higher than predicted and a shorter irrigation interval will be necessary. Additional help in using the irrigation scheduling plan can be obtained with soil water measuring devices such as the tensiometer.

Some current irrigation installations cannot be used effectively to apply the small amount per event on a frequent schedule. However, the basic scheduling principles of the plan can be helpful in getting the most efficiency from the available installation or in making modifications to it, and above all in planning of new installations. The above plan is a simple one, but it is workable and will lay the ground work for the more advanced irrigation systems and scheduling plans already in the research and development stages.

C. Water Policy for Agriculture in Florida

The findings from the current study as well as others in the broad field of soil-water-climate relationships can be integrated with information on the geology-soil-climate-hydrologic system in Florida to develop a physically-based philosphy on water-use policy in agricultural production.

The current study revealed an important characteristic of water use by plants. Crop yield increased linearly with increasing seasonal ET. Reduction in actual ET at one stage of crop growth cannot be recovered at a later stage and yield reduction occurs irreversibly. Consequently, water use is less efficient, and returns from other production inputs (capital, fertilizer, pesticides, fuel, and labor) are reduced. The conclusion is that agricultural production must be based on a full utilization of water up to the maximum ET demand of the atmosphere. The adoption of an agricultural water policy based on this management objective is compatible with Florida's unique soil-climate-hydrologic resource.

The average annual rainfall in Florida ranges from about 132 to 165 cm, while potential ET has been estimated to range around 100 cm. Consequently, the excess of rainfall over actual ET recharges the water storage capacity of soils, aquifers, lakes, and streams, and maintains a net outflow of water from the State through streams and underground seepage along the coast. The storage components of the hydrologic cycle are the source of water for municipal, industrial and agricultural use.

Important differences in water requirement and use among the above users need to be recognized in water planning and policymaking. Much of municipal and industrial use is non-consumptive. It is not lost to the atmosphere, but disposal of the physically and/or chemically altered water is a necessary phase of the water-use operation. Multiple cycles of use before discharge reduces the overall quantities needed. Municipal and industrial activities are commonly so concentrated on land areas that the water requirement exceeds the rainfall input of those areas. The resultant imbalance in local hydrology must be eventually offset by water input from adjacent or remote sources.

On the other hand, agricultural water use is largely consumptive since most of it is transpired through plants and evaporated from soil. Water evapotranspired or consumptively used is finite in quantity, the upper limit being equal to the evaporative demand of the atmosphere. In Florida, this is less than average rainfall. Consequently, if only the consumptive use is recognized as an agricultural use, then agriculture does not cause an imbalance in the local hydrology.

There is a seasonal crop production water need which turns out to be larger than consumptive-use need during that season. The reason for this is the uneven rainfall distribution on a soil root zone of limited water storage capacity. During droughts, the farmer must recall water from stored sources mentioned earlier in order to meet evaporative demands and to keep crops growing and producing efficiently. It is inevitable that not all rainfall and irrigation inputs will be used for evapotranspiration and storage in the soil; some will contribute to runoff and deep seepage. The latter quantities are not consumptive uses, do not represent a loss from the available water resource, and should not be so designated if assigned as an agricultural use. Nevertheless, the agricultural producer must do his part to minimize surface runoff and deep seepage during the crop production season, since non-consumptive uses represent increased production costs in pumped water not used by the crop and in fertilizers and pesticides lost by leaching.

Crop production enterprises in Florida which utilize seepage irrigation require total water inputs greatly in excess of consumptive-use or evapotranspiration needs. Consequently, alternative crop production and water management systems may be needed in some of these agricultural areas in order to meet the economic demands as well as to avoid undue disturbance of the hydrologic balance. It should be stated that the majority of the irrigated cropland in Florida is irrigated by overhead sprinklers. Moreover, on an annual basis, except for perennial crops, crop production water needs are usually less than potential evapotranspiration because the land is fallow during part of the year. In fact, ET water needs of agriculture are less than for natural vegetation.

In view of the characteristics of water use in agriculture and the findings of this study, the objectives of research and education in this field should be to develop crop production systems which maximize return from production factors other than water, but which incorporate a water management scheme which meets actual ET demands while minimizing the loss of water by runoff and drainage. The implication in terms of water policy are:

1. The Florida climate, characterized by rainfall in excess of ET, justifies a full use of ET for crop production, especially for annuals where the farmer can be considered to have accumulated a stored-water credit from earlier rainfall in excess of ET. Irrigation to maintain potential ET is the most efficient use of water.

