WATER CONSTRAINTS TO CORN
PRODUCTION IN CENTRAL BRAZIL

A Thesis
Presented to the Faculty of the Graduate School
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Doctor of Philosophy

by
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BIOGRAPHICAL SKETCH

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He is a member of the American Society of Agronomy and the author of five published articles.

He is married to the former Marilea Adams of Quincy, Florida. They have two boys, Thomas, age 6 and Jeremy, age 4.

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PREFACE

Successful agricultural development hinges upon a good economic climate and broad understanding of the physical and social environments relevant to the country/region in question. The physical environment may be thought of as the resources of land, water and air; the social environment includes the people, the institutions and the political framework requisite for that development. For completeness of detail, each environment is most appropriately studied separately. For the development process to succeed, the results of studies of both environments should be combined into a plan for development which takes ample recognition of both environments and which does this before, not after, development has occurred. The development spawned by the City of Brasilia offers challenge in this respect for it will be the precursor of a type of agricultural development and a model for a vast area of Central Brazil. For it to be a success, these conditions, joint recognition of and planning for physical and social factors, must be met.

Increased food production will be a large contribution to, but not the final measure of successful agricultural development. Success implies an equitable distribution of the benefits from that production for the betterment of the lives of a large segment of the population.

In terms of agricultural development, this thesis is a narrow study generally confined to the physical environment. Yet the work is a broad one embracing land and water aspects of that environment and how these may influence the agronomics of food production. It is toward that objective that this thesis makes a small contribution.

CHAPTER I

INTRODUCTION

Background

Brazil's Central Plateau is an immense area occupying almost one-quarter of the area of the country. The Federal District of Brazil, slightly larger than the state of Delaware, occupies a central position on the Plateau, both geographically (see figure 1), and in the eyes of planners who see the City of Brasilia as the nucleus for regional development of this vast area.

In the early 1800's the area of the present Federal District was mentioned by some as a possible location for an interior capital. The Constitution of 1891 made provision for the establishment of a capital in this region, and in the following year, the Cruls Commission surveyed and set the boundaries on an area which would become the Federal District. Present boundaries were established in 1956. Under the direction of President Kubitschek, construction of Brasilia began in 1957. The city and surrounding Federal District currently have a population of over 800,000.

Although the Federal District is higher and somewhat cooler than much of the Plateau, physically the District is typical of a vast area of Central Brazil.

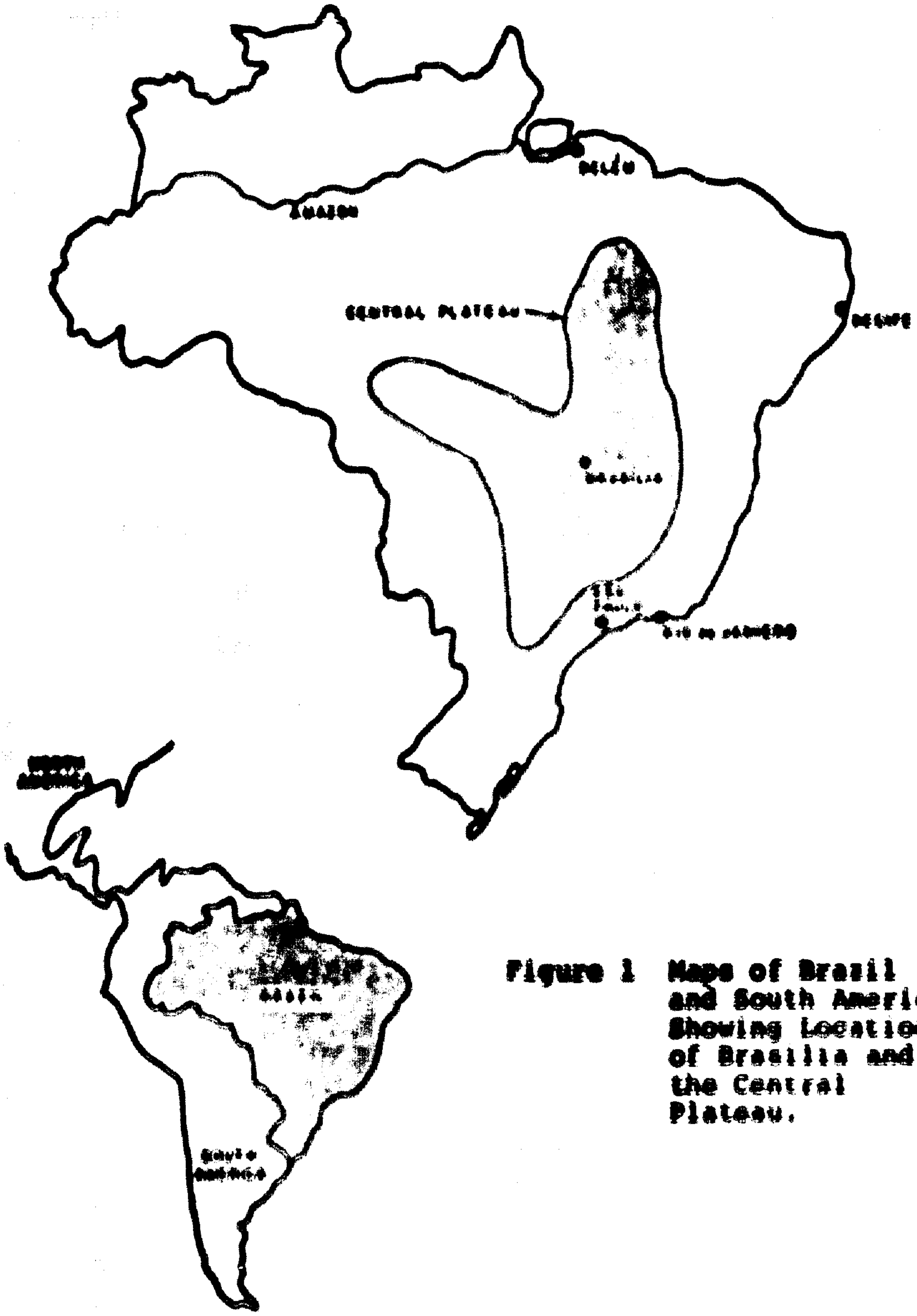

Figure 1 Maps of Brazil and South America Showing Locations of Brasilia and the Central Plateau.

The topography is gently sloping, though steeply dissected areas do occur. This is an area of savannah vegetation, the "campo cerrado", marked by low trees and shrubs, and by gallery forests lining the water courses. The general aspect of the land is one of vast spaces only occasionally marked by any sign of man.

Limitations to Development

Until the last decade, the limiting factors for agricultural development in any part of the region were social and logistic. There were relatively few people and few, if any, infrastructural services. With the creation of the new capital, a dynamic population center has been established in the region. Road linkages have been established to other parts of Brazil, such as the recently inaugurated Brasilia-Belem highway. These transect the Central Plateau and serve as major arteries of access. But a single population center and general accessibility do not spawn development in a region so vast and sparsely populated, and the traditional limitations to development still exist on the Plateau.

For the area immediately around Brasilia, change has occurred. With the population center, communications, markets, and services have been established, and the traditional limitations to agricultural development have been altered. There, the earlier limitations to development have been replaced by a "new" set of constraints, those imposed by the physical environment.

The Physical Environment

Soils

The bulk of the Central Plateau consists of a basement complex of Pre Cambrian intrusive rocks often overlaid by Paleozoic and Mesozoic sediments. Much of the area has been uplifted and subjected to numerous erosion cycles.

Weathering factors and time have reduced the original parent materials to soils which are practically devoid of nutritional value, but heavily laden with toxic concentrations of aluminum. Further, the soils have a tremendous ability to fix phosphorus and render it unavailable for crops. The low fertility status, high aluminum concentrations, and phosphorus fixation properties of these soils are presently serious limitations to agricultural development in the Central Plateau.

Phosphorus problems and general soil infertility may only be corrected through the application of the fertilizer materials. Fertilizers are available, but costly, not only because of soaring fertilizer prices, but because of the huge amounts per hectare which will be required. Research is currently underway to devise specific fertilizer management practices for these soils which may help reduce current application requirements. In comparison with other parts of the world, the fertility problems associated with soils of the Central Plateau of Brazil will be some of the most severe and costly to correct.

The aluminum problem may be partially resolved through the use of amendments. High quality limestone is abundant and cheap in the area. Limestone applications have been made to reduce soil aluminum concentrations to levels not detrimental to crop growth. Unfortunately, limestone applications are only effective to the depth to which the limestone may be practically incorporated, presently at most, 10 cm. For crops such as corn, cotton and soybeans, the rooting patterns have been observed to parallel the incorporation depths (NCSU, 1973). For these crops, the zone of soil which may be exploited for water and nutrients is effectively limited to the depth to which limestone may be applied.

Climate

In general, there are no climatic barriers to human settlement and population of the Central Plateau. However, the area is characterized by marked wet and dry seasons, the latter lasting five months, from May until September. The dry season causes a drastic decline in the production, digestibility and nutritional value of native grasses, and this in turn is the major constraint on the development of even extensive cattle operations.

Most reports recognize a need for dry season irrigation to sustain production and to support a stable agriculture in the region. (For example, see Landers et al., 1967, and Codeplan, 1971). Conventional measures of wet season water adequacy would indicate that the area receives ample rainfall. However, rainfall distribution is erratic and this will be shown to have a profound effect upon the production of intensively cropped species which are sensitive to the soil aluminum.

More detailed aspects of the climate will be developed in Chapter II.

Hydrology

The District is a source of water for three major South American drainage basins. Approximately 5/8 of the area of the District drains South through the Paraná and Plata systems, 2/8 to the Northeast through the São Francisco system, and 1/8 to the North through the Tocantins and Amazon Rivers.

Because of a hydrologic balance in which wet season precipitation excesses average 400 - 500 mm (Belcher, 1955, and Pruntel, 1975), most streams flow year-round. In fact, water has and continues to be a common source of power for electricity on many remote fazendas (ranches).

Water generated power from the local man-made dam was the first source of electricity for the City of Brasilia.

Subterranean water is also thought to be abundant (Pruntel, 1975). However, detailed studies of the utility of this supply in relation to agricultural demands have not been made.

Vegetation[1]

The native vegetation on the Central Plateau is commonly known as "cerrado", which in Portuguese means "closed" or "enclosed". Although cerrado is a type of upland savannah, the vegetation is enclosed in the sense that the grassland is covered by trees and low shrubs of varying densities.

In the field, cerrado type vegetation is referred to by one of the following structural types:

1. Campo Limpo
2. Campo Sujo
3. Campo Cerrado
4. Cerrado
5. Cerradão

Increasing:

Percentage canopy cover

Number of trees

Average height of the stand

Field distinctions are subjective since certain observers may be at home with some but not all of the structural types. Correlation has been made between higher nutrient

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[1] Excellent information on this vegetative type is contained in Eiten (1972).

status of the soil and increased density of the vegetative form (toward cerradão), but there is not yet positive evidence of cause and effect between nutrient status and structural type.

Trees and shrubs are unique in a cerrado. Almost all are semideciduous, losing a portion of their leaves in the dry season. Generally leaves are large and thick. Bark is thick and often cork-like and fire resistant. Trunks and branches of the woody plants are twisted and knarled in Bonzai-like distortions. Experts differ on the reasons for the tortuosity, with fire and limited rooting zones having been advanced as hypotheses. Rooting zones of the species are enigmatic as well. While the trees must presumeably have deep rooting zones to resist the dry season, they are easily knocked over in land clearing operations.

While cerrado covers the great majority of the upland part of the Central Plateau, along the numerous small streams gallery forests predominate. At springs or along wet spots, palm groves occur. Certain species of palms are used by many as a selection criteria for the best land.

Thesis Organization

This thesis presents the results of a year and a half of water oriented research conducted across the subject areas of meteorology, soils and agronomy. The Brasilia area has been used as a single point location for the research; corn has been used as the single test crop. Results are most applicable to that immediate area and crop, but the research and agricultural technology package which develop from this and other studies will in time be applied and tested throughout the region.

The organization of this dissertation will be as follows:

Chapter II will be a climatic assessment of water adequacy for cropping during the wet season. Detailed climatic information will be presented.

Chapter III presents results of research on the soil-water properties of soils where agronomic experimentation was conducted.

Chapter IV describes the cropping methodology for dry and wet season field experimentation.

Chapter V presents results regarding a) the effect of soil-water stress upon yield, and b) the relationship between yield and the various water treatments.

Chapter VI describes the relationships between evapotranspiration and water utilization, and the various climatic parameters. The potential for cropping in the dry versus the wet season will be discussed.

Chapter VII describes the results from experiments having two depths of limestone incorporations and various levels of water adequacy. Nutritional and water hypotheses to account for yield differences will be discussed.

Chapter VIII brings together data from earlier chapters to assess the need for wet season irrigation in Central Brazil.

Chapter IX discusses the implications of these results upon the development process in the region and suggests possible options to reduce the constraints caused by water inadequacies.

CHAPTER II

CLIMATE

Introduction

The Federal Experiment Station, Estação Experimental de Brasilia (EEB), at Planaltina, D.F., is located at an elevation of 1010 m at latitude 15° 36' S, longitude 47° 42' W. The area is characterized by a marked dry season from May until September. Present agriculture in the area, limited as it is, is mostly confined to the wet season. But even during this season, 2-3 weeks or more without rain is not uncommon. This is known locally as a "veranico", or little summer. Since the rainy season corresponds to the time of traditional cropping, the effect of these dry spells may be severe. For example, the 1968-69 crop year had higher than average rainfall, but there were 3 weeks without rain in January. Were it not for irrigation on the experiment station, a corn crop that year would have been lost. In 1970-71, rainfall was half the average and the experimental corn crop that year was lost.

The principal objective of this chapter is to determine the adequacy of water for cropping during the wet season, through:

1. An analysis of the likelihood of occurrence

of veranicos of various lengths. This analysis deals with the questions, "How long do veranicos last?", and "What are the chances of a veranico of n-days?"

2. An analysis of the time distribution of dry days, which will indicate the most likely time for dry days and veranicos. This analysis attempts to answer the question: "When are veranicos most likely to occur?"

Background information is also presented on long-term climatic conditions and on the specifics of the 1973-74 weather phenomena.

Climate of the Brasilia Area

The climate of the Federal District is classified in Koppen's system as Aw, with "A" indicative of tropical summers with no months under 18°C and "w" indicating 4-6 months of a winter dry season. The winter dry season creates a severe limitation on cattle carrying capacity in the absence of improved management practices such as silage production, haying or irrigation. With irrigation, the area is suited to year-round cultivation of many crops.

The length of weather records, both for the DDB and for the City of Brasilia, are inadequate to describe long-term climatic phenomena for the area. The Belcher report (1955) analyzed annual rainfall variation between years for four stations in the Cerrado surrounding Brasilia: Formosa, Goiás, Piranópolis and Luziania. There was no significant variation between stations. Thus, data have been gathered from three sources and combined to create a long-term record for the area.

1. Formosa is a city 41 km ENE of the DDB. A weather station existed there from 1930-1963. The elevation is 912 m.
2. The weather station at Brasilia is 30 km WSW of the DDB. The station began operations in 1963. Installation of a class A pan and a solar radiation meter were made in 1973. The elevation is 1158 m.
3. The DDB began keeping precipitation records in 1966. In 1973 a weather station was established. Measurements taken in 1973-74 included: rainfall, max-min temperature, relative humidity, total wind, class A pan evaporation and solar radiation. The elevation is 1014 m.

Precipitation records from these stations have been merged to give a continuous length of record of 42-47 years, depending on the month. Weisner (1970) has stated that 25-50 years of precipitation data are required to give a meaningful record. Long-term temperature, insolation and evaporation data are from Formosa alone.

As shown in table 1, annual precipitation averages 1580 mm, with 80% of that total occurring from November until March. Wet season coefficients of variation for monthly means are large, and standard deviations of the mean for these months range from 110 to 200 mm. These large fluctuations in monthly precipitation during the wettest months suggest that averages are not a good index of adequacy of water for cropping.

It is well to point out here that not only is rainfall poorly distributed with respect to time, (from one year to the next), but with respect to space as well. Table 2 gives the monthly precipitations for 14 months at Brasilia and at the EDB. These sites are 30 km apart and are at about the same elevation. In spite of the proximity of the weather stations, many monthly amounts are quite different from one site to the other. It should be re-emphasized that the sites have long term yearly precipitation totals which are nearly identical.

Table 3 gives monthly values of temperature, insolation and Piche evaporation. Temperatures throughout the year are mild, an influence of the elevation. The hottest month is September, when the lack of cloud cover combines with day length and sun angle to produce maximums. Minimums occur in July. Except for certain crops, e.g. rice, minimums are not a barrier to year-round

Table 1 Long Term Averages of Monthly Precipitation for the Brasilia Area.

Month	Years	Sources*	Average
Jan.	44	(33, 3, 8)	239.5
Feb.	44	(33, 3, 8)	210.0
March	45	(34, 3, 8)	225.9
April	45	(35, 3, 8)	104.7
May	45	(35, 3, 8)	17.8
June	46	(36, 3, 8)	3.4
July	45	(35, 3, 8)	5.4
Aug.	47	(37, 3, 8)	6.7
Sept.	47	(37, 3, 8)	37.0
Oct.	47	(36, 3, 8)	144.6
Nov.	46	(35, 3, 8)	251.9
Dec.	42	(31, 3, 8)	330.9
			1580.7

Month	% of Total	Standard Deviation**	Coef. of Variation**
Jan.	15.2	150.1	60.1
Feb.	13.4	111.4	53.3
March	14.0	123.3	57.0
April	6.7	71.6	75.5
May	1.1	20.1	117.5
June	0.2	5.7	154.5
July	0.3	12.4	221.1
Aug.	0.4	10.6	155.2
Sept.	2.4	32.3	113.0
Oct.	9.3	65.5	50.6
Nov.	16.3	105.1	45.5
Dec.	21.2	201.6	58.0
	100.0		

80% 5 months Nov.-March

* Number of years at (Formosa, Brasilia, DDB)

**Formosa data only. Source = Department of Meteorology, Rio de Janeiro

Table 2 Monthly Precipitation for Brasilia Compared with Precipitation for the Estação Experimental de Brasilia (EEB). The EEB is 30 Kilometers from Brasilia and at the Same Elevation.

Month	Precipitation (mm)	
	BRASILIA	EEB
JAN 1973	176	183
FEB	174	130
MAR	219	332
APR	85	60
MAY	10	---
JUNE	24	3
JULY	---	---
AUG	---	---
SEPT	220	105
OCT	311	310
NOV	196	104
DEC	162	140
JAN 1974	91	174
FEB	206	100
MAR	260	506

Table 3 Monthly Values of Temperature, Insolation, and Evaporation for 30 Years of Data from Formosa.

	TEMPERATURE				
	Average (°C)	Average Maximum (°C)	Average Minimum (°C)	Insolation (hrs. & tenths)	Piche Evap. (mm)
Jan.	22.0	27.4	17.8	180.5	73.2
Feb.	22.1	27.8	18.0	159.3	63.7
March	21.9	27.6	17.9	186.8	67.1
April	21.5	27.6	17.0	222.2	75.3
May	20.1	27.0	14.8	270.3	97.8
June	19.0	26.4	13.1	279.9	113.0
July	18.9	26.3	12.6	278.0	141.3
Aug.	20.7	28.4	13.7	303.2	188.3
Sept.	22.8	30.1	16.2	236.2	189.2
Oct.	22.9	29.2	17.8	300.7	138.1
Nov.	21.9	27.4	18.0	142.7	75.2
Dec.	21.6	26.6	18.1	135.1	60.8
	21.3	27.6	16.2	2614.9	1283.0

Source: Diagnóstico do Espaço Natural do Distrito Federal, CODEPLAN, 1971, Brasilia.

cultivation.

At these latitudes, winters are 10-11 hours and summers 13-14 hours. Lack of day length variance is not a factor with species and varieties whose photoperiod is day length insensitive, e.g. new varieties of corn. On the other hand, local varieties of soybeans are not suited for winter production because of lack of sufficient day length. In spite of shorter days, average insolation is greatest during the clear winter months.

Piche evaporation records indicate a tendency for high evaporation, due to lower humidity during the dry season, and possibly due to advective effects. It should be noted that Piche records do not correlate satisfactorily with class A pan data (Utah State, 1972), nor do they give good estimates of potential evaporation in tropical areas (Rijks and Walker, 1968). Unfortunately, no long-term records of class A pan evaporation or solar radiation are available.

1973-74 Weather Phenomena

Weather data for the EEB for 1973-74 are given in table 4. Three aspects of the weather during this period are noteworthy in that they differed specifically from the average and had a substantial effect upon the experiments.

1. The rainfall in September 1973 was the second

Table 4 Weather Data for 1973-74 - Estação Experimental de Brasilia

Month	Precip (mm)	Evap[1] (mm/day)	Wind[2] (m/sec)	Solar Rad. (K.cal/cm²/day)	Min Temp (°C)	Max Temp (°C)	Mean Temp (°C)
JUN 1973	3.4	4.76	0.80	354			
JUL		5.79	1.09	435	16.0	27.8	21.9
AUG		7.14	0.85	451	16.0	29.4	22.7
SEPT	104.6	6.47	0.89	425	17.4	30.2	23.8
OCT	318.2	4.75	0.67	370	17.7	26.4	22.0
NOV	183.8	5.22	0.70	411	18.1	26.5	22.3
DEC	140.0	5.59	0.92	433	17.2	26.8	22.0
JAN 1974	174.3	5.67	0.90	441	17.4	26.8	22.1
FEB	108.3	5.24	0.80	453	17.2	27.5	22.4
MAR	506.4	4.92	0.85	340	17.7	25.7	21.7
APR	140.2	4.97	0.85	416	17.0	27.4	22.2
MAY	23.7	4.53	0.90	416	15.9	26.4	21.2

[1] Class A Pan
[2] At 40 cm above ground

highest in 47 years of record. The rains were almost continuous commencing on 23 September, and signaled an abrupt and untimely end to the dry season. This also ended irrigation treatments for the dry season; after this date, all water treatments became identical.

2. Precipitation was recorded for every day in March 1974, and totaled 506 mm or 225% of the average. This was the highest amount for March in the 45 years of record. The effect upon cropping at the Experiment Station (and regionally) was severe. The wet weather provided a humid environment conducive to the spread of Northern Leaf Blight, which attacked the corn. Because of the rains, foliar sprays to control the disease and insects were ineffective and yields suffered greatly.

3. Rains were unusually well distributed throughout the remaining months so that the longest dry period was only 8 days. This kept the crops unusually well supplied with water, and thereby limited the effectiveness of control or non-irrigated treatments to show the effects of veranicos.

Probabilities of Veranicos

Probability analyses have been used a great deal in studying precipitation phenomena. Two types of studies are common, the continuous and the discrete. The continuous usually deals with total amounts of precipitation, while the discrete deals with persistance and/or short term sequences of precipitation events. Among the former, a common approach is one which makes use of yearly, monthly or weekly precipitation totals to evaluate precipitation probabilities for specified periods. An example of this approach can be found in "Precipitation Probabilities for Mississippi" (McWhorter et al. 1966). Their method is one of determining parameters for the incomplete gamma distribution and, using this distribution, assigning probabilities for period-specific rainfall amounts. Short term sequence analyses (discrete) of precipitation events have been made by Feyerherm and Bark (1965), Wiser (1965), and van Bavel and Verlinden (1956), among others.

In reviewing precipitation data for the Brasilia area, the author felt that an analysis based upon wet season rainfall amounts was not satisfactory in describing the severity and location in time of wet season droughts which were common to the area. For example, figure 2 is a graph of computed soil-water storage vs time[1] for two years chosen because the 5-month wet

[1] Soil-water storage vs time was empirically determined

[1] continued.

using the formula:

$$SWS_n = SWS_{n-1} + Precip_{n-1} - ET_{n-1}.$$

Actual precipitation data for the years plotted were used together with estimates of ET. The following assumptions have been used to determine ET and to calculate soil-water storage:

1. Crop rooting was for a 60 cm profile. (This root zone stores 70 mm of available water. See Chapter III.)

2. A 5-month growing season was assumed, with a planting date of November 1.

3. Base ET was assumed to be 5.1 mm/day. This value was obtained from Pruntel (1975), who calculated Penman constants for the Brasilia area using 11 years of data. His average for the 5-month wet season is 5.1 mm/day.

4. Base ET was modified to account for crop stage and soil-water influences on ET.

   a) Crop stage modifications follow:

Crop Stage (days after planting)	ET (mm/day)
Less than 35	1.7
35-50	1.7 + .127(crop stage - 35)
51-70	0.072(crop stage)
71-108	5.1
109-120	5.1 - (crop stage - 108)(.28)
more than 120	1.7

Modifications were based in part on experimental data shown in figure 25.

   b) Soil-water modifications follow:

[1] continued.

Soil-Water Storage (mm)	ET (mm/day)
28-70	Independent of soil-water status and dependent only on crop stage.
6-28	(ET from Crop Stage)(mm in storage)/28
Less than 6	1.0

Modifications were based in part on experimental data shown in figure 17. 28 mm of soil-water storage corresponds to 60% soil-water depletion or average root-zone tensions of 1/2 bar. Models for this type of relationship between ET and soil-water content have been proposed by Closs (1958), Slatyer (1956), and Wartena and Veldman (1961).

5. Maximum soil-water storage was limited to 70 mm.

6. Soil-water storage on November 1 equaled 70 mm.

A comparison of actual and computed soil-water storage vs time is presented in figure 3. In general, the computed storage closely follows the actual.

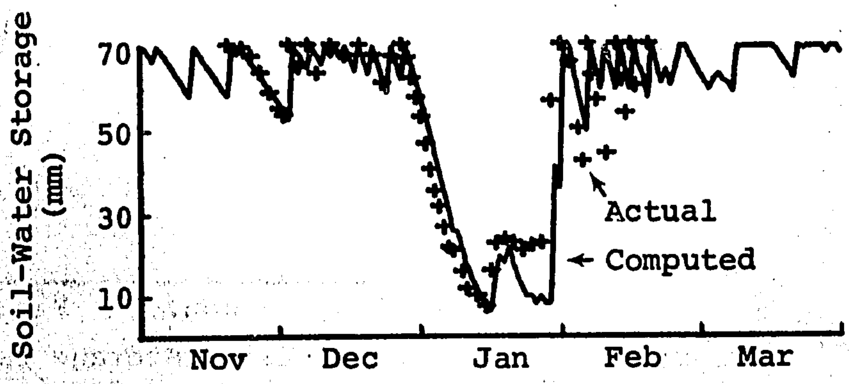

Figure 3 A Comparison of Computed Soil-Water Storage vs Time from Rainfall Data for 1953-54, with Actual Soil-Water Storage vs Time from Field Data Taken from Irrigation Treatments which Simulated Rainfall in that Year.

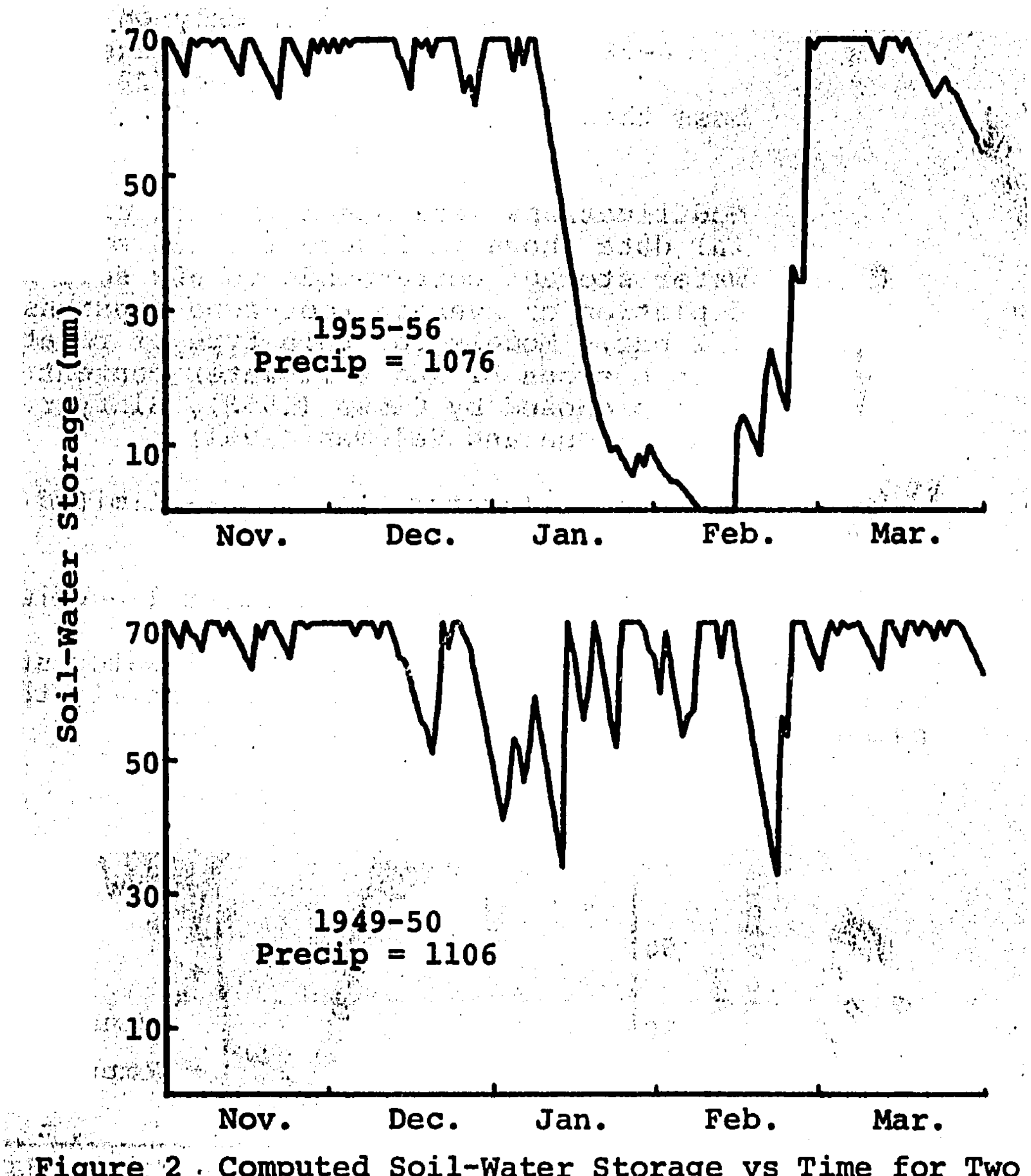

Figure 2 Computed Soil-Water Storage vs Time for Two Years in Which 5-Month Precipitation Totals were Similar. A 60-cm Root Zone has Been Assumed.

season precipitation amounts for each were nearly the same. Vastly different soil-water conditions occurred because in 1949-50 the rains were well distributed whereas in 1955-56 they were not.

Furthermore, water treatments in wet season field experiments were geared to breaking veranicos of various lengths (or on sequences of dry-days) and it seemed logical to analyze the weather data in a similar manner, and later to link weather record analysis and results of field experimentation. Therefore, rainfall data have been analyzed in a discrete manner based upon sequences of dry days. This approach is one which places emphasis on rainfall distribution vis-a-vis amount.

A dry day may be defined as a day receiving less than a certain amount of rainfall, hereafter called the "threshold". The purpose of this definition is to avoid designating a day as a wet one when rainfalls are small and relatively unimportant to growing crops. Others have used the threshold concept to draw the line between dry and wet days, (eg. Ison et al., 1971; Chatfield, 1966; Hershfield, 1970; Lowry and Guthrie, 1968). For this analysis the threshold has been set at 5 mm, which means that a day receiving 5 mm or more of precipitation will be considered a wet day. In actuality, daily precipitation totals were rounded to the nearest millimeter prior to data coding for computer analysis and a day with more than 4.5 mm would therefore be considered wet; a day with 4.5 mm, or less, of rainfall would be considered dry. Designation of 5 mm as the appropriate threshold is arbitrary, but based upon the fact that evapotranspiration will generally be on the order of 5 mm per day. Five millimeters was also the criteria used in the field to separate dry from wet days, and on that basis, to trigger irrigations. Rainfall analyses were performed for other thresholds but, except as noted, results herein reported are for the 5 mm threshold.

The parameter "longest dry spell" was used as the basis for establishing water treatments for the wet season experiments. To tie results of treatments (reported in chapter V) to the historical record of precipitation events on the Cerrado, there was a need to determine a frequency distribution for this random variable.[1] Longest dry spell was determined for the 5 mm rainfall threshold for the 5 month wet season from November to March. To determine this parameter, each year is characterized by a single dry spell. For example, in 1973-74 the longest dry spell was of 8 days. A histogram of observed frequencies is presented in figure 4. It may be noted from the histogram that 1973-74 was

[1] In statistical terminology, "longest dry spell" is a random variable. When dealing with probability distributions that terminology will be used. At other times it will be considered a parameter.

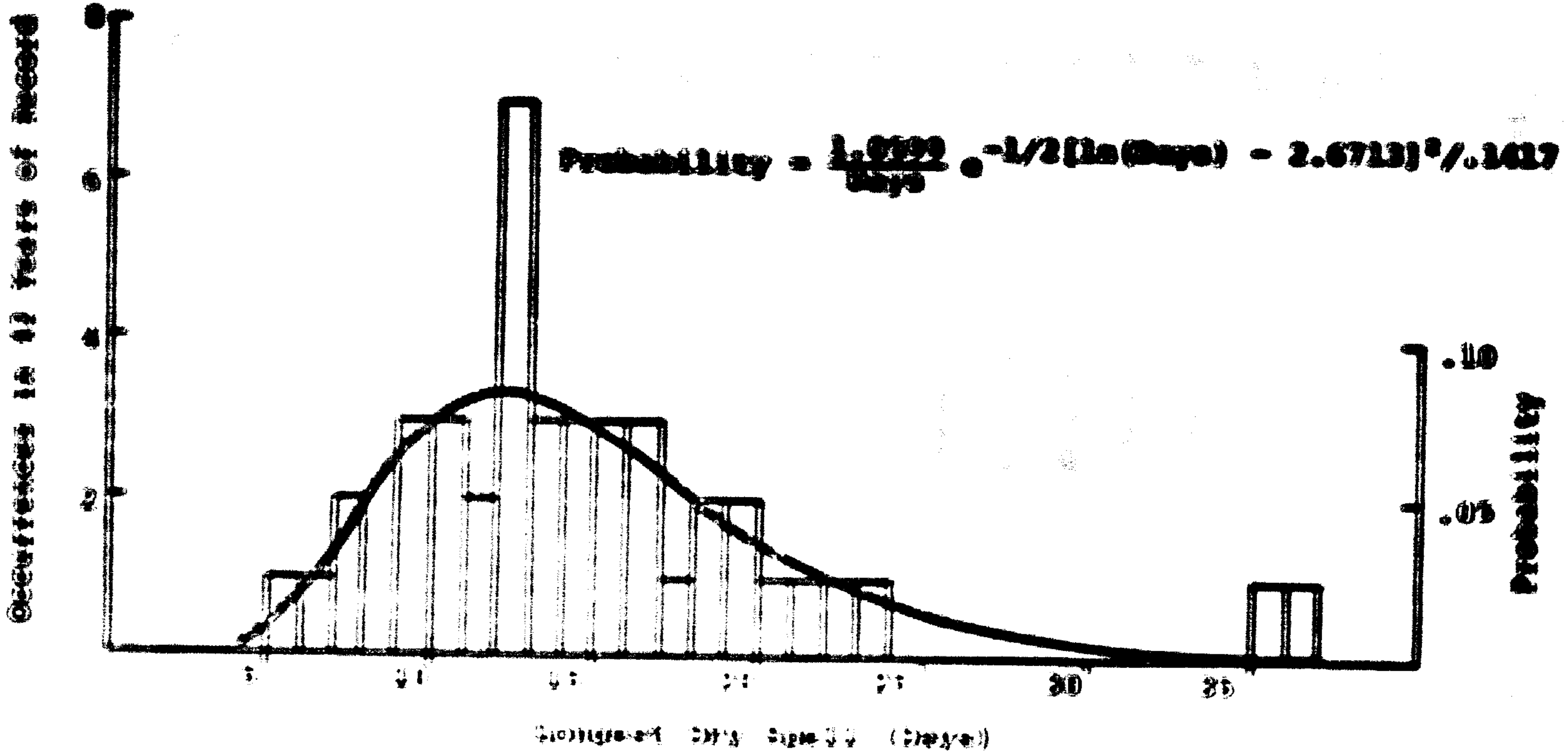

Figure [illegible] Histogram of the Number of Occurrences of the Longest Wet Season Dry Spell for Brasilia, Based upon Precipitation for 42 Years of Record. Also Given is the Fit of the Log-Normal Probability Distribution Function for the Longest Dry Spell.

one of only four years in which dry spells were so restricted, ie. rainfalls so well distributed.

The observed frequencies were fitted to the log normal probability distribution so that expected probabilities could be predicted from the observed frequency data. The log normal distribution assumes that the logarithm of the random variable is normally distributed. This distribution has been used by others to describe precipitation amounts (Markovic, 1965) and hydrologic runoff (Brakensiek, 1958). The log normal fit gave an expected frequency distribution (figure 4). Observed frequencies were tested against expected frequencies using the chi-square goodness of fit test. Results indicated that the log normal probability distribution function is appropriate and may be used to determine the probability that the longest dry spell will be of "n" days.

The distribution predicts that there is only an 8% chance that in any year the longest dry spell will be restricted to 8 days <u>or less</u>. In other words, only 1 year in 13 will rainfalls be this well distributed. There is a 50% chance that the longest dry spell will be of 14 days or more and a 15% chance that the longest dry spell will exceed three weeks. Probabilities associated with dry spells of various lengths or longer (cumulative distribution function) are given in table 5.

Table 5 Cumulative Distribution of the Random Variable "Longest Dry Spell". The Log Normal Distribution is Assumed. These Data are for a 5 mm Precipitation Threshold and for 42 Years of Record for Brasilia.

Length of Longest Dry Spell (Days)	Probability of a Longest Dry Spell of n Days, or Longer
4	.999
5	.995
6	.984
7	.960
8	.922
9	.868
10	.803
11	.729
12	.650
13	.572
14	.497
15	.426
16	.363
17	.306
18	.256
19	.213
20	.177
21	.146
22	.120
23	.098
24	.080
25	.066
26	.054
27	.044
28	.036

In addition to the analysis just presented, a second analysis was performed which counts and totals all or multiple dry spells in a given year. To analyze the period from November 1 to March 31 for the 42 years of record, a computer program was devised which counted sequences of dry days. The sequence of a wet day followed by "n" days without rain and then another wet day would be counted as a n-day dry spell. The average number of dry spells per wet season was approximately 28 and these ranged from dry spells lasting a single day to a dry spell of 37 days in 1960-61.

Table 6 is a computer print out of the results from this analysis for the wet season in Brasilia. Column 1 gives the length of a dry spell. Columns 2 and 6 are the total number of dry spells of specified length, and specified length and longer, respectively, which have occurred in the 42 years of record. The relationship of wet days to dry days is in the ratio 3:5, or 37.5% of the days were wet and 62.5% dry. These numbers may be found from simple multiplication and addition of columns 1 and 2, divided by the total number of days considered in the analysis.

Columns 3 and 7 are the conditional probabilities that, given a dry spell, it will last n days, or n days or longer, respectively. From the definition of conditional probability,

Table 6 Numbers, Proportions, Frequencies and Return Periods of Wet-Season Dry Spells for the Brasilia Area.