2. In view of the economic and energy waste incurred by water deficit during crop growth, there should be no drought-triggered reduction in allocation of water to agricultural enterprises which use water within the bounds of average annual ET. Further justification in terms of food and fiber needs can be made on the basis that not all of agricultural cropland is under irrigation. Thus, production from irrigated farms will be needed to make up for production inefficiencies of non-irrigated farming.

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ABSTRACTS OF PUBLISHED PAPERS

1. Rao, P. S. C., J. M. Davidson, and L. C. Hammond. 1976. Estimation of nonreactive and reactive solute front locations in soils. In: Residual Management by Land Disposal. Proc. Hazardous Waste Residue Symposium. Tucson, AZ p. 235-242.

A technique, based on the physical principles of water and solute transport, was used to describe the position of nonreactive and/or reactive solute fronts in a soil profile. The procedure estimates the solute front location after infiltration and redistribution of the soil water to "field capacity," and includes extraction of soil water by plant roots between irrigation/rainfall events. Linear equilibrium adsorption-desorption of the reactive solutes was assumed. The approximation procedure was based on the principles that (i) the soil water residing in all pore sequences participates in the transport processes, and (ii) the soil water initially present in the profile is completely displaced ahead of the water entering at the soil surface. An analysis of published field and laboratory data on infiltration of nonreactive solutes (Cl^- and NO_3^-) indicated that these assumptions were valid. Agreement between predicted solute front location using a sophisticated one-dimensional transient flow models and the above procedure further support the validity of the assumptions. Field data for chloride movement in a sandy soil, in the presence of a fully established millet crop, during a 60-day period were in agreement with the simplified model. The major drawback of the present technique is in its failure to describe the attenuation or spreading of a solute pulse as it is leached through the soil profile.

2. Selim, H. M., L. C. Hammond, and R. S. Mansell. 1977. Soil water movement and uptake by plants during water infiltration and redistribution. Soil and Crop Sci. Soc. Fla. Proc. 36:101-107.

A numerical solution of the equation governing soil water movement and uptake by plants during infiltration and redistribution was used to investigate the influence of the amount of irrigation and soil nonuniformity on deep seepage loss and soil water storage in the root zone. For a uniform Lakeland sandy soil the deep seepage loss increased as the amount of water applied in an irrigation event increased. However, the presence of a low permeability lower layer in a two-layered soil profile was beneficial in increasing soil water storage and in minimizing deep seepage loss. Such a decrease in deep seepage loss was more pronounced when large amounts of irrigation were applied and the hydraulic conductivity of the lower layer was extremely small. For small irrigations, the influence of a low permeability lower layer on deep seepage loss was essentially negligible.

3. Rhoads, F. M., R. S. Mansell, and L. C. Hammond. 1978. Influence of water and fertilizer management on yield and water-input efficiency of corn. Agronomy Journal. 70:305-308.

Damaging plant water stress develops in corn grown on coarse-textured, low water retaining soil of the southeastern U.S. during 1 to 2-week periods without rainfall. However, in most years rainstorms cause leaching of soluble fertilizers from the root zone. This study was conducted to evaluate efficiency of water input in terms of corn grain yield per unit of water, with two fertilizer systems on a Troup loamy sand (Grossarenic Paleudult). Water management consisted of (a) control--natural rainfall only, (b) trickle irrigation scheduled daily (0.64 cm/day), and (c) trickle irrigation scheduled by tensiometer (1.30 cm/application). Tensiometers were placed in each treatment at six depths between 15 and 150 cm below the soil surface and readings were recorded daily. Methods of applying fertilizers were designated (a) conventional--1/3 of N and all P and K applied broadcast preplant, and remainder of N applied in two sidedressings; (b) program fertilization--N-P-K applied broadcast in small increments (5, 5, 10, 20, 20, 20, and 20%) at 2-week intervals after corn emerged. Average grain yields for the above water management treatments were 2,790, 4,160, and 5,700 kg/ha respectively. Conventional fertilization had an average grain yield of 3,680 kg/ha and program fertilization 4,760 kg/ha. Water-input efficiencies based on grain yields and total water input were 57, 42, and 76 kg/ha/cm for no irrigation, daily irrigation, and tensiometer scheduled irrigation respectively. Highest irrigation water-input efficiency (150 kg/ha/cm) occurred with program fertilization and tensiometer scheduled irrigation. Irrigtion water-input efficiency was lowest (10 kg/ha/cm) with corn receiving daily irrigation and conventional fertilization.

4. Robertson, W. K., L. C. Hammond, J. T. Johnson, and G. M. Prine. 1978. Root distribution of corn, soybeans, peanuts, sorghum, and tobacco in fine sands. Soil and Crop Science Soc. of Fla. Proc. 38:54-59.