1 LENGTH OF DRY SPELL	2 NUMBER OF DRY SPELLS (42 YEARS)	3 PROPORTION OF DRY SPELLS OF A GIVEN LENGTH	4 AVERAGE NO. OF DRY SPELLS OF THIS LENGTH/YEAR	5 NUM. YEARS TO GET A DRY SPELL OF THIS LENGTH	6 # OF DRY SPELLS OF A GIVEN LENGTH OR LONGER (42 YEARS)	7 PROPORTION OF DRY SPELLS OF THIS LENGTH OR LONGER	8 AVERAGE NUM. DRY SPELLS THIS LENGTH OR LONGER/YEAR	9 NUM. YEARS TO GET A DRY SPELL THIS LENGTH OR LONGER
1	460	0.3959	10.952	0.091	1162	1.0000	27.667	0.036
2	235	0.2022	5.595	0.179	702	0.6041	16.714	0.060
3	113	0.0972	2.690	0.372	467	0.4019	11.119	0.090
4	84	0.0723	2.000	0.500	354	0.3046	8.429	0.119
5	61	0.0525	1.452	0.689	270	0.2324	6.429	0.156
6	50	0.0430	1.190	0.840	209	0.1799	4.976	0.201
7	32	0.0275	0.762	1.313	159	0.1368	3.786	0.264
8	30	0.0258	0.714	1.400	127	0.1093	3.024	0.331
9	11	0.0095	0.262	3.818	97	0.0835	2.310	0.433
10	19	0.0164	0.452	2.211	86	0.0740	2.048	0.488
11	16	0.0138	0.381	2.625	67	0.0577	1.595	0.627
12	9	0.0077	0.214	4.667	51	0.0439	1.214	0.824
13	10	0.0086	0.238	4.200	42	0.0361	1.000	1.000
14	6	0.0052	0.143	7.000	32	0.0275	0.762	1.313
15	7	0.0060	0.167	6.000	26	0.0224	0.619	1.615
16	4	0.0034	0.095	10.500	19	0.0164	0.452	2.211
17	3	0.0026	0.071	14.000	15	0.0129	0.357	2.800
18	1	0.0009	0.024	42.000	12	0.0103	0.286	3.500
19	2	0.0017	0.048	21.000	11	0.0095	0.262	3.818
20	2	0.0017	0.048	21.000	9	0.0077	0.214	4.667
21	1	0.0009	0.024	42.000	7	0.0060	0.167	6.000
22	1	0.0009	0.024	42.000	6	0.0052	0.143	7.000
23	1	0.0009	0.024	42.000	5	0.0043	0.119	8.400
24	2	0.0017	0.048	21.000	4	0.0034	0.095	10.500
25	0	0.0	******	0.010	2	0.0017	0.048	21.000
26	0	0.0	******	0.010	2	0.0017	0.048	21.000
27	0	0.0	******	0.010	2	0.0017	0.048	21.000
28	0	0.0	******	0.010	2	0.0017	0.048	21.000
29	0	0.0	******	0.010	2	0.0017	0.048	21.000
30	0	0.0	******	0.010	2	0.0017	0.048	21.000
31	0	0.0	******	0.010	2	0.0017	0.048	21.000
32	0	0.0	******	0.010	2	0.0017	0.048	21.000
33	0	0.0	******	0.010	2	0.0017	0.048	21.000
34	0	0.0	******	0.010	2	0.0017	0.048	21.000
35	0	0.0	******	0.010	2	0.0017	0.048	21.000
36	1	0.0009	0.024	42.000	2	0.0017	0.048	21.000
37	1	0.0009	0.024	42.000	1	0.0009	0.024	42.000
38	0	0.0	******	0.010	0	0.0	******	0.010
39	0	0.0	******	0.010	0	0.0	******	0.010
40	0	0.0	******	0.010	0	0.0	******	0.010

$$P(D_n|D) = \frac{P(D_n)}{P(D)} ,$$

it follows that $P(D_n) = P(D_n|D) \times P(D)$, where,

$P(D_n)$ = Probability of a dry spell of length n.

$P(D)$ = Probability of a dry day. = .625

$P(D_n|D)$ = Conditional probability that, given a dry day, the dry spell will last n days, or n days or longer. (Columns 3 and 7)

Use of conditional probability and columns 3 and 7 will be illustrated through a series of questions and answers.

1. What is the probability that if today is dry, it will be wet tomorrow? .3959
2. What is the probability that if today is dry it will be dry tomorrow and it will be wet on the following day? .2022
3. What is the probability that if today is dry it will continue to be dry for exactly 7 more days? (8-day dry spell) .0258
4. What is the probability that if today is dry it will continue to be dry for at least 7 more days? .1093
5. What is the probability that a certain day will be dry and that the dry spell will last only one day?

   $P(D_1) = (.3959)(.625) = .247$
6. What is the probability that a certain day

will be dry and that the dry spell will last exactly 5 days?

$P(D_5) = (.0525)(.625) = .033$

7. What is the probability that a certain day will be dry and that the dry spell will last at least 5 days?

$P(D\ _5) = (.2324)(.625) = .1453$

8. What is the probability of two dry spells of 5 days or longer? $(.1453)(.1453) = .0211$

Columns 4 and 8 give the average number of dry spells of length specified, or of length specified or longer, respectively, for the average year. These numbers are the totals from columns 2 and 6, divided by 42. In the hypothetical average year we would expect two dry spells of exactly 4 days and three dry spells of 8 days or longer, two dry spells of 10 days or longer and one dry spell of 13 days or longer.

Columns 5 and 9 are return periods for the number of years to experience a dry spell of the specified length, or the specified length or longer, respectively. These numbers are the reciprocals of the numbers in columns 4 and 8. Dry spells of 18 days or longer may be expected every 3 1/2 years, or 2 years in 7; a dry spell lasting 22 days or more can be expected 1 year in 7. There were six dry spells of 22 days or more, in the 42 years of record. These data have been summarized in table 7.

Although the frequency of dry spell occurrences has been determined, it remains very difficult to apply this information, other than qualitatively, to the effect upon cropping. Reasons for this will be covered in Chapter VIII.

Table 7 Frequency of Wet-Season Dry Spells of Various Lengths, or Longer, for Brasilia Based Upon 12 Years of Record.

DRY-SPELL (Days)	FREQUENCY
8	3/Year
10	2/Year
13	1/Year
18	2 Years in 7
22	1 Year in 7

Time Distribution of Dry Days

Whether or not dry days occur more frequently during one period of the rainy season is a question which has important agronomic implications. If no one time period is revealed as the most likely for short droughts, management options for minimizing their effects must be restricted to practices such as varietal selection, deep incorporation of amendments or supplemental irrigation. If a certain time period can be pinpointed as a likely one for a veranico, other management options exist for risk minimization, such as varying date of planting. For certain other crops, for example, hay, knowledge of the most likely time for dry spell occurrence would be of advantage in planning farm operations to take advantage of likely dry spell occurrence.

For the 5-month period November 1 to March 31, precipitation data were analyzed to determine if any one period or periods were most likely for the occurrence of dry days. A continuous record of 42 years of precipitation data from the EEB, Brasilia and Formosa were analyzed for this objective. Days were numbered sequentially from 1 (November 1) to 151 (March 31), and for each day the number of occurrences of dry days (maximum = 42) were counted using a simple computer program. The program permitted varying the criteria for a dry day, so that a dry day might be defined as receiving less than a minimum threshold precipitation. For example, using a 5 mm threshold, a day receiving 0 - 4.9 mm of precipitation would be considered dry, whereas a day receiving 5 mm or more would be considered wet. The analysis was performed for precipitation thresholds from 1 to 10 mm. For the threshold of 2 mm, the counting program revealed that 50% of the days from November 1 to March 31 would be considered dry. The percentage of dry days rose to 62 and 73% as the threshold was raised to 5 and 10 mm, respectively.

Regardless of threshold, visual analysis of the results indicated a tendency for the 20-day period beginning 27 December to have a larger percentage of dry days compared to periods before or after. That 20-day period was divided into two 10-day periods, and the encompassing 140-day period from November 7 to March 26 was divided into 14 ten-day periods for the purposes of statistical analysis. The average percentage of dry days for each period were determined for precipitation thresholds of 2, 5 and 10 mm. While the percentage of dry days increased for the 10 mm threshold, fewer differences between period means were noted -- this an indicator of an induced tendency toward period homogeneity caused by ignoring rains of less than 10 mm.

An analysis of variance was run by considering each 10-day period as a treatment and each day as one of 10 repetitions. The null hypothesis, that there were no differences in period means, was tested and rejected by generating the F statistic which was significant, for each threshold, at the 0.0001 level. Duncan's new multiple range test was performed at the 5% level of significance, a very acceptable level for ascertaining statistical differences in means for metereological events. Statistical differences between period means are shown in table 8 for the 5 mm threshold. Means for periods connected by lines are not significantly different, while period means not joined by the same line are significantly different. For the 5 mm threshold, the 20-day period was significantly drier than the 10-day period before it, and January 6-15 was significantly drier than January 16-25.

The same data are presented in histogram form, in figure 5, and show a sharp increase in the average number of dry days for the 20-day period, December 27 to January 15. The average number of dry days for that period is most similar to the number of dry days for March 7-26. This latter period signals the transition to the dry season. (April's average precipitation is less than half of March's.) Moreover, the statistical measures and visual evidence presented indicate that 27 December to 15 January is considerably different from the 10-day periods either before or after. It also may be noted that the period December 17-26 is one of an unusually large number of wet days.

If comparisons are made on the basis of precipitation amounts during 10-day intervals, similar results are obtained. Figure 6 is a graph of 10-day wet season precipitation totals, together with a conventional histogram of monthly totals. It is noteworthy that the tendency for wet season veranicos remains hidden in the monthly means.

The conclusions from these analyses are as follows:

Table 8 Mean Percentage of Dry Days by Time Period for the 5-mm Rainfall Threshold for Brasilia. Means for Periods Connected by Lines are not Significantly Different; Period Means not Joined by the Same Line are Significantly Different.

Time Period	Mean Percentage of Dry Days
Mar 17-26	70.7
Jan 6-15	69.3
Mar 7-16	66.7
Feb 5-14	65.7
Feb 25-Mar 6	65.0
Feb 15-24	64.8
Jan 26-Feb 4	64.0
Dec 27-Jan 5	63.8
Jan 16-25	60.0
Nov 7-16	59.5
Dec 7-16	58.6
Nov 27-Dec 6	58.6
Nov 17-26	56.0
Dec 17-26	45.2

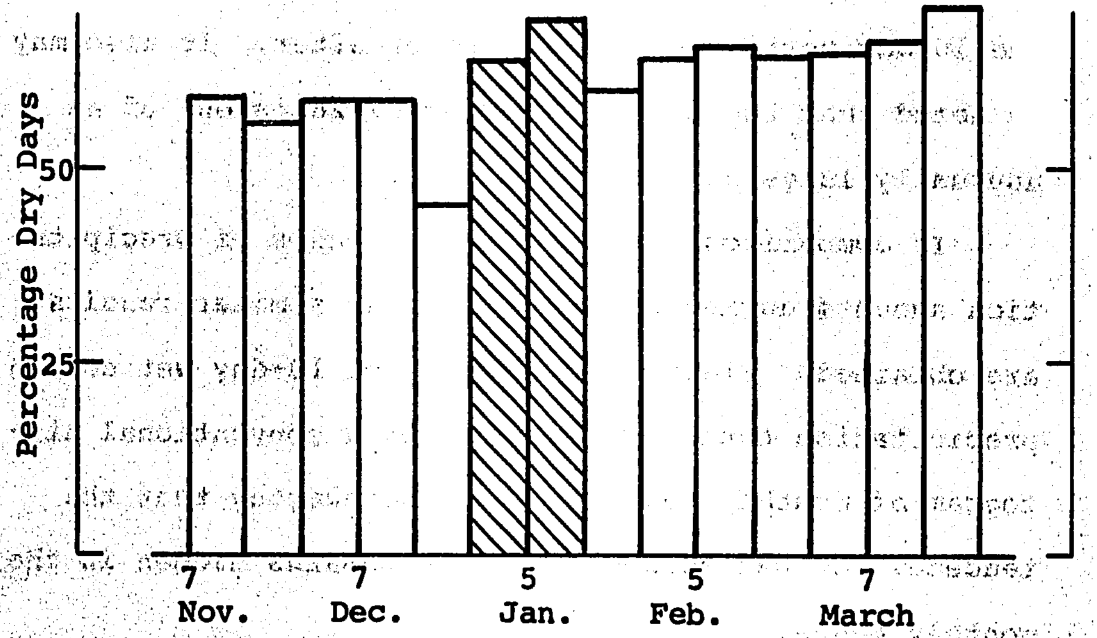

Figure 5 Mean Percentage of Dry Days by Time Period for the 5-mm Rainfall Threshold for Brasilia.

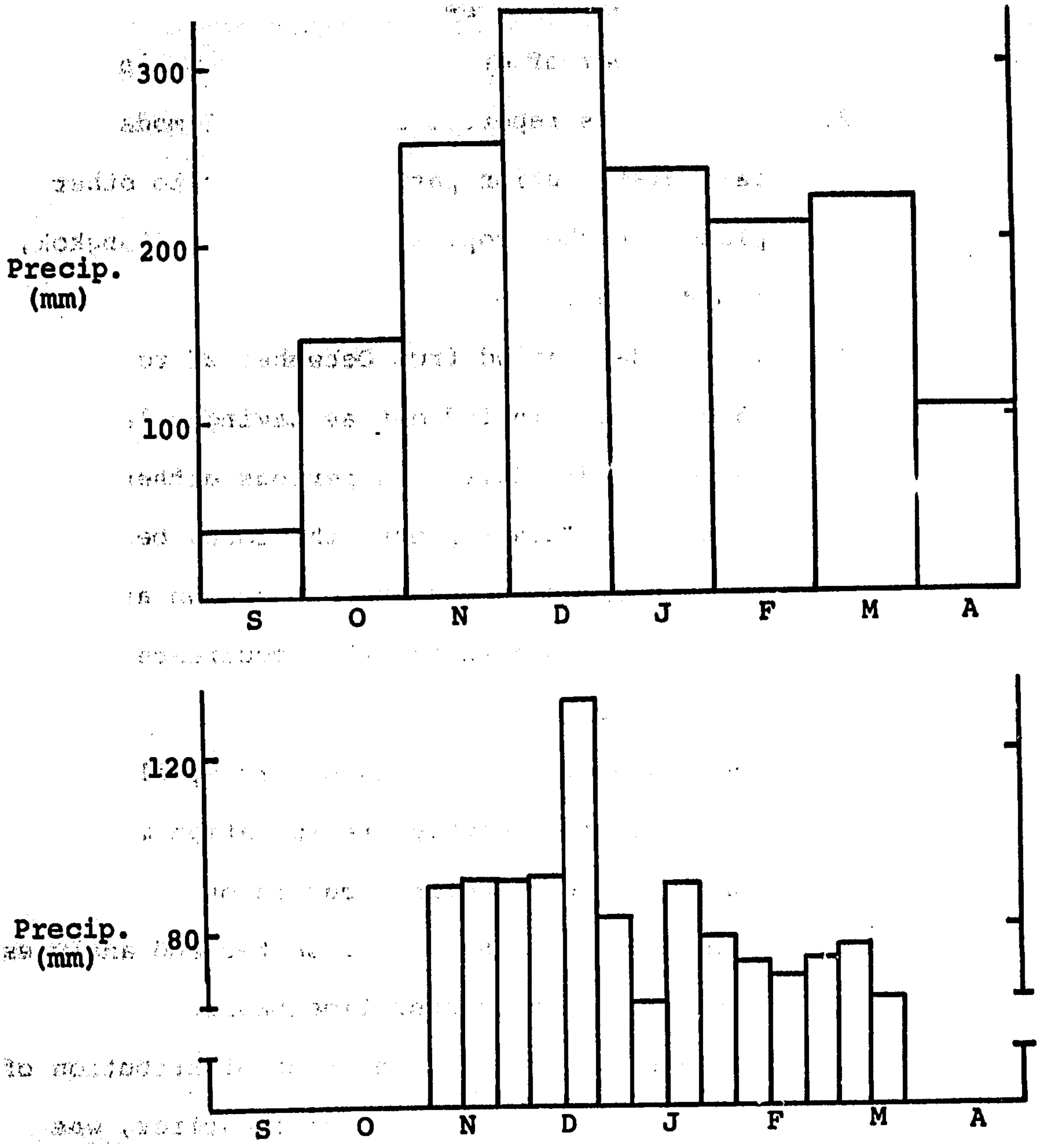

Figure 6 Histograms of 42-Year Average Rainfall Amounts for Brasilia, Presented as Monthly Totals (Top) and 10-Day Totals (Bottom).

1. There are significant statistical differences between 10-day periods of the rainy season when analysis is performed on the basis of mean number of dry days for each period.
2. Evidence is reported of a weak bi-modal rainfall distribution pattern similar to other places in the tropics (eg. Nairobi, Bangkok, and Bogota).
3. The 20-day period from December 27 to January 15 has been singled out as having a larger number of dry days than periods either before or after. This supports the local belief that certain times during the wet season are more likely than others for the occurrence of veranicos.
4. The tendency for wet season dry spells is hidden in the monthly precipitation means. That these dry spells occur is only revealed when monthly means are dissected and analyses performed on a shorter time basis.

To confirm these results, the time distribution of parameter, longest dry spell, discussed earlier, was plotted in time and is presented in figure 7. This graph plots when veranicos have occurred in the past. Significant is the sharp increase in veranicos in late December. The tendency continues throughout January,

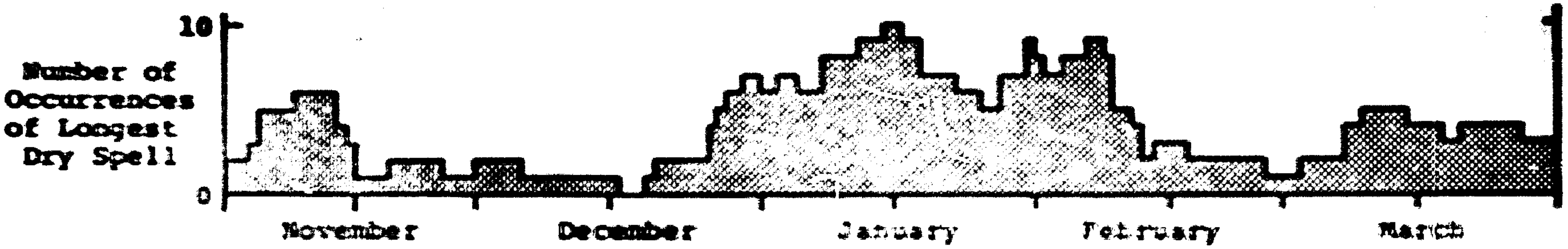

Figure 7 Histogram Showing When Longest Dry Spells Have Occurred in the Past, for Brasilia.

until about February 10 when veranico occurrence diminishes. These results are somewhat different than the results reported for dry days in that they indicate a period of about 45 days when droughts have regularly occurred.

The implications of these results will be discussed in Chapter IX.

Summary

1. Data were presented which characterize the long term weather records for the Brasilia area.
2. Detailed weather data were presented for the 1973-74 crop year.
3. Rainfall data for 42 years were analyzed from the standpoint of the longest dry spell in any year. Analysis reveals:
    a. There is only an 8 percent chance that in any year the longest dry spell will be limited to 8 days or less. In other words, only 1 year in 13 will rainfall be this well distributed during the rainy season.
    b. There is a 50 percent chance that the longest dry spell will be 14 days or more, and a 15 percent chance that the

longest dry spell will exceed 3 weeks.

4. The frequency of occurrence of multiple dry spells within any one year was revealed by analysis of all dry spells in the 42 years of record. On the average, the Brasilia area may expect 3 dry spells per wet season of 8 days or longer, 2 dry spells of 10 days or longer, 1 dry spell of 13 days or longer, and in 1 year in 7, wet-season dry spells will exceed three weeks in length.
5. Wet season occurrence of dry spells was found to be most prevelant during late December and January.
6. The tendency for wet season dry spells is hidden in the monthly precipitation means. When monthly means are divided into time periods of 10 days in length, marked differences were observed between adjacent 10-day periods.

CHAPTER III

SOIL-WATER PROPERTIES OF SOILS AT THE BRASILIA EXPERIMENT STATION

Introduction

Many areas of the humid tropics may be characterised by rains adequate in amount but irregular in distribution. On soils where crop rooting may be restricted, eg. by soil chemical or physical properties (aluminum toxicity, or the presence of a hardpan), the effect of less than ideal rainfall distribution is to produce soil-water deficits which can adversely affect yields. Too often soil-water deficits are not measured in field experimentation even though it is widely acknowledged that water stress will cause some degree of yield depression. To properly interpret and make recommendations from the results of agronomic experimentation, it becomes necessary to know the soil-water status under which the crop was grown. A convenient method for monitoring soil-water status is to instrument a growing crop with tensiometers and electrical resistance blocks and to follow changes in instrument readings on a regular basis. This has been done for several crops on the *Latosol Vermelho Escuro* (or dark red latosol) (LVE) at the Estação Experimental de Brasilia (EEB), and reported here are the data and relationships which have been established and which together give insight into the soil-water properties of this soil. Soil-water data will also be presented for a second important soil at the Experiment Station, the *Latosol Vermelho Amarelo* (or red-yellow latosol) (LVA).

Materials and Methods

During 1972 and 1973, soil-water experiments were conducted at the Estação Experimental de Brasília (EEB), near Planaltina, D.F. The primary objective of the experiments was to establish soil-water characteristics (the relationship of volumetric soil-water content to soil-water tension) for soils on which agronomic experimentation was in progress or planned. Two sites were chosen for study: Site I is located in the *agrostologia* area. This had been planted to bermuda grass and had been used for grass trials for 6 years. Site II is in the *soils* sector. This site had never been cropped, but during the course of the investigations it was planted to corn.

The soil at both sites is Latosol Vermelho Escuro, distrófico, textura argilosa, fase cerrado, a Typic Haplustox, fine, isohyperthermic, kaolinitic in the soil taxonomy system of the United States (Cline and Buol, 1973). On the basis of recommendations contained in the Cline-Buol Report, agronomic experimentation began on a second soil, an Acrustox, of lighter texture, and red-yellow color, the Latosol Vermelho Amarelo. Soil-water experiments were conducted in conjunction with the fertility experiments to characterize the water supplying properties of that soil. These soils, the LVE and the LVA have been mapped over a large portion of the EEB and occur extensively on the Campo Cerrado with only slight physical modifications (Cline and Buol, 1973). Chemical and granulometric properties of the soils are described in tables 9 and 10.

Soil-water instrumentation at Site I consisted of tensiometers installed at 7.5-, 30-, 60-, and 90-cm depths. These were replicated four times for a total of 16 instruments. For any time the average value of the four instruments at a given depth was taken to represent the soil-water tension at that depth. At Site II, tensiometers were installed at 15, 30, 60, and 90 cm in 12 plots planted to corn. In addition, gypsum blocks (purchased from the Delmhorst Instrument Company, Boonton, New Jersey, USA and read with a Delmhorst Soil Moisture Tester) were installed at 15- and 30-cm depths in all plots. Instrumentation at the LVA site consisted of tensiometers installed at 15, 30, and 60 cm in four plots planted to corn. Gypsum blocks were installed at the 15- and 30-cm depths.

Table 9 Chemical and Physical Characteristics of the LVE Soil Used in Experiments at the EEB. Typic Haplustox, Fine, Kaolinitic, Isohyperthermic.

Horizon	Sand	Clay	Water-dispersible Clay	pH H_2O	pH KCl	Org C	Total N	Exchangeable Al	Exchangeable Ca&Mg	Exchangeable K	CEC (sum)	Base Saturation
cm	%	%	%			%	%	meq/100g				%
0- 10	36	45	14	4.9	4.2	1.8	0.21	1.9	0.4	.10	2.4	21
10- 35	33	48	6	4.8	4.3	1.2	0.08	2.0	0.2	.05	2.2	11
35- 70	35	47	1	4.9	4.2	0.9	0.05	1.6	0.2	.03	1.8	12
70- 50	35	47	0	5.0	4.2	0.7	0.05	1.5	0.2	.01	1.7	12
150-260	39	42	0	4.6	4.4	0.3	0.03	0.7	0.2	.02	0.9	24

Mechanical analysis courtesy of Mr. Marcelo Camargo, Centro de Pesquisas Pedológicas, EMBRAPA.

Source: Cline and Buol (1973)

Table 10 Chemical and Physical Characteristics of the LVA Soil Used in Experiments at the EEB. Acrustox Integrade to Haplustox, Medium, Kaolinitic, Isohyperthermic.

Horizon	Sand	Silt	Clay	Water-Dispersible Clay	pH		Org C	Tot N	Exchangeable					CEC (Sum)	Base Saturation
					H_2O	KCl			Al	Ca	Mg	Na	K		
cm	%	%	%	%			%	%	meq/100g						%
0-20	60	9	31	4	5.0	4.2	1.24	.095	.40	.02	.03	.01	.06	.52	23
40-60	54	12	34	6	4.9	4.3	0.74	.065	.07	.02	.01	.01	.03	.14	50
100-120	55	16	29	8	5.6	5.0	0.37	.030	<.01	.02	.01	.01	.01	.05	93

Sources: Weaver (1974) and Weaver (Personal Communication)

To provide a direct relationship between soil-water tension (or gypsum block reading) and soil-water content, gravimetric soil samples were taken in the vicinity of the instruments. More than 600 samples were collected from the three sites and these provided a wide range of soil-water conditions.

Data in the tension range 0-3/4 bar were obtained by associating corrected tensiometer readings from instruments installed in the field with corresponding results of gravimetric sampling. In the range 1 to 15 bars, disturbed soil samples were used with conventional pressure plate apparatus techniques.[1] Justification for using gravimetric sampling techniques to determine soil-water contents in the wet range (0-3/4 bar), and pressure plate techniques in the dry range (1-15 bars), can be found in Wolf and Drosdoff (1974) or MacLean and Yager (1972).

Soil samples for gravimetric analyses were dried at 105°C for calculation of percent soil water by weight. This was converted to percent soil water by volume using measured bulk density values determined from more than 90 undisturbed soil core samples taken from two pits

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[1] Pressure plate analyses for Site II and for the LVA were performed at North Carolina State University. The author is indebted to Dr. S.W. Buol for providing these analyses.

adjacent to each experimental area. Bulk density was calculated on the basis of oven dry weight of soil per core colume.

At Site II, a satellite experiment was established to determine internal drainage. The center of a 4 m x 4 m area was instrumented with tensiometers, two per depth, at 15, 30, 60, 90 and 120 cm. The area was flooded with water and then covered with plastic. Soil-water tension changes were monitored for 103 rainless days. Thus, assuming no evaporative water loss, all tension changes were due to continued downward redistribution of the water, i.e., internal drainage.

Rate of water infiltration versus time was determined for Site I by completely flooding a nearly level area 6 m x 11 m with a known volume of water. Rate and amount of water infiltration were determined by observing the time required for water to enter the soil.

Results

Bulk Density

Bulk densities for the three sites are given in table 11. For the LVE, values decrease slightly with depth in the profile. This may possibly be attributed to man-made causes. Landers (unpublished data) has also determined bulk density for this soil, and, in general, his results are similar. For the LVA, bulk density is relatively constant with depth. Due to a greater proportion of sand in the LVA, bulk densities for that soil are higher than for the LVE.

Table 11 Bulk Density Values at Various Depths for Soils at the EEB.

Depth (cm)	Bulk Density (g/cc)		
	LVE		LVA
	Site I	Site II	
0-10	1.05		
10-20		1.06	1.26
25-35	1.02	1.06	1.27
55-65	0.95	1.00	1.23
85-95	0.96	0.95	

Infiltration

A graph of cumulative infiltration versus time for two irrigations at Site I is given in figure 8. Prior to irrigation 1, soil-water contents (percent by volume) ranged from 15% (at the soil surface) to 20% (at depth), while prior to irrigation 2, water contents ranged from 20-27%. Regardless of initial water content, rate of infiltration was unusually rapid and ranged from 17 to 22 cm/hr. Further, there was apparently little diminution in rate of infiltration over the course of the experiments. No lateral water movement was observed and all water was assumed to have percolated vertically.

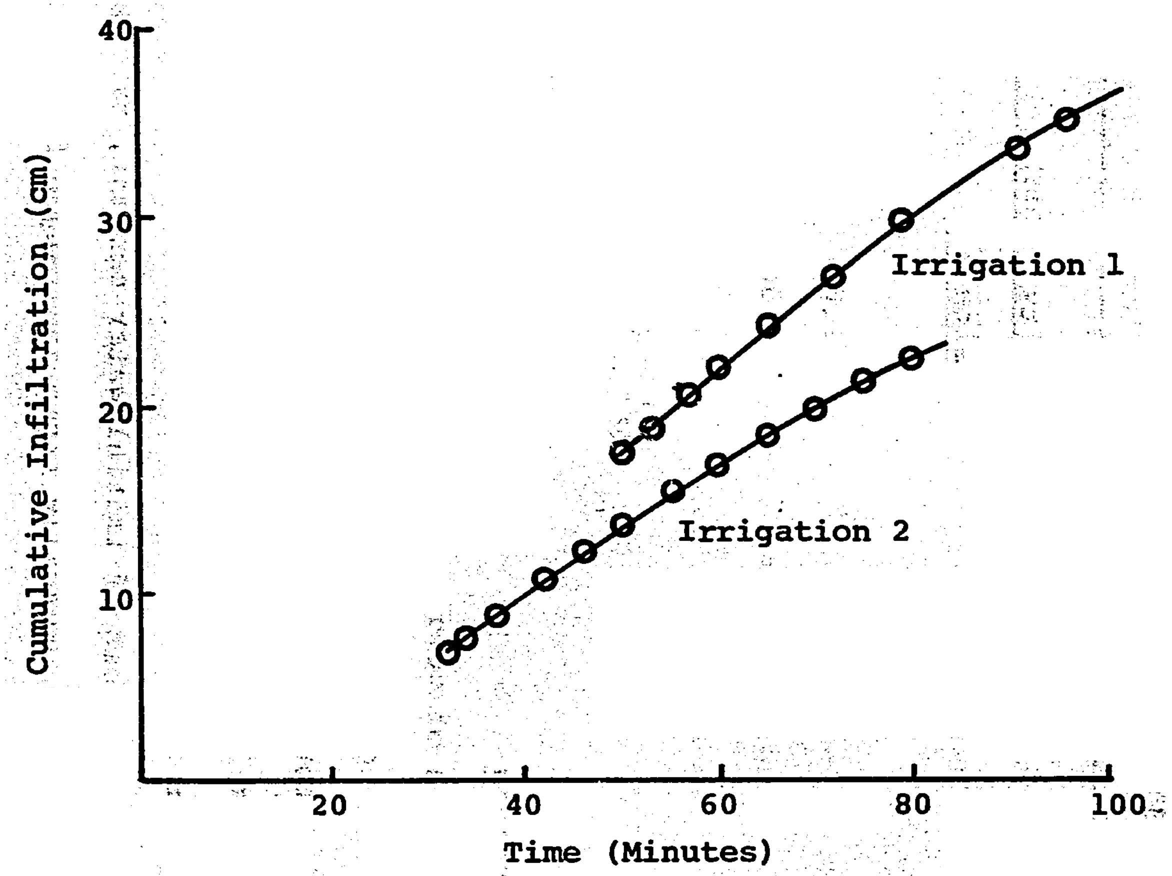

Figure 8 Cumulative Infiltration vs Time for Two Irrigations at Site I, LVE Soil, EEB, Brasilia.

Rates of infiltration were very similar to those observed on other Oxisols in Puerto Rico (Wolf and Drosdoff, 1974). Further, Pruntel (1975), reports infiltration rates of from 10-70 cm/hr on similar soils in the Federal District. In view of the high degree of aggregate stability of these soils, these results are not surprising.

It has been noted that heavy rains result in surface runoff from this soil. This will occur even though rainfall rates probably do not approach 17-22 cm/hour even for a few minutes. The divergence of the experimental results from observations during rains may possibly be explained by air entrapment in large conducting pores which may partially block entry of the water. This is suggested in the experimental results since it may be noted from figure 8 that neither curve, if extended, would pass through the origin. One may speculate that a certain initial time is required to fill the large conducting pores, after which infiltration proceeds rapidly.

Internal Drainage

Particularly at high soil-water contents, water losses due to internal drainage (deep percolation) may constitute a large percentage of that water otherwise designated as crop evapotranspiration (ET). As described previously, an experiment was designed to separate the drainage component from ET. This has been done for Site II.

One day after an irrigation or a heavy rain on the LVE at Site II, soil-water contents may be 31% (by volume). At that water content, drainage from the top 45 cm of the root zone is 4.8 mm/day, or 80% of likely ET. This diminishes rapidly so that after three days of combined drainage and ET, water losses due to drainage are only 0.26 mm/day (@ 27% moisture) or only 4% of ET. For water management purposes, when the ratio drainage to ET first becomes small, the associated soil-water content can be taken as the upper limit of available soil-water storage.

Internal drainage as a function of water content for the two soil zones on the LVE is presented in figure 9. It should be observed that at the same water contents, drainage occurs considerably faster from that portion of the profile below 45 cm. This is suggested by increasing porosity (decreasing bulk density) with depth. It is possible that differences between depths have been caused by tillage operations.

Table 12 gives drainage as a function of soil-water content for each 30 cm of the profile. This table may be used to determine water losses due to drainage for a crop planted on the LVE if soil-water contents

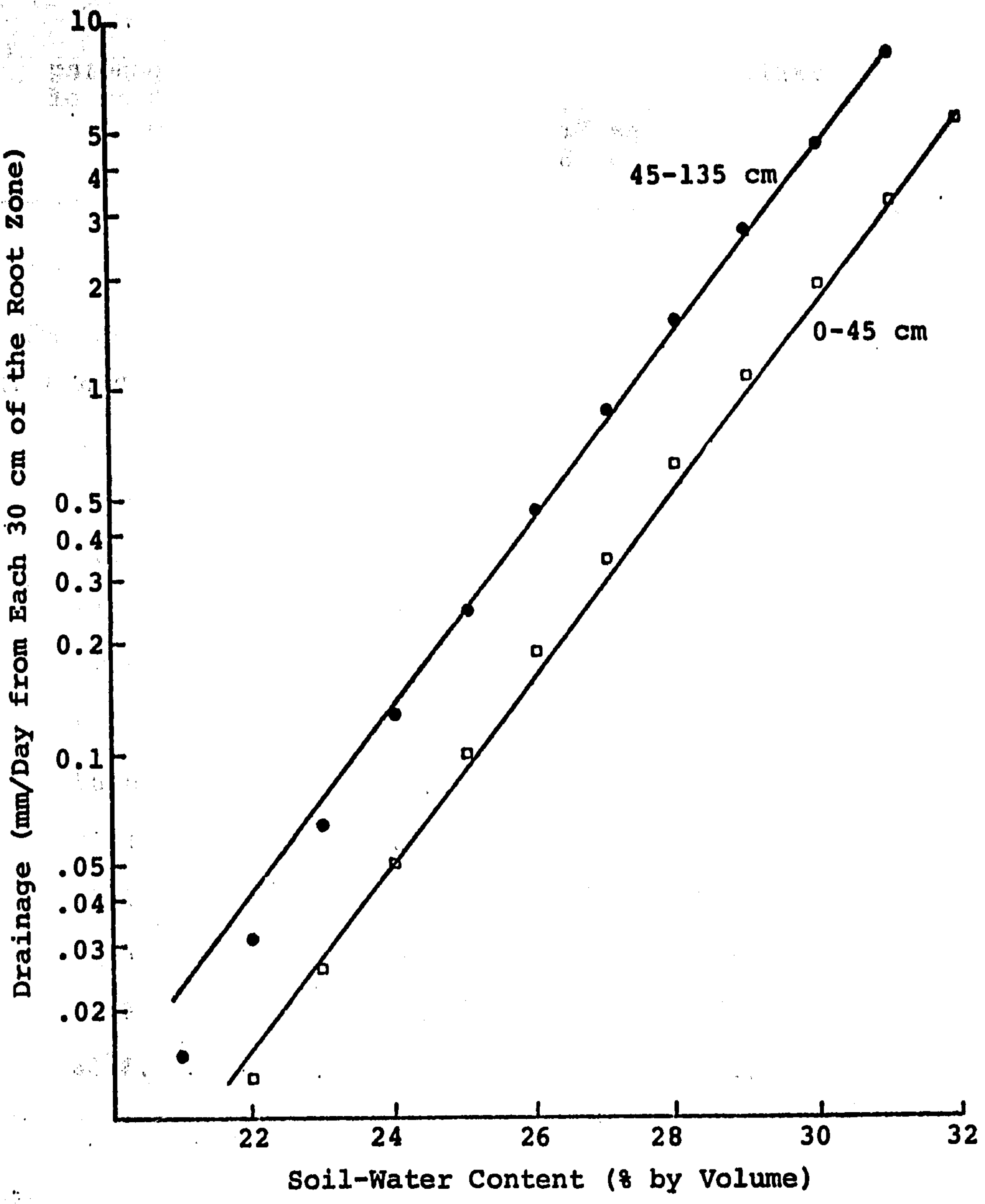

Figure 9 Drainage from Each 30 cm of the Root Zone vs Soil-Water Content for Two Soil Depths at Site II, LVE Soil, EEB, Brasilia.

Table 12 Soil-Water Contents and Corresponding Values of Drainage from Each 30 cm of the Profile for Site II, LVE Soil, EEB, Brasilia.

Soil-Water Content (% by volume)	Drainage (mm/day from each 30 cm of the rooting zone) 0 - 45 cm	45 - 135 cm
20	less than 0.01	less than 0.01
21	" " "	0.02
22	0.01	0.03
23	0.03	0.07
24	0.05	0.13
25	0.10	0.25
26	0.19	0.47
27	0.35	0.87
28	0.62	1.56
29	1.10	2.74
30	1.90	4.73
31	3.23	8.01
32	5.40	13.36

are known. For example, if the top 30 cm of the rooting zone was at 28% moisture (drainage = 0.62 mm/day), and from 30-60 cm the moisture content averaged 29% (drainage = 1.10 mm/day in 0-45 cm zone, and 2.74 mm/day in 45-135 cm zone), drainage would be occurring at:

$$\begin{array}{rl} & 0.62 \\ +\ 1/2\ (1.10) = & 0.55 \\ +\ 1/2\ (2.74) = & \underline{1.37} \\ & 2.54\ \text{mm/day.} \end{array}$$

In other words, 2.54 mm/day would be passing a plane located at the 60 cm depth. That water would be lost from the root zone and unavailable for the crop, but would need to be included in determining crop water requirements for planning purposes.

Capillary Conductivity

Capillary conductivity for the LVE for Site II has been determined and is presented in figure 10. Table 13 gives the same information in tabular form, together with the best fit equation relating capillary conductivity and soil-water content, associated R^2 values, and the range in water contents over which the equation was developed. The method used for the calculation of capillary conductivity can be found in Nielsen et al. (1964), Nielsen et al. (1973), and Wolf and Drosdoff (1974).