A knowledge of the root distribution of plants contributes to decisions on how to fertilize, irrigate, select cultivars, and till the soil more effectively. In this paper, we report root patterns to a depth of 150 cm for corn (*Zea mays* L.) on Lakeland fs, a thermic, coated, Typic Quartzipsamment; soybeans (*Glycine max* (L.) Merr.) on Kendrick fs, a loamy, siliceous, hyperthermic, Arenic Paleudult; peanuts (*Arachis hypogaea* L.) on Lake fs, a hyperthermic, coated, Typic Quartzipsamment; sorghum (*Sorghum bicolor* L. Moench) on Arredondo fs, a loamy, siliceous, hyperthermic, Grossarenic Paleudult; and tobacco (*Nicotiana tabacum* L.) on Lakeland fs, a thermic, coated, Typic Quartzipsamment. The line intercept technique was used to determine root density in 5.0 cm diameter soil cores. Lakeland fs was located on the Agricultural Research Center near Live Oak and the remaining soils were on the

Agricultural Experiment Station farm, Gainesville. All soils were fine sands; however, depth to clay for Kendrick and Arredondo was shallower (120 to 150 cm) than for the remaining soils. The latter two soils had higher Al contents associated with the clay but it was not believed to be at a high enough level to be toxic to plants.

The crops ranked in order of root length density as follows: soybeans > corn > tobacco > peanuts > sorghum; but on a single plant basis the order was: tobacco > corn > soybeans > peanuts > sorghum. On the basis of length per unit weight of root the order of crops was: peanuts > soybeans > corn = tobacco = sorghum. In most instances, root size was greater and root length density less in the area of the plow sole at 30-45 cm. The roots of corn, soybeans, and sorghum were finer, tobacco coarser, and peanuts the same size in the middle between the rows as compared to under the row.

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The efficient recovery by crops of added nutrients and water is influenced by plant rooting characteristics. Published data on the relationship of irrigation water and root distribution of certain crops grown on sandy soils in humid regions are limited and needed. This field of study was a part of an investigation on three soil types to determine the effect of plant-water stress and irrigation on root distribution of corn (*Zea mays* L.), soybeans [*Glycine max* (L.) Merr.], and peanuts (*Arachis hypogaea* L.). The basic irrigation plan was to replenish the water deficit in only the top 30 to 60 cm of the soil profile. Depth of wetting and the degree of soil water depletion below the irrigated soil layer varied with irrigation frequency and amount of water per application. Although treatments were not the same in the four experiments reported, the major part of the study involved four water management treatments: 1) no irrigation; 2) light, infrequent irrigation; 3) light, frequent irrigation; and 4) medium, infrequent irrigation. Seed yields were obtained at maturity and root length measurements were made at full canopy. Root lengths per unit volume of soil were measured by the line intercept method. Yields of corn and peanuts increased with total amount of irrigation water used, but there was no yield response to irrigation in the soybean experiment. Peanut and soybean root growth (root length per unit area to a depth of 150 cm) was not affected by water management. In the corn experiments, irrigation increased the length of roots in the 150 cm soil profile. The largest root length value was found in the light, infrequent irrigation treatment. Crops vary in rooting response to plant-water stress and irrigation strategy. Limited rooting of corn under stress very likely decreases the efficiency of water and fertilizer use.

APPENDIX TABLE

Soil water characteristic data used in water balance simulations.

Soil type[1]	Depth	Field capacity	15-bar
	cm	cm^3/cm^3	cm^3/cm^3
Lakeland, f.s.	0-32	0.100	0.025
	32-92	0.085	0.022
	92-152	0.075	0.022
	152-180	0.065	0.022
Lakeland, f.s. with barrier	0-8	0.100	0.025
	8-16	0.120	0.025
	16-32	0.120	0.025
	32-40	0.150	0.022
	40-44	0.200	0.022
	44-52	0.220	0.022
	52-64	0.260	0.022
Arredondo, f.s.	0-32	0.100	0.025
	32-60	0.085	0.022
	60-132	0.070	0.020
	132-148	0.085	0.020
	148-168	0.150	0.020
Lake, f.s.	0-28	0.075	0.022
	28-180	0.065	0.022
	180-200	0.065	0.022
Kendrick, f.s.	0-16	0.090	0.022
	16-32	0.080	0.022
	32-128	0.075	0.020
	128-136	0.110	0.025
	136-148	0.210	0.100

[1] Lakeland soil located at Live Oak; others located at Gainesville. Abbreviation f.s. means fine sand.