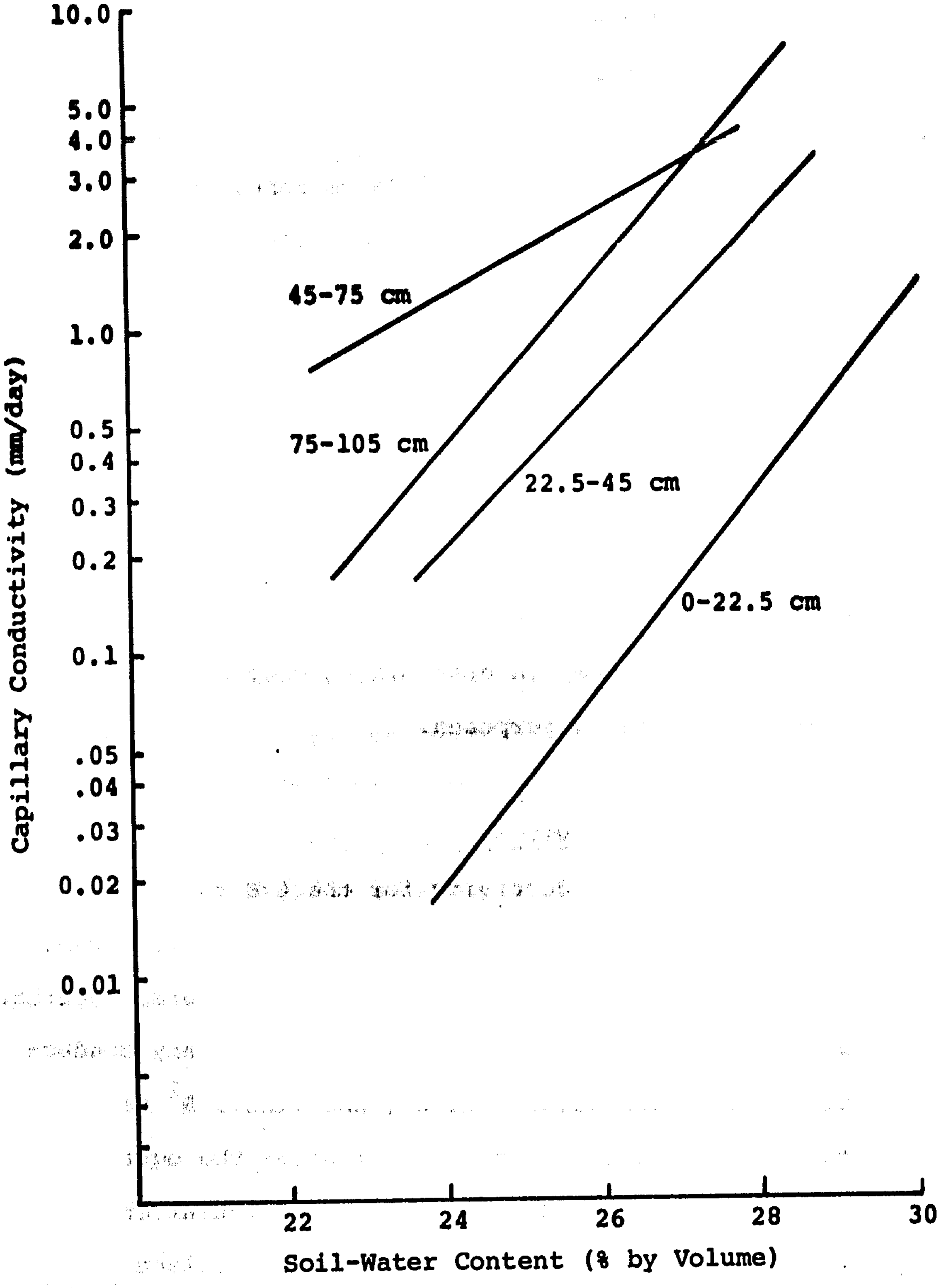

Figure 10 Capillary Conductivity vs Soil-Water Content for Four Depths for Site II, LVE Soil, EEB, Brasilia.

Table 13 Soil-Water Contents and Associated Values of Capillary Conductivity for Four Depths for Site II, LVE Soil, EEB. Also Given are the Equations Relating Capillary Conductivity (K) to Soil-Water Content (θ), and Associated R^2 Coefficients. Vertical Lines Indicate the Range in Soil-Water Contents Over Which the Equations were Derived.

Soil-Water Content (% by Volume)	Capillary Conductivity (mm/day)			
	Depth (cm)			
	0-22.5	22.5-45	45-75	75-105
31	2.43	8.26	9.33	23.86
30	1.31	5.37	7.22	14.37
29	0.69	3.44	5.54	8.51
28	0.35	2.17	4.21	4.94
27	0.18	1.35	3.17	2.82
26	0.087	0.82	2.36	1.57
25	0.041	0.49	1.74	0.86
24	0.019	0.29	1.26	0.46
23	0.0085	0.16	0.91	0.24
22	0.0037	0.092	0.64	0.12
21	0.0015	0.050	0.44	0.058
20	0.00061	0.026	0.30	0.027
19	0.00023	0.013	0.20	0.012
18	0.00008	0.0066	0.13	0.0053
Equation K=	$e^{-64.117}\theta^{18.930}$	$e^{-42.963}\theta^{13.126}$	$e^{-24.593}\theta^{7.812}$	$e^{-49.931}\theta^{15.464}$
R^2	.90	.77	.62	.86

Capillary conductivity values may be used with water potential gradients (obtained directly from tensiometer readings, or indirectly from soil-water contents and a moisture release curve) to calculate soil-water flux. The flux is the amount of water per unit time which redistributes within the soil profile as a result of differential moisture gradients. The gradients may be established by differences in water extraction patterns with depth. One may wish for example to determine upward flow of water to a water-stressed crop, where rooting is restricted by aluminum concentrations, and where the uppermost portion of the soil is relatively dry, and at deeper depths it is wet. Actual data for a water-stressed corn crop at Brasilia have shown tensions at 30 cm of 2 bars (soil-water content - 20.9%) and tensions at 60 cm of 0.28 bars (soil-water content - 22.9%). Upward flow to the 30 cm zone may be calculated from the Darcy Equation,

$$v = - K\frac{d\Psi}{dx} ,$$

where v = flux (volume of water passing a given area in a given time) - units are mm/day

Ψ = water potential in cm - This is the sum of matrix potential (soil-water tension) and gravity head

x = vertical distance in cm between sensing points (tensiometers)

K = capillary conductivity mm/day.

For the example, the water potential gradient was:

$$\frac{2000 - 280 - 30}{30} = 56.3$$

Capillary conductivity, extrapolated from figure 10 or from table 13 would be approximately 0.035 (for the limiting case of the 30 cm depth and the low water content at that depth). Upward flow to the 30 cm zone can be calculated at approximately 2 mm per day, or about 1/3 of the daily water requirement. This appears to be a realistic figure, water sufficient to restore overnight crop turgidity, but inadequate to maintain turgidity or sustained growth under normal atmospheric conditions.

For the LVE, this suggests that upward flow to the crop root zone may be an important component of water supply to a crop under drought conditions. Compared with other soils in the literature, reviewed by the author, values of capillary conductivity for the LVE were higher than for any other soil reported, at comparable soil-water tensions, (Cassel 1971; van Bavel et al. 1968; Reicosky et al. 1972; Nielsen, 1973; Wolf and Drosdoff, 1974). The high capillary conductivities associated with this soil may help explain why certain local grasses eg. Brachiaria, remain green well into the dry season. This may also partially explain why the native vegetation of the Campo Cerrado is able to survive the long dry season.

Soil-Water Characteristics

Changes in soil-water contents with time reflect ET and deep drainage. The separation of ET from deep drainage can be made, as indicated above, having once established a relationship between drainage and soil-water content. The problem remains as to how to determine water contents. The standard method of gravimetric sampling is excellent, but time consuming, and if water contents are to be monitored over time, an indirect measure of soil-water content is the only feasible solution. Use of tensiometers and gypsum blocks have been used to provide an indirect and workable method of determining soil-water contents. This is done by relating instrument readings to soil-water contents through the use of soil-water characteristics.

Soil-water characteristics, relating volumetric soil-water contents, and soil-water tensions for the LVE, are presented in figures 11 and 12, covering soil-water tensions in the range 0 to 1 bar, and 0 to 15 bars, respectively. These data are presented in tabular form in table 14. At each site, data were obtained for four depths, but, because of similarities between depths, data have been recombined to represent two depth ranges, 0-45 cm and 45-105 cm. Like data for the LVA are presented in the same table, and in figure 12. For that soil, data from three depths were combined into a single

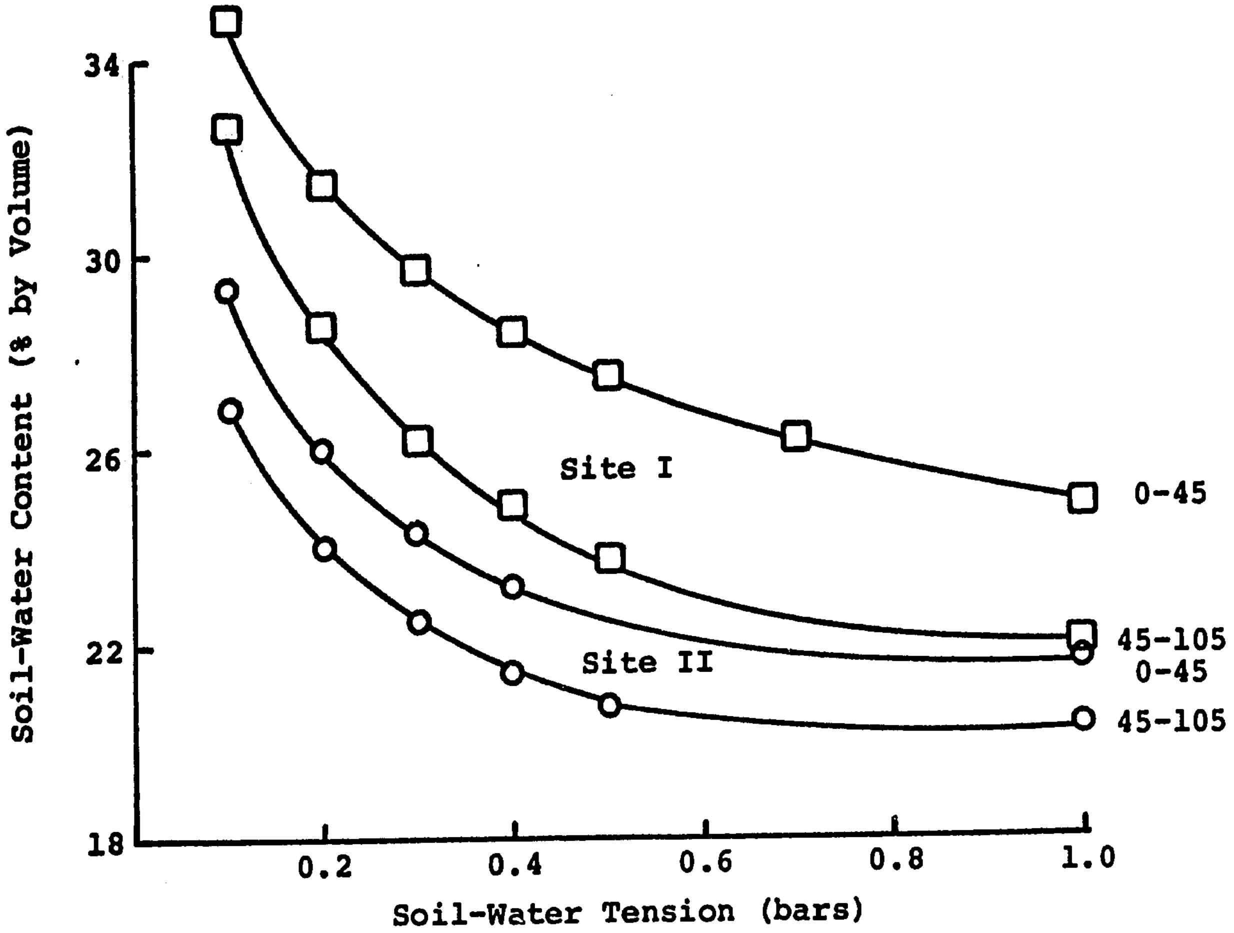

Figure 11 Soil-Water Release Curves for the Tension Range 0-1 Bar for the LVE Soil at Two Sites at the EEB.

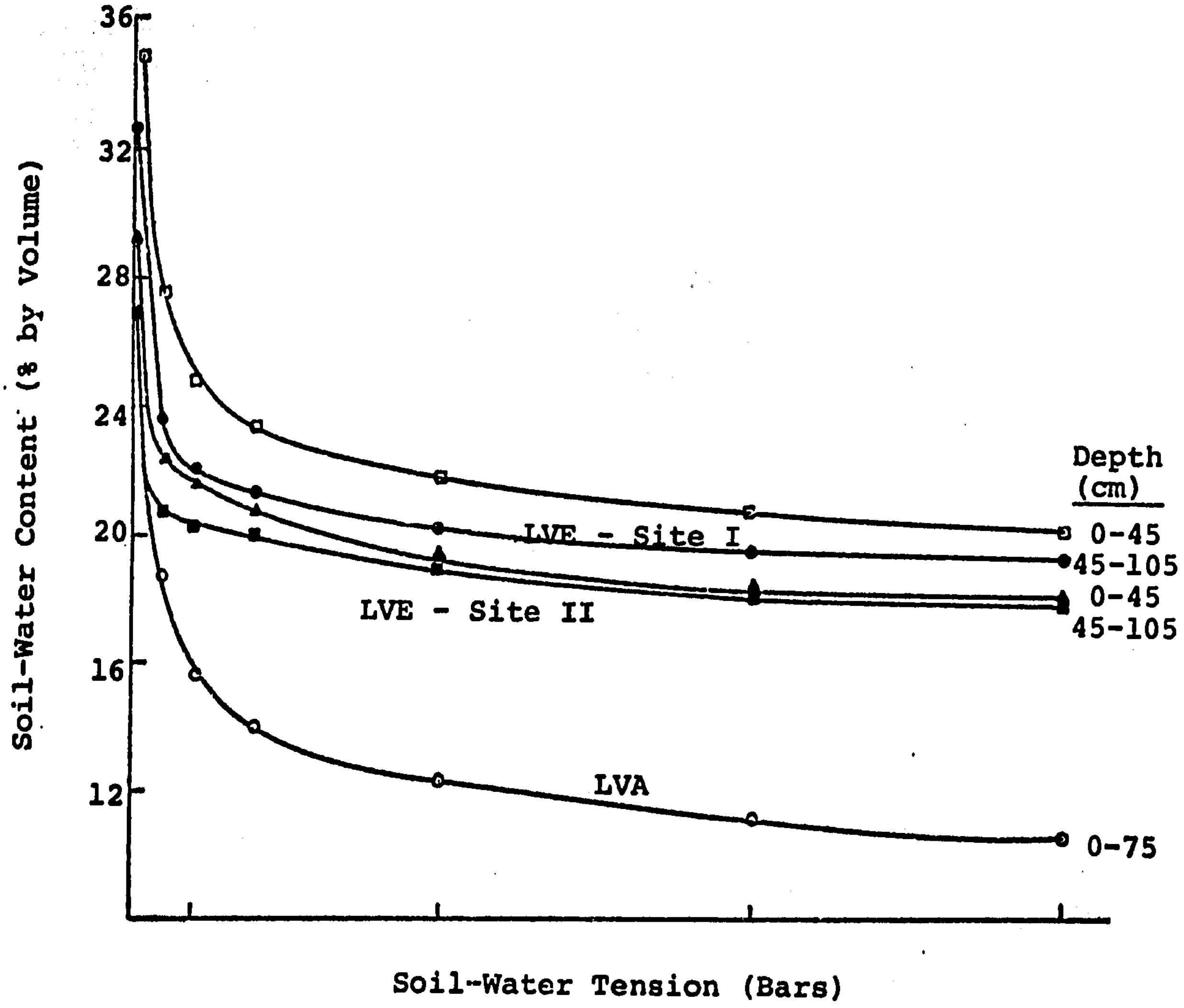

Figure 12 Soil-Water Release Curves for the Tension Range 0-15 Bars for LVE and LVA Soils at the EEB.

Table 14 Soil-Water Contents (% by volume) at Various Tensions for LVE and LVA Soils at the EEB.

Tension (Bars)	Soil-Water Content (% by volume)				
	LVE				LVA
	Site I Depth (cm)		Site II Depth (cm)		Depth
	0-45	45-105	0-45	45-105	0-75
0.1	34.8	32.7	29.3	26.9	24.7
.2	31.5	28.5	26.0	24.0	22.0
.3	29.7	26.3	24.3	22.5	20.6
.4	28.4	24.8	23.1	21.4	19.6
.5	27.5	23.7	22.2	20.7	18.7
.7	26.2	22.2	22.1	20.5	17.2
1.0	24.8	22.0	21.7	20.3	15.5
2.0	23.4	21.3	20.9	20.0	14.0
5.0	21.9	20.3	19.5	19.0	12.4
10.0	20.7	19.6	18.5	18.2	11.2
15	20.1	19.2	18.0	17.8	10.6

soil-water characteristic since differences between depths were minor.

To facilitate computerized calculation of water contents for these soils, equations have been developed which express the relationships graphed in figures 11 and 12. All curves were regressed to be logarithmic, taking the general form:

$$Y = KT^C$$

where Y = soil-water content (percent by volume)

T = soil-water tension (cm of water)

K, C = constants.

Coefficients for these equations are presented in table 15. Also presented for the LVE is the relationship between soil-water content and gypsum block reading, (Delmhorst blocks when read with a Delmhorst Soil Moisture Tester on a scale of 0 to 200). This linear relationship was determined from field data by associating block readings with results of gravimetric sampling.

Soil-water release for the LVE may be characterized by a sharp break in water release between 1/2 and 3/4 bar. Two-thirds of the soil water is stored and released at tensions less than 1 bar. These clayey soils behave like sands in their water release patterns in that the bulk of the water is held and released at tensions less than 1 bar. This is due to a dewatering of large pores between structural units. From 1 bar to 15 bars the

Table 15 Coefficients for the Equation $Y = KT^C$ Relating Soil-Water Tension and Soil-Water Content for Various Depths for Soils at the EEB.

Soil	Depth (cm)	Valid for Range of Tension (Bars)	K	C	R^2
		Soil-Water Content vs Soil-Water Tension			
LVE Site I	0-45	0-1	68.4857	-0.1468	.905
	0-45	1-15	41.2972	-0.0745	.916
	45-105	0-0.7	81.6035	-0.1988	.950
	45-105	0.7-15	31.5642	-0.0518	.977
LVE Site II	0-45	0-0.5	64.5733	-0.1716	.892
	0-45	0.5-15	37.1185	-0.0753	.987
	45-105	0-.5	56.7986	-0.1626	.729
	45-105	0.5-15	31.2057	-0.0581	.991
LVA	0-75	0-0.8	60.0679	-0.1897	.840
	0-75	0.8-15	42.9363	-0.1455	.995

Soil-Water Content vs Gypsum Block Reading

LVE Site II $Y = 18.872 + .0259\ (\text{Delm})$ $R^2 = .799$

Y = Soil-Water content (% by volume)
T = Soil-Water tension (cm of water)
Delm = Delmhorst meter reading
K,C = Constants
R^2 = Correlation coefficient

difference in water released is only 3-4%, or 1 cm of water per 30 cm of soil. The utility of that water for cropping is slight because:

(1) The absolute quantity of water is small.

(2) The water is held at high tensions.

(3) The water is stored in micropores which would be difficult for plant roots to tap.

The soil at Site I holds somewhat more water than the soil at Site II. This may be a result of organic matter accumulations at the former site which has been planted to grass for 6 years. At both sites, the soil from 0-45 cm holds and releases more water than the soil from 45-105 cm. This may be due to a destruction by tillage of some of the macropores which results in decreased porosity (increase in compaction) and increased water storage in micropores. In this respect one may note a slightly less abrupt pattern of water release in the surface soil.

The soil-moisture characteristic of the LVA is less abrupt and of greater range than that for the LVE. Although the absolute amount of water released at high tensions is small, the LVA continues to release some water at tensions above 1 bar. This is especially interesting since the LVA is of lighter texture than the LVE.

Soil-Water Availability

Using tables or the soil-water characteristics, one may compute the accumulated water released (or stored) by these soils. This has been summarized in table 16. For the upper limit of water availability a water content associated with a soil-water tension of 1/10 bar has been used. This is the approximate tension of these soils after saturation and 2-3 days of free drainage in the absence of ET. For the LVE, 1/3 bar percentage is not reached until after 80 days of free drainage, or perhaps 3 days of drainage and ET. The lower limit of available water was set at the 15 bar percentage.

Table 16 Accumulated mm of Water Released as Soils are Dewatered from 1/10 Bar to the Tension Indicated.

Tension (Bars)	Water Released (mm)					
	LVE				LVA	
	Site I		Site II			
	Depth of Effective Rooting (cm)					
	30	60	30	60	30	60
1/10	0	0	0	0	0	0
1	30	61	22	43	28	55
15	44	86	34	65	42	85

Depending on site and depth, these soils store from 27 to 44 mm of water per 34 cm of soil. In the absence of rainfall, a crop rooted in the top 30 cm of the LVE profile at Site II would deplete the soil water to tensions greater than 1 bar in less than 4 days (typical ET = 6 mm/day). Field observations on shallow rooted corn have confirmed slight wilting due to a 4 day period of high evaporative demand without rain or irrigation. In 6 days, crops were severely wilted. Even if a crop were able to exploit a 60 cm root zone, wilting could be expected after a week without supplemental water.

The LVA has roughly twice the sand content and half the clay plus silt content of the LVE. Nevertheless, it can supply 30% more water than the LVE soil at the main experimental site (Site II). Approximately 2/3 of that water is available between 1/10 and 1 bar. The amount of water in storage should permit crops grown on this soil to withstand wilting for perhaps up to 10 days.

Crops grown on both soils can be expected to suffer from the effects of drought given the restricted rooting regimes and the poor rainfall distribution.

Summary and Conclusions

1. Soil-water data are presented for three sites on the Brasilia Experiment Station.
2. Although the soil at the main experimental site contains almost 50% clay, it is highly aggregated and structurally stable. For this

reason, soil-water properties of this soil are similar to those of sands.

3. The soils are characterized by rapid infiltration ranging from 17-22 cm/hr, and by extensive and continued internal drainage.
4. For the main experimental site, capillary conductivity was determined to be high, and greater than for other soils reported in the literature.
5. Available water storage on the LVE is limited to approximately 34-44 mm per 30 cm of soil.
6. The LVA, though lighter in texture than the LVE, contains 30% more available water.
7. These soils, like sands, release 2/3 of the available water between 1/10 and 1 bar.
8. The unfavorable water supplying properties of these soils together with the occurrence of wet-season dry periods and the limitations of root growth in the subsoil due to aluminum toxicity make water management a critical factor for successful crop production in the region.

CHAPTER IV

CROPPING - INTRODUCTION & METHODOLOGY

Introduction

The physical constraints to providing adequate water for cropping in Brazil's Central Plateau, i.e., the erratic rainfall distribution and the physical characteristics of the soil which limit crop water supply have been documented in Chapters II and III. The manner in which these constraints affect crop production still required determination through agronomic experimentation.

For Central Brazil, there is a general lack of information in the area of water management in relation to crop patterns and soil fertility practices. This is true in spite of the fact that in the dry season there can be no production without irrigation. Landers et al. (1967) have described the vast potential for dry season irrigation in the cerrado. Further studies are necessary to determine the most effective use of the limited water resources of this area. The use of supplemental irrigation during the wet season has been acknowledged in practice, yet to date nothing has been done to determine the requirements for or benefits from these practices. Although experiments have been conducted, little is published on the potential for production in the dry and wet seasons.

Among local agriculturalists, knowledge is widespread that aluminum toxicity is severe on these soils and limits depth of effective rooting of species such as corn which are not tolerant to aluminum. Other work of the collaborative Cornell and North Carolina State University project at the Brasilia Experiment Station in cooperation with Brazilian soil scientists has shown large yield increases to incorporations of limestone to 30 cm as opposed to the conventional 15 cm incorporations. The cause of the yield response still needed to be ascertained, though Gonzalez, in NCSU, (1973) has shown that for corn, deeper lime incorporation results in a more effective crop root system especially at depths below 15 cm. Likely reasons for yield differences were better nutrient exploitation and/or improved utilization of the soil water, both commensurate with the greater crop root system.

To investigate these and other points, a dry season experiment was planted in June 1973, followed by wet season experiments planted in September, October and November 1973. Objectives of the experiments were as follows:

1. Determine crop response to various water environments.
2. Determine crop water use in relation to me-

teorological factors.

3. Determine effects of differential depths of limestone incorporation in relation to water treatments.

Results of the experiments will be discussed in Chapters V-VII which deal, respectively, with experimental results discussed in relation to these objectives.

Dry Season Experiment - Materials and Methods

The dry season experiment, using corn (Zea Mays L.) as a test crop, was established at the Estaçāo Experimental de Brasilia (EEB) on the Dark Red Latosol described in Chapter III. The corn variety used was a Brazilian hybrid, Cargill 111. This variety has consistently been one of the best yielders in variety trials at the EEB. The variety is of long duration (130-150 days depending on the season). By U.S. standards, the corn may be considered as a silage type because of the amount of green matter production under very high fertility conditions. Through hand thinning, plant population was established at 62,500 plants per hectare.

The experiment was designed without treatment replication. This design differed greatly from conventional replicated experiments which have as their objective to establish whether one irrigation or agronomic treatment is significantly different from a second. Such an objective requires replication, but not necessarily range. In this experiment, the objective was to establish functional relationships for the water variable. Twelve unreplicated treatments were established which provided both a wide range of water treatments and definition within the range. Regularly scheduled irrigation treatments alone provided the range; year-simulation treatments gave definition within the range. Statistical analyses were performed through regression techniques.

Treatments consisted of two depths of limestone incorporation and six water management regimes. Limestone incorporations were:

1. Shallow - 4 tons calcium carbonate equivalent of calcitic limestone (5.4 tons actual material) per hectare incorporated between 0 and 15 cm. The material was finely ground with more than 60% passing a 60 mesh and more than 40% passing a 100 mesh.
2. Deep - 4 tons calcium carbonate equivalent of calcitic limestone per hectare incorporated between 0 and 30 cm.

The six water management regimes may be separated into two types:

1. Regularly scheduled irrigations were watered with a fixed irrigation interval. This resulted in regular patterns of water applications

and soil-water depletions:

a. Irrigate every 3 days, corresponding to an approximate pan evaporation of 15 mm, or to soil-water depletion of 21% (60-cm root zone).

b. Irrigate every 7 days, corresponding to an approximate pan evaporation of 35 mm, or to soil-water depletion of 50%.

c. Irrigate every 14 days, corresponding to an approximate pan evaporation of 70 mm, or to soil-water depletion approaching 100%.

Patterns of computed soil-water storage with time for regularly scheduled irrigation treatments are presented in figure 13.[1]

2. Year-simulation irrigations which called for irrigations to simulate the rainfall distribution and amount during the cropping season in certain bench mark years. The years chosen for simulations were representative of many years in which dry periods (veranicos) of various severities and/or durations occurred.

a. Irrigate to simulate the rainfall pattern at Formosa in 1945-46.

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[1] See footnote page 22 for computational method.

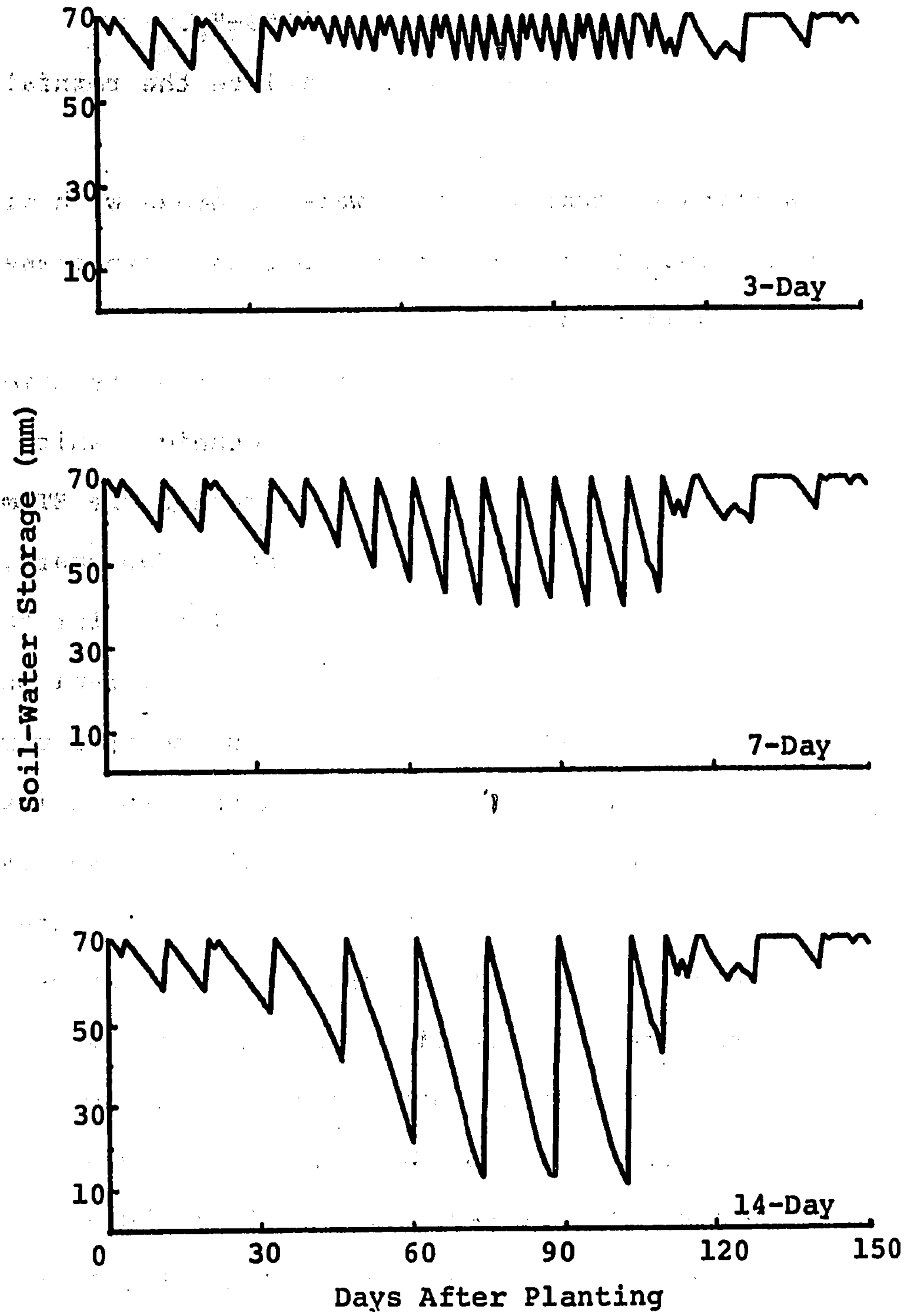

Figure 13 Soil-Water Storage vs Time for Regularly Scheduled Irrigation Treatments. A 60 cm Root Zone has Been Assumed.

b. Irrigate to simulate the rainfall pattern at Formosa in 1953-54.

c. Irrigate to simulate the rainfall pattern at the EEB in 1972-73.

Patterns of computed soil-water storage with time for year-simulation irrigation treatments are presented in figures 14 to 16.[1]

Year selection for year-simulation treatments was based upon a computer plotting technique which used actual wet season precipitation data and the ET model to graph likely soil-water conditions. Two years, 1945-46 and 1953-54 were selected for simulation for they were representative of many years in which veranicos were common. The pattern of 1945-46 is one of 2 veranicos of 12 and 13 days separated by 10 days when soil-water conditions were adequate. The veranico in 1953-54 resulted in one period of almost 30 days when soil-water conditions were deficient for crop growth. The year, 1972-73 was selected because of a short veranico during the critical crop stage, and a longer veranico close to harvest. Other reasons, discussed later, also called for selection of this year. For each of these years, the 5-month rainfall totals were within 90% of the average.

Figures 14 to 16 are comparisons of computed soil-

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[1] See footnote page 22 for computational method.

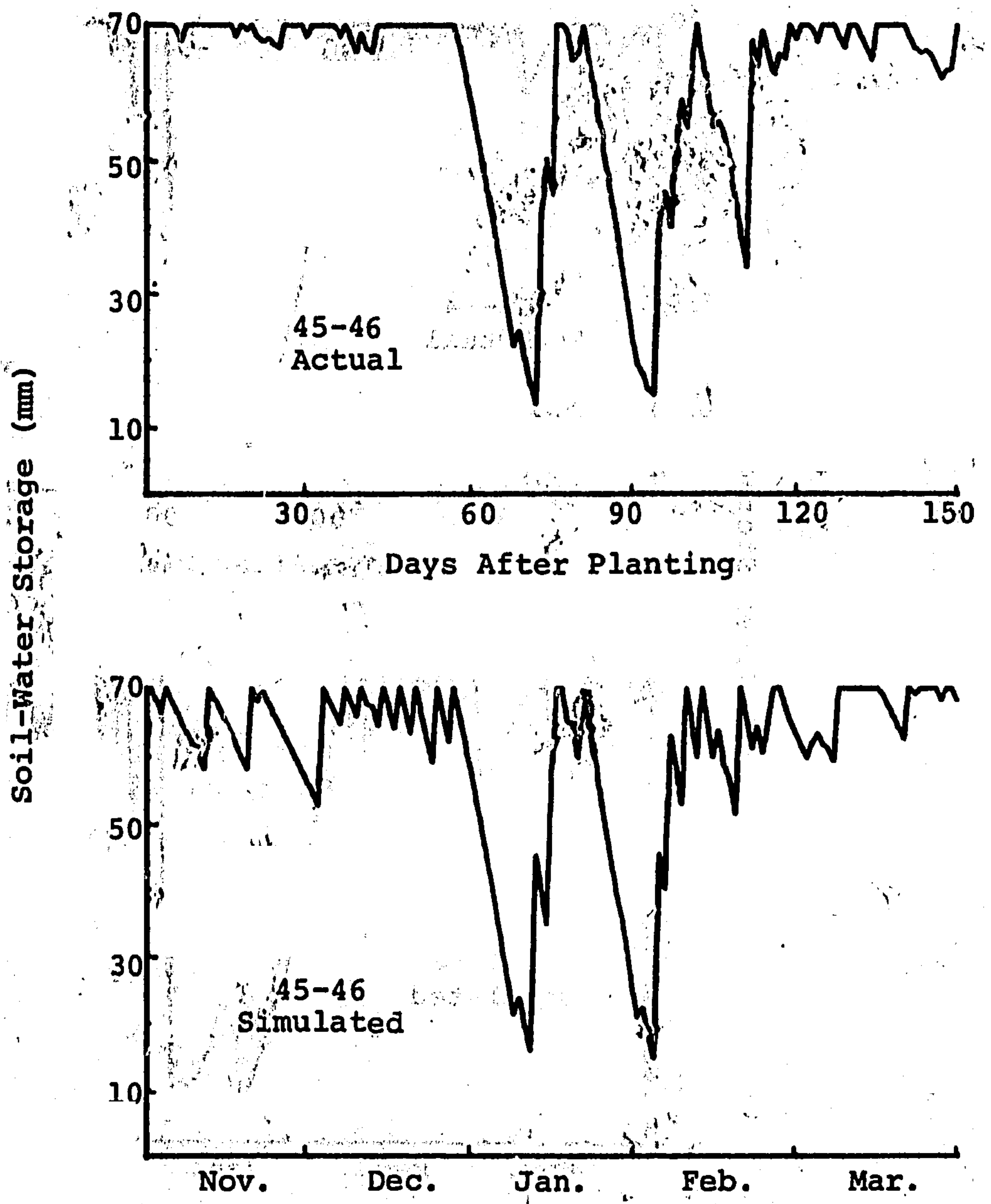

Figure 14 Soil-Water Storage vs Time for Actual and Simulated 1945-46. A 60-cm Root Zone has Been Assumed.

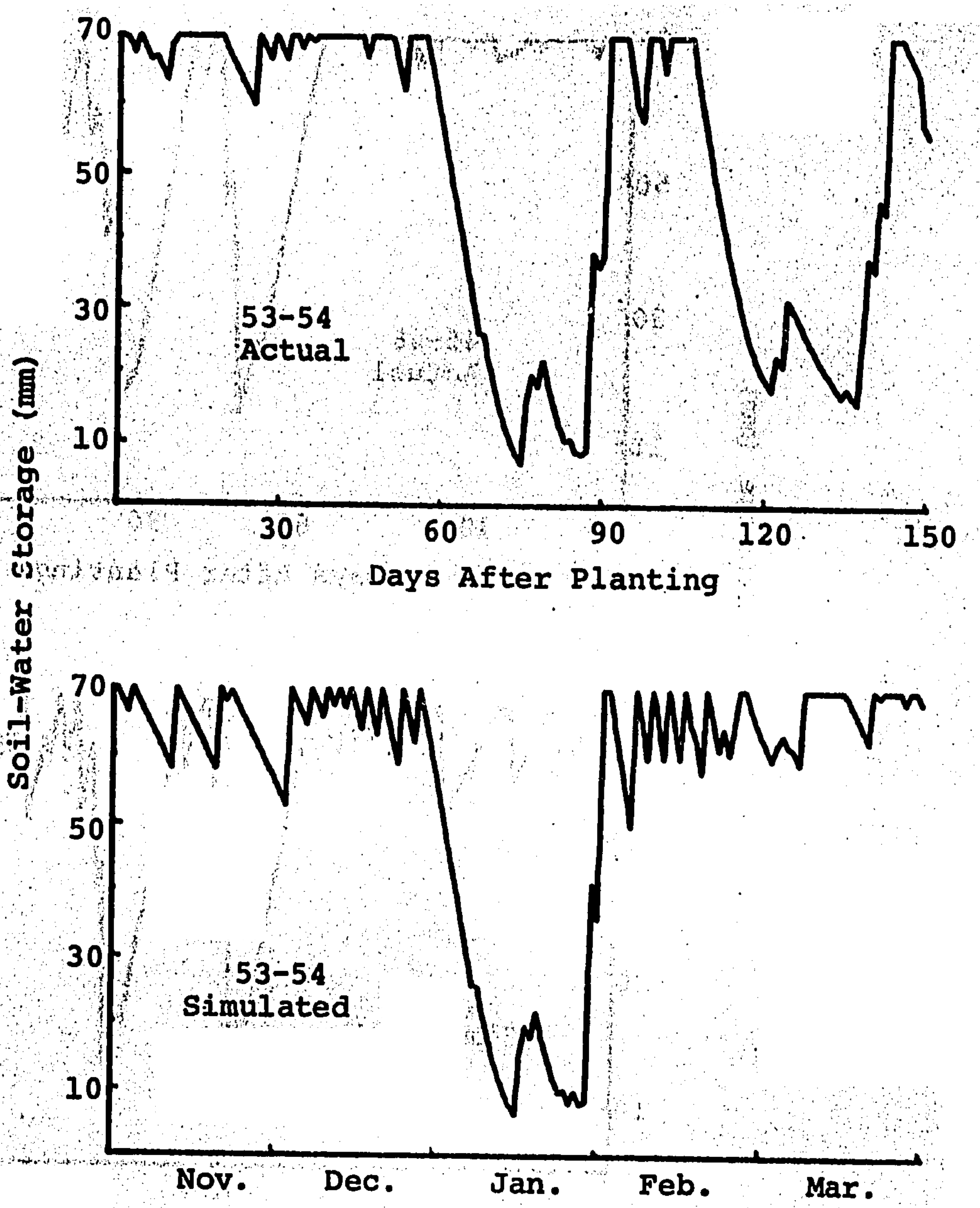

Figure 15 Soil-Water Storage vs Time for Actual and Simulated 1953-54. A 60-cm Root Zone has been Assumed.

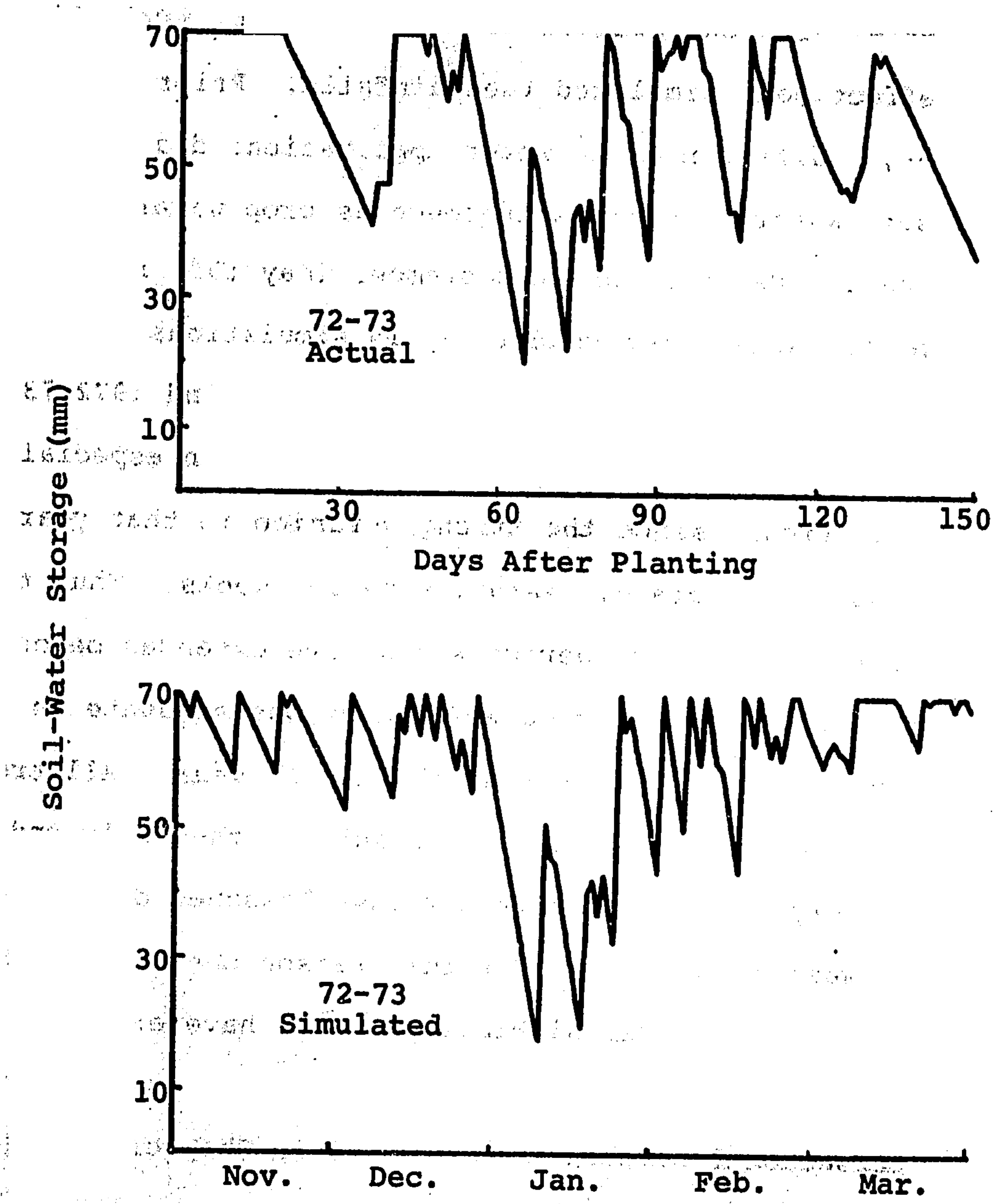

Figure 16 Soil-Water Storage vs Time for Actual and Simulated 1972-73. A 60-cm Root Zone has Been Assumed.

water conditions desired (based on rainfall during the actual year) and simulated (based on irrigations and late dry season rains in September, October and November). It is evident that for most but not all of the water critical periods of the corn crop, irrigations effectively simulated the rainfalls. Prior to day 56, differences in water applications did not affect soil-water conditions inasmuch as crop water use was small. Early rains in September (day 109) resulted in better soil-water conditions in simulations than in the actual years, particularly for 1953-54 and 1972-73. In the 1953-54 simulation this may have been especially significant since the strong veranico in that year's simulation retarded maturity by 1-2 weeks. Thus the critical moisture period would have extended beyond 109 days and into a period when water was adequate in the simulated year but not in the actual year. All treatments made late gains as a result of the early end to the dry season and this may have lessened differences between treatments. For this reason one may speculate that yields under simulations would have exceeded those under actual precipitation conditions. However, the interseasonal comparison discussed in Chapter VI fails to bear out this hypothesis.

The simulation of the rainfall pattern in 1972-73 also permitted a comparison of interseasonal production potentials between dry and wet seasons. The basic fertilizer application on all dry season treatments was identical to that applied in the 1972-73 wet season. This was the following:

N	100 kg N/ha
	20 kg N/ha banded, preplant as ammonium sulfate
	40 kg N/ha sidedressed as urea at both 19 and 58 days after planting
P	300 kg P_2O_5/ha
	200 kg P_2O_5/ha broadcast as triple superphosphate
	100 kg P_2O_5/ha banded as triple superphosphate
K	100 kg K_2O/ha broadcast as potassium chloride
Zn	13.4 kg Zn/ha broadcast as zinc sulfate
B	1.0 kg B/ha broadcast as borax
Mo	0.5 kg sodium molybdate/ha broadcast

Plots were instrumented with tensiometers and gypsum blocks at 15-, 30-, 60-, and 90-cm depths. Tensiometer and block readings, taken daily, were converted to soil-water contents using the relationships described in Chapter III. Changes in soil-water content were attributed to evapotranspiration and drainage. Drainage was calculated from soil-water contents using equations presented in Chapter III. Evapotranspiration was set equal to change in soil-water storage less drainage. It should be noted that water content changes which are a result of capillary conductivity considerations, ie., upward movement of soil-water, are accounted for using this approach to calculation of ET and drainage.

The appropriate water balance for the dry season was: Water Applied = ET + Drainage ± Change in Seasonal Soil-Water Storage. The sum of the calculated values on the right hand side of the equation was compared with water applied as determined independently using an in-line flow meter which had been field calibrated. The calculated values underestimated water applied by 16%. This discrepancy was due to the system of taking instrument readings. These were taken on the morning before an irrigation and in the morning on the day following an irrigation. The time lag between an irrigation and the following instrument reading (at times 16 hours) had the effect of ignoring maximum soil-water contents which occurred immediately following the irrigation. For example, soil sampling one hour after a heavy irrigation revealed soil-water contents of up to 42%. The following morning water contents were typically 31%. This latter figure was the one which went into calculation of ET and drainage. In reality, a larger portion of the water applied, on the order of 16%, should be additional water attributed to deep drainage losses.

Wet Season Experiments - Materials and Methods

Three experiments, using corn (Zea Mays L., var. Cargill 111), were planted during the 1973-74 wet season. Commencing with September 26, planting dates were approximately 30 days apart. Water and fertility treatments were designed to reflect possible management options to lessen the effect of wet season dry spells which, as described in Chapter II, occur with frequency in Central Brazil.

In each experiment, treatments included the following:

1. Two depths of incorporation of limestone, 0-15 cm (shallow) and 0-30 cm (deep). Method of incorporation and rate and type of limestone applied (4 tons $CaCO_3$ equivalent calcitic limestone/ha) were identical to amendment applications in the dry season experiment.
2. Water treatments designed to "break" - by irrigating - dry spells lasting 4 days and 7 days. Control treatments of never irrigating were included. An additional water treatment, that of breaking a 10-day dry spell - should it occur - was also included in combination

with the shallow incorporation only. Thus, each experiment had seven basic treatments which are listed below:

	Water Treatment	Incorporation Treatment
a.	4-day	Shallow
b.	4-day	Deep
c.	7-day	Shallow
d.	7-day	Deep
e.	10-day	Shallow
f.	Never Irrigate	Shallow
g.	Never Irrigate	Deep

Treatments were replicated three times in a completely randomized design.

It should be emphasized that the water treatments as stated were simply nominal water treatments and that actual imposition of these treatments depended upon the rainfall. Given in table 17 are the number of irrigations which were applied to the crops and which correspond to each nominal water treatment. Also given in the table are the precipitation totals for the 130-day growing seasons, and a summation of dry spells of various lengths. Since precipitation events for each planting differed, it would be improper to consider this a single experiment with identical nominal treatments and three dates of planting. Separate plantings are most aptly interpreted as three experiments, labeled I, II and III.

Table 17 Precipitation, Number of Irrigations, and Length of Dry Spells for Three Wet Season 1973-74 Water Experiments.

	Experiment Number		
	I	II	III
Precipitation (mm)	870	724	1004
Nominal Water Treatment	**Number of Irrigations**		
4 days	5	6	5
7 days	1	3	2
10 days	0	0	0
Never	-	-	-
Length of Dry Spell	**Occurrences**		
5 days	2	1	1
6 days	1	0	0
7 days	1	1	1
8 days	1	3	2
9 days	0	0	0

To monitor soil-water conditions for each treatment, two-thirds of the plots (or 14 plots per experiment) were instrumented with tensiometers and gypsum blocks at depths of 15, 30 and 60 cm. Readings from these instruments were converted to soil-water contents using relationships presented in Chapter III. Because of frequent rains, it was not possible to determine crop ET using this instrument package in the wet season.

The site for the experiments was adjacent to the dry season experimental area. The soil there is the LVE, a Haplustox, the relevant properties of which have been described in Chapter III. Table 18 provides pertinent chemical properties of the soil prior to working the area for cropping. Results of soil tests taken after harvests are given in table 19.

Table 18 Results of Soil Tests for the LVE Soil Prior to Working the Area for Wet-Season 1973-74 Water Experiments.

Depth (cm)	Exchangeable Al (meq/100 g soil)	Exchangeable Ca + Mg (meq/100 g soil)
0-15	1.09	0.32
15-30	1.09	0.12
30-45	0.86	0.13

(The pH of the soil was approximately 4.8.)

Table 19 Results of Soil Tests from Composite Samples Taken after Harvest from the Wet-Season 1973-74 Water Experiments.

	pH (in water 1:1)		Exchangeable Al (meq/100g)		Exchangeable Ca+Mg (meq/100g)		Aluminum Saturation (%)	
	Shallow	Deep	Shallow	Deep	Shallow	Deep	Shallow	Deep
Experiment I								
0-15	5.39	5.04	.08	.38	3.01	1.54	3	20
15-30	4.91	5.14	.71	.52	1.18	1.77	38	23
30-45	4.95	5.06	.58	.43	0.81	1.26	42	25
Experiment II								
0-15	5.37	4.92	.09	.41	2.75	1.68	3	20
15-30	4.89	5.35	.86	.32	0.78	1.86	52	15
30-45	4.82	5.19	.92	.48	0.52	1.05	64	31
Experiment III								
0-15	5.35	4.75	.22	.82	3.50	1.31	6	38
15-30	4.67	4.91	.89	.61	1.05	1.54	46	28
30-45	4.56	4.87	.90	.55	0.61	1.42	60	28
All Experiments								
0-15	5.37	4.90	.13	.54	3.05	1.51	4	26
15-30	4.82	5.13	.82	.48	1.00	1.72	45	22
30-45	4.78	5.04	.80	.49	0.65	1.24	55	28

The fertilizers applied to all treatments were as follows:

1. N 140 kg N/ha

   20 kg N/ha as ammonium sulfate banded, preplant.

   40 kg N/ha as urea sidedressed at 23, 22 or 20 days depending on the respective experiment.

   40 kg N/ha as urea sidedressed at 56, 46 or 44 days depending on the respective experiment.

   40 kg N/ha as urea sidedressed at 72, 70 or 67 days depending on the respective experiment.

2. P 500 kg P_2O_5/ha

   400 kg P_2O_5/ha as triple superphosphate broadcast, preplant.

   100 kg P_2O_5/ha as triple superphosphate banded, preplant.

3. K 100 kg K_2O/ha as potassium chloride broadcast, preplant.

4. Zn 13.4 kg Zn/ha as zinc sulfate broadcast, preplant.

5. B 1.0 kg boron/ha as borax broadcast, preplant.

6. Mo 0.5 kg sodium molybdate/ha broadcast,

preplant.

7. Mg 20 kg Mg/ha

10 kg Mg/ha as magnesium sulfate side-dressed at 23, 22, 20 days depending on the respective experiment.

10 kg Mg/ha as magnesium sulfate side-dressed at 56, 46, 44 days depending on the respective experiment.

These fertilizer amounts differed from the dry season applications in that they contained an additional 200 kg P_2O_5/ha, 40 kg N/ha and 20 kg Mg/ha.

Similar to the dry season, plant populations were established by hand thinning at 62,500 plants per hectare.

Leaf sampling for nutritional analyses[1] were made at 92, 96 and 89 days depending on the respective experiment. The leaves for analysis were taken at silking from leaves immediately opposite the lowermost ear.

During the course of the experiments, very serious plant diseases occurred which could not be controlled. The first and second experiments, but not the third, were attacked by a disease which first became evident at 55 and 40 days, respectively. The center part of

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[1] The author is grateful for the analyses on these samples performed by IPEACO, EMBRAPA, Sete Lagoes, Brazil, the Soil Science Department, North Carolina State University, Raleigh, North Carolina, and by the Department of Pomology, Cornell University.

affected plants wilted and died, resulting in plant death. Microscopical analysis of the growing tips of these plants revealed the presence of a highly motile rod-shaped bacteria which may have caused rotting and death of the tip. However, when this bacteria (cultured on agar) was injected into healthy plants, no new incidence of the disease was noted. Although evidence points to Bacterial Wilt, Xanthomonas Stewartii, identification is still enigmatic. The disease affected and killed up to 10% of the plants, though the effect upon grain production may not have been too serious inasmuch as the disease struck early, permitting other plants to take advantage of reduced plant populations.

A far more serious disease was identified under the microscope as Northern Leaf Blight, Helminthosporium Turcicum. The disease appeared first as elliptical lesions which in time coalesced, causing premature necrosis of most leaves. No attempt was made to control the disease with fungicides. This probably would have been futile due to damp weather and daily rains during March. The disease affected the second and especially the third experiments. As a result, grain yields in the third experiment were less than 50% of the first experiment.

CHAPTER V

CROP RESPONSE TO SPECIFIC WATER ENVIRONMENTS

Introduction

The background information and methodology for dry and wet season field experimentation have been described in detail in the previous chapter. The purpose of this chapter is to give results from those experiments, particularly results which pertain to the questions: (1) What was the effect of soil-water stress upon yield?; and (2) What is the relationship between yield and the various water treatments?

Relationships between yield and the water treatments are empirical determinations which may have practical utility. Such relationships may be termed "yield-water response functions". Relationships between soil-water stress and yield are physical relationships, of perhaps less practical utility than the response functions, but valuable in providing insight and understanding for those response functions. In this chapter, results will be presented to develop response functions to be used in Chapter VIII as a component of a model to predict long term yields under adverse soil-water conditions on the Campo Cerrado.

Before discussion is made of yields and soil-water stress, the first two parts of this chapter will discuss 1) comparative results from year-simulation and regularly scheduled irrigation treatments, and 2) recovery of corn from severe water stress.

Results

Comparison of Year-Simulation and Regularly Scheduled Irrigation Treatments

Irrigation practice in arid areas results in additions and depletions of soil-water on a regular basis. For example, during the peak of the growing season, a farmer will irrigate a crop on regular cycles, since climatic conditions, the driving force for water use, will be relatively uniform. In humid areas the pattern of water additions and depletions will be random, a product of random rainfalls and changeable weather conditions. Using irrigation during the dry season, both regular and random (year-simulation) patterns of water additions were achieved and the results compared to determine if there were differences in response due to varying the basic pattern of soil-water replenishment. This comparison was an attempt to find areas of commonality, or differences, between irrigation treatments representing rainfed (year-simulation) and arid land (regularly scheduled) water management practices.

Yields for both types of irrigation treatments are presented in table 20. There was no difference in production between simulated years, or between year-simulation and the average of the regularly scheduled treatments. After day 109, irrigations were suspended because of the onset of the rainy season. The effect of the early rains may have minimized differences between treatments.

Table 20 Yield of Shelled Corn at 15.5% Moisture from Regularly Scheduled and Year-Simulation Irrigation Treatments from the Dry Season Water Experiment, Brasilia, 1973.

Treatments	Yield (kg/ha)
Regularly Scheduled Irrigations	
3-day	4417
7-day	3726
14-day	3205
Year-Simulation Irrigations	
1945-46	4118
1953-54	4213
1972-73	4266

A direct comparison of average yields from regularly scheduled irrigations versus average yields from year-simulation treatments lacks validity since the water regimes were entirely different. Additional understanding may be obtained from a comparison of parameter correlations from table 21, which reveals apparent differences between treatment types and correlation parameters. Crop ET, in the period from planting to

126 days, showed a highly significant correlation with yield in regularly scheduled treatments only. Correlation of ET and yield in year-simulation treatments was not significant. Amount of water applied and yield were significantly correlated for regularly scheduled treatments, but the same variable for year-simulation irrigations showed a complete lack of correlation, r = .27. When the two types of treatments are combined and analyzed together, correlations were significant. Correlation of yield and soil-water stress parameters for the two types of treatments shows basic agreement. This will be discussed later in this chapter.

Table 21 Correlation Coefficients Relating Selected Parameters and Yield for Two Types of Water Management Treatments, Brasilia, Dry Season, 1973.

	Values of r, the Correlation Coefficient		
Parameter	Reg. Scheduled	Year-Sim.	All Treatments
ET (126 days)	.94**	.54	.62*
Amt. Water Applied	.83*	.27	.76**
ET + Drainage (126 days)	.87*	.64	.69*

* Significant
**Highly Significant

Correlation differences between treatments for the parameters in table 21 may be explained by noting the range in the values of the parameters and the yields for each type of treatment. That range, shown in table 22, is always greater for regularly scheduled treatments. This aids in producing significance.

Table 22 Range in Parameter Values and Yields for Two Water Management Types, Dry Season, Brasilia, 1973.

Parameter	Reg. Scheduled		Year-Simulation	
	Min.	Max.	Min.	Max.
Yield (kg/ha)	2952	4661	3780	4469
Amt. Water Applied (mm)	456	847	582	735
ET (126 days) (mm)	333	701	383	470
ET+Drainage (126 days) (mm)	528	928	576	767

Differences were not primarily due to crop response differences induced by the two water management types, but were influenced markedly by the physical experimental conditions which were wide ranging in the case of the regularly scheduled treatments, and restricted in the case of the year-simulation treatments. No basic difference between treatment types is indicated by these results.

If the results from the two methodologies are similar, this would open the possibilities for more widespread utilization of the results. If there is a basic difference between results from regularly scheduled and from year-simulation treatments, this would lend assistance in understanding why research results are not easily extrapolated. Utilization of a technology developed for one physical environment and applied to a second is difficult on two accounts. First, there are always location specific differences which call for careful attention to and evaluation of the physical conditions. Secondly, there may be actual differences in the interaction of the environments and the technology which means that the latter cannot be extrapolated and successfully applied without basic understanding and modification. The results reported later in this chapter are an example of this second type of difficulty. To show basic agreement between "rainfed" (year-simulation) and "arid land" (regularly scheduled) treatments, understanding and modification were required to explain apparent differences between treatments in terms of the effect of water stress upon yield. Similar attention to technology - environment interactions as well as to physical condition differences must accompany more complex information transfers, as in the case of extrapolation from one environment to another.

Recovery of Corn After Severe Water Stress

Observations made on the 14-day, severely stressed treatments showed that, although recovery from visual wilting was practically immediate following an irrigation, these treatments failed to use water in a normal manner for three days after the irrigation. Crop ET and soil-water content have been graphed for five drying cycles and are presented in figure 17. For each cycle, ET decreases as drying progresses indicating that soil moisture conditions are regulating crop water use. After stress is relieved, peak ET is delayed which implies that plants are not transpiring normally even though water is available in the root zone. In comparison, ET, calculated in the identical manner, on treatments not stressed was initially high after the irrigations. These treatments showed no stress aftereffects.

To establish the time over which plants appeared normal yet did not transpire normally, figure 18 has been drawn. This is a composite of five drying cycles. The graph reveals that ET increases after an irrigation but that it takes 4 days before peak rates are attained. One may then conclude that at least some of the effects of a severe drought have continued for three days subsequent to an irrigation to relieve severe plant-water stress.

It may also be noted that crop water use from the zone 0-22.5 cm is more severely affected by previous soil-water stress than is water use from 22.5-45 cm. This implies that in the surficial part of the profile,

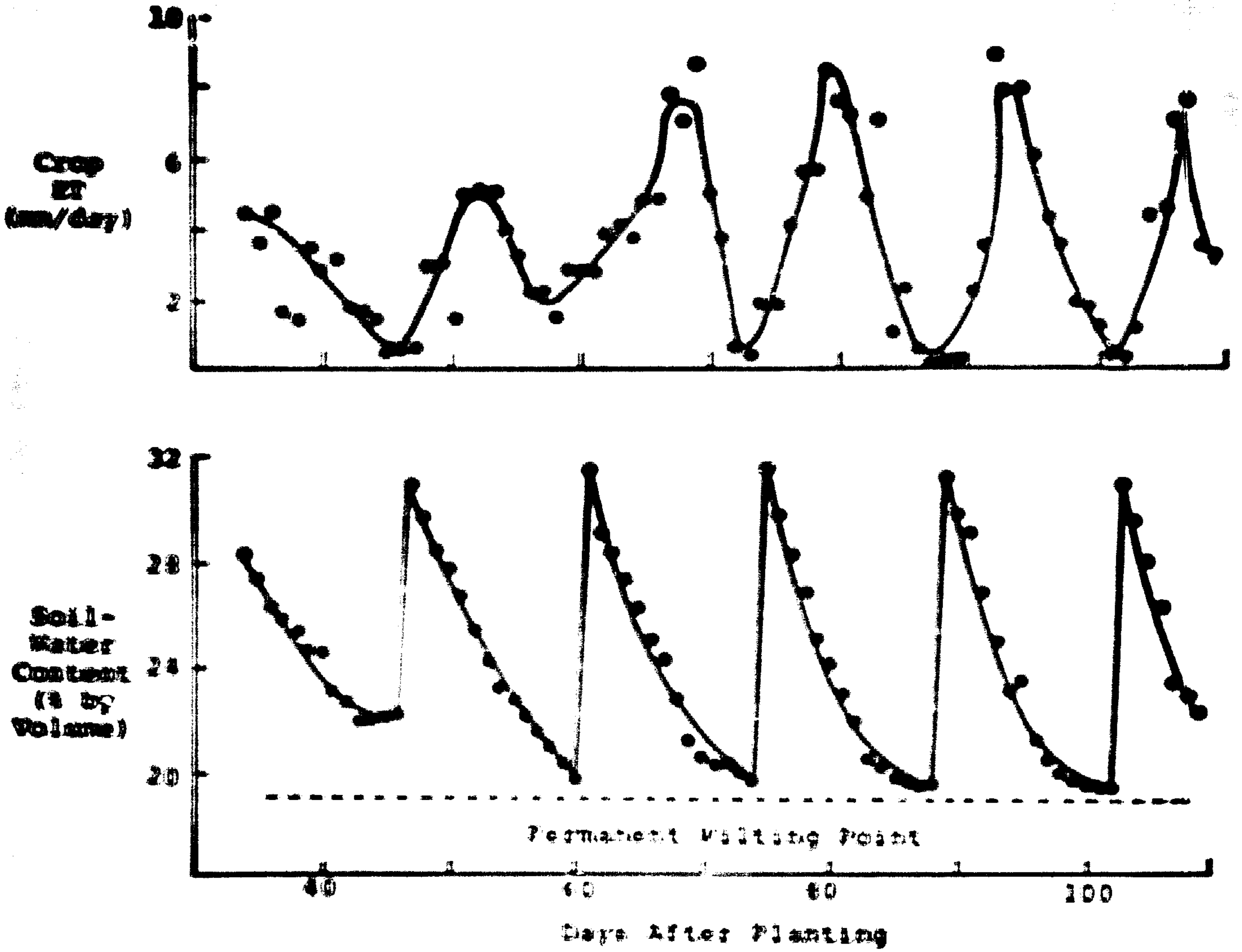

Figure 17 Crop ET and Soil-Water Content for Five Drying Cycles on 14-Day, Severely Stressed, Irrigation Treatments. Note that ET Lags Restoration of Soil-Water Content.

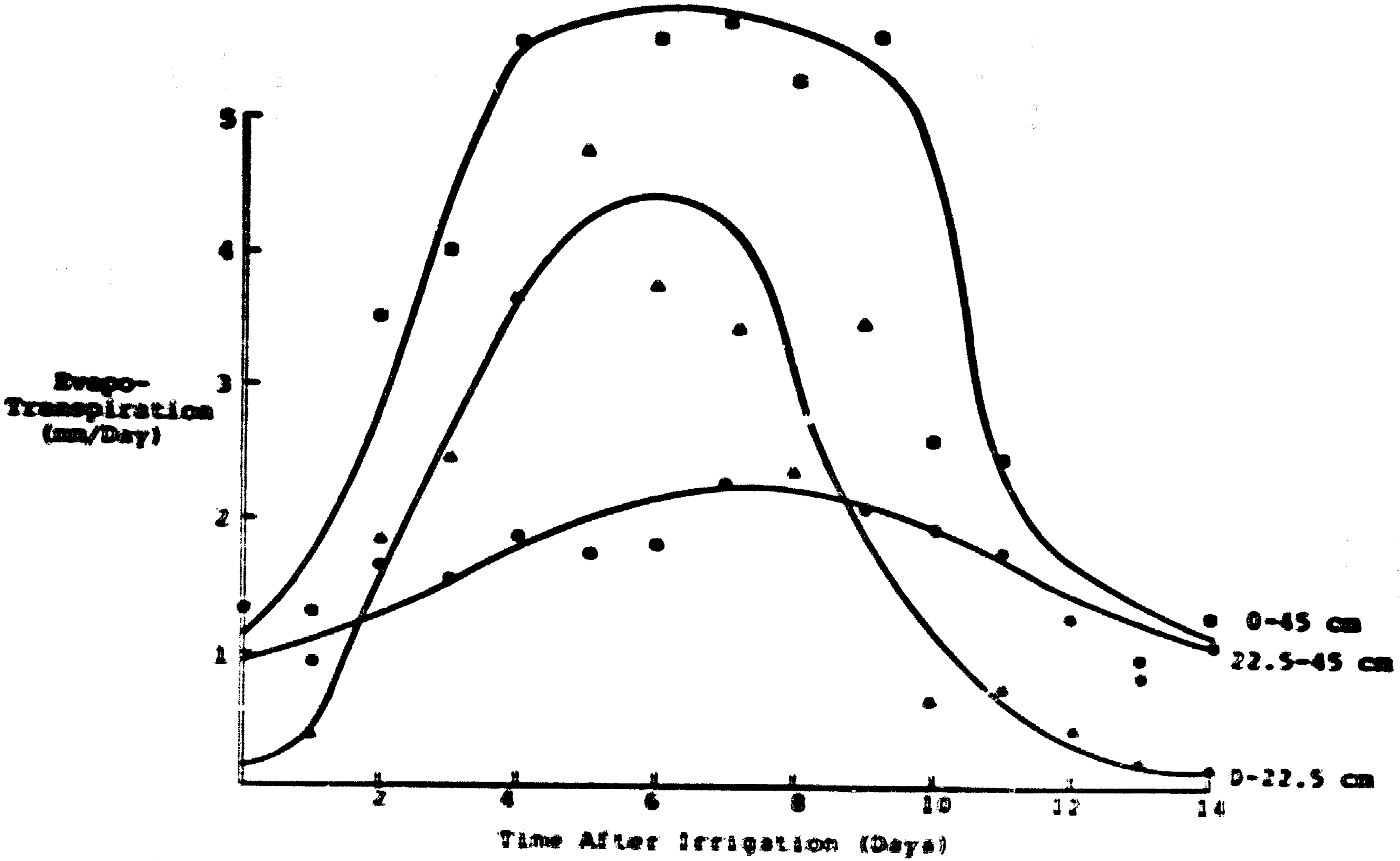

Figure 19 Evapotranspiration vs Time in Days After Irrigations To Relieve Severe Water Stress Conditions. Full ET Lagged the Irrigations by 4 Days. Curves are Composites of 5 Irrigation Cycles.

root inactivation has occurred as a result of excessive drying. The root inactivation may in part contribute to prolonging the effect of the drought once it has been relieved.

Presented in figure 19 are water extraction patterns with depth for 3-4 days subsequent to irrigations. These are composite patterns representing the days following the relief of stress for the five cycles. In going from no stress to severe stress a shift occurs in the water extraction pattern. Even though water is available throughout the root zone, severely stressed treatments are not able to use as much water from the top of the profile, again implying root inactivation in this zone. Slatyer (1967) states that death of root hairs and increased suberization of the root system accompany severe drought and may reduce rates of water absorption and nutrient uptake.

Not only is the water extraction pattern altered by a severe stress, but transpiration remained less even though water had been resupplied and presumably was completely available. In the composite 3-4 day periods after irrigation, severely stressed treatments used water at the rate of 3.9 mm/day whereas treatments not stressed used water at 5.9 mm/day. This may be explained in part since non-stressed plants were generally taller with more leaf area. Another likely explanation

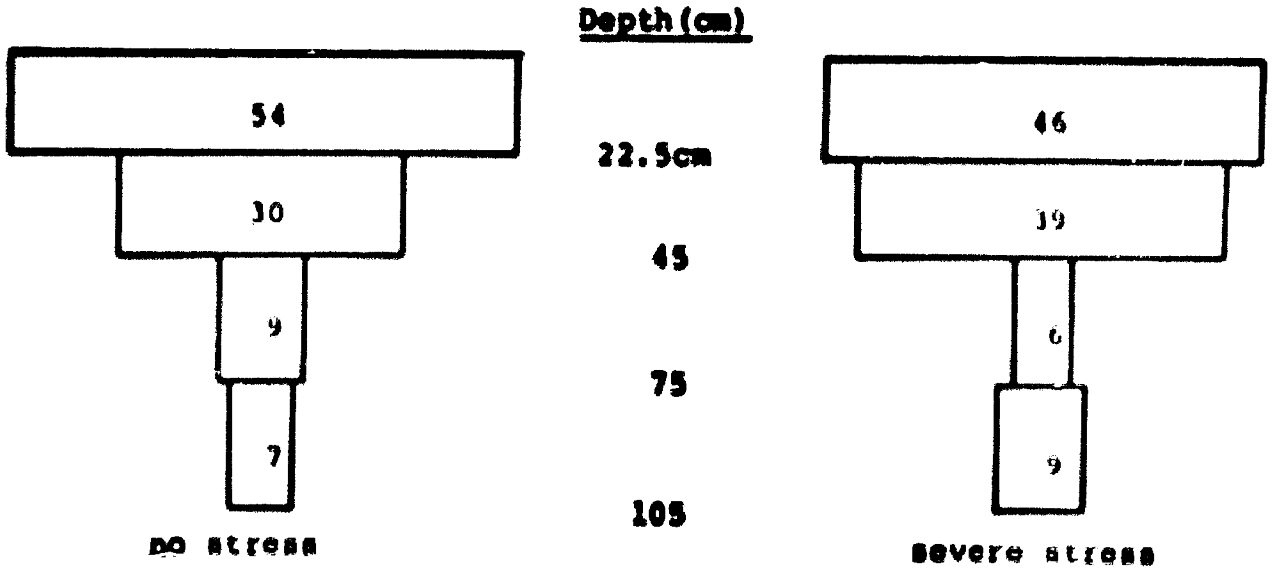

Figure 19 Percentage Water Extraction by Depth in the 3-4 Days Following an Irrigation to Relieve the Type of Water Stress Indicated.

for the decreased crop-water use subsequent to severe plant-water stress are drought induced metabolic changes which occur in plants. For example, Hsaio (1973), in a summary article, has pointed out that as a result of water stress, Abscissic Acid (ABA) accumulates in plant tissue and modulates stomatal behavior. Since ABA is not dissipated immediately upon restoration of turgidity it may continue to regulate aspects of plant metabolism. Others have shown that following relief of stress, transpiration and photosynthesis occurred at reduced rates. (See for example, Ashton (1956); Clark (1961); Kaufmann (1968); Pallas et al. (1967)).

Severe soil-water stress and decreased root activity may have also induced fertility problems which contributed to the poor yields on the 14-day treatments. These treatments showed phosphorus deficiency symptoms (purpling of leaves). With severe soil-water stress there were times that few active roots were present in the zone of high fertility. Since phosphorus, (and other nutrients such as zinc), was confined to the upper 15 cm of the profile, it was not surprising to observe the deficiency of this element in the 14-day treatments. Water induced phosphorus deficiency, may partially explain the results of Yost, in NCSU (1973), at the EEB which showed broadcast phosphorus applications to be generally superior to banded applications when water supply was limited.

These results point out the need for integration of soil-plant-water studies. As a result of root inactivation and internal metabolic changes we may expect lingering effects of soil-moisture stress even after turgidity has been restored and soil-water is in adequate supply. Determination of stress aftereffects is generally ignored and may be particularly important if repeated stresses are placed on the crop. Also, it must be noted that, taken alone, measurements of soil-water stress for a crop grown under cyclic stress conditions do not have validity for gaging the effect of stress upon yield. The implications of this observation will be covered in more detail in the next section.

Yield and Soil-Water Stress

Readings from tensiometers and gypsum blocks taken at 15- and 30-cm depths were used to develop two stress parameters, Average Daily Stress and Stress Count, which were used as indices to yield.

1. Average Daily Stress (ADS) - in units of bars per day. The calculation of ADS was made by addition of soil-water stress on days when soil-water tension was above a certain minimum value (the threshold stress). This total was divided by the number of days in the observa-

tional period, giving ADS. A similar measure of stress has been devised by Taylor (1953).

2. Stress Count (SC) - This is a count of the number of days that the crop was subjected to a minimum threshold stress.

These two parameters were determined:

1. At two depths, 15 and 30 cm.
2. Above certain minimum stress thresholds:
    a. Dry season
        .37 bars corresponding to 50% soil-water depletion;
        .50 bars corresponding to 60% soil-water depletion;
        .75 bars corresponding to 68% soil-water depletion.
    b. Wet season
        For .2, .35, .5, .65, and .8 bars.
3. For crop periods, each of 63 days. Dale and Shaw (1965) have identified a critical water period for corn of 9 weeks, 6 weeks prior to silking to 3 weeks thereafter.

a. Dry season	b. Wet season
49-112 days	45-108 days
63-126 "	52-115 "
74-137 "	59-122 "
	66-129 "

These stress parameters, 36 in the dry season and 80 in the wet season, were correlated with yield. For regularly scheduled irrigations in the dry season, initial attempts at correlations were poor because SC and ADS parameters for 14-day treatments were less than for 7-day treatments. This observation was a direct result of the stress aftereffects described in the previous section. It was concluded that the aftereffects of a severe stress cannot be measured by soil moisture sensors for although the sensors indicate an adequate soil moisture supply, the plants still acted as though water was somehow deficient. This conclusion called for a modification of the soil-water stress concept as an index to yield. For the 14-day treatments, the stress count parameters were increased by 3 days for each irrigation cycle. This parameter modification reflects plant behavior on those days following termination of soil-water stress when the plant system was not functioning normally. Stress parameters for 7-day irrigation treatments were not modified since those treatments rebounded from drying cycles with rapid rates of ET. Severely stressed year-simulation treatments appeared to rebound from the stress in 1-2 days. Since the stresses were not repeated (except for 1945-46) no modification was made in the SC parameter for year-simulation treatments.

These modifications were specific to the treatments in the experiment. It would be valuable if future research could for example establish the relationship between per cent root inactivation and soil-water stress, and per cent recovery from stress aftereffects and time.

Correlation coefficients for the dry season variables are presented in table 23. The following conclusions are appropriate:

1. Yield is strongly and negatively related to soil-water stress. Correlations as high as -.98 were attained, many with significance at the .01 level.
2. The SC type of stress measure is a better index to yield than is the ADS. It is also easier to compute and modify.
3. The SC measurement at 15 cm is a better index to yield for regularly scheduled irrigations; the SC measurement at 30 cm is a better index to yield for year-simulation irrigations. This may be explained because regularly scheduled irrigations exhibited a wide range in stress measurements at 15 cm, (3-day treatments were always wet and 14-day treatments generally dry), whereas for year-simulation treatments, the range in SC at the 15 cm depth was narrow. The fact that SC at 15 cm was not significantly correlated with yield is an indication of the

Table 23 Correlation Coefficients Relating Yield and Selected Dry Season Stress Parameters for Two Types of Irrigation Treatments.

Regularly Scheduled Treatments		Year-Simulation Treatments		All Treatments	
Parameter	r	Parameter	r	Parameter	r
SC(.75,74-137,15)**	-.95	SC(.37,63-126,30)**	-.98	SC(.75,74-137,15)**	-.83
SC(.50,74-137,15)**	-.94	SC(.37,49-113,30)**	-.97	SC(.50,74-137,15)**	-.81
SC(.50,63-126,15)**	-.93	SC(.37,74-137,30)**	-.96	SC(.75,49-113,15)**	-.78
SC(.75,63-126,15)**	-.92	SC(.50,49-113,30)*	-.89	SC(.50,49-113,15)**	-.77
SC(.37,74-137,15)*	-.92	SC(.50,63-126,30)*	-.89	SC(.50,74-137,30)**	-.77
SC(.50,63-126,30)*	-.91	SC(.75,74-137,30)*	-.87	SC(.37,74-137,15)**	-.77
SC(.37,74-137,30)*	-.91	SC(.50,74-137,30)*	-.84	SC(.37,74-137,30)**	-.76
SC(.37,63-126,15)*	-.90	ADS(.50,74-137,15)	-.66	SC(.74,74-137,30)**	-.76
SC(.50,49-113,15)*	-.90			SC(.50,49-113,30)**	-.73

* Significant .05

**Highly Significant .01

ADS = Average Daily Stress

SC = Stress Count

(Threshold stress (bars), period of stress measurement (days), depth of stress measurement (cm)) uniformity of water extraction and stress build up in the uppermost part of the root zone for all year-simulation treatments. Consequently, only the SC at the 30 cm depth revealed differences between simulation treatments.

4. On the basis of the correlation analysis, no clear cut picture was obtained as to which threshold or time period was the most appropriate as an index to yield.

For the dry season, regression equations of the linear form,

$$Y = K + C * \text{Parameter},$$

have been developed and are presented in table 24. The constant, K, may be taken as the top yield in the absence of water stress. The constant, C, is the slope of the yield-water-stress relationship, using stress count as the measure of water stress. Table 25 presents average values of C by threshold, period and depth for each type of treatment. Regressions presented assume a straight line relationship between yield and stress count and are most appropriate for the range in stress count over which the equations were developed. For an increased number of stress count one may expect the relationship to become more steeply sloping as droughts extend to longer durations.

The following conclusions may be drawn from tables 24 and 25:

1. Under the established fertility constraints, (notably limited phosphorus), top yields in the absence of water stress would be in the range 4.5 - 5.0 ton/ha, with an average of about 4.7 ton/ha.
2. The impact of SC upon yield above thresholds of .37 and .50 bars is nearly the same. However, as threshold is increased from .50 to .75 bars, the effect upon yield becomes more pronounced. The difference between .50 and .75 bars implies that .50 bars, or 60% soil-water depletion, may be considered a critical level above which yields become increasingly reduced as a result of water stress. The fact that yields are depressed even at these low tensions is not surprising in view of the water release characteristics of this soil. Similar yield response differences to low levels of moisture tension have been obtained on corn grown on a sandy soil (Rhoads and Stanley, 1973).
3. It would appear that stress in the latest peri-

Table 24 Coefficients for Selected Regression Equations of the Form $Y = K + C * \text{Parameter}$, Relating Yield and the Stress Parameter Indicated.

Parameter	K	C	R^2
For Regularly Scheduled Irrigation Treatments:			
SC(.75,74-137,15)**	4505	-41.7	.89
SC(.50,74-137,15)**	4604	-36.8	.88
SC(.50,63-126,15)**	4628	-30.0	.87
SC(.75,63-126,15)**	4511	-33.1	.85
SC(.37,74-137,15)*	4687	-36.4	.84
SC(.50,74-137,30)*	4463	-38.5	.82
SC(.37,74-137,30)*	4503	-37.3	.82
SC(.37,63-126,30)*	4529	-29.5	.75
For Year-Simulation Irrigation Treatments:			
SC(.37,63-126,30)**	5849	-53.2	.98
SC(.37,49-113,30)**	5859	-53.5	.94
SC(.37,74-137,30)**	5335	-53.3	.92
SC(.50,49-113,30)*	5673	-54.9	.80
SC(.50,74-137,30)*	5100	-47.8	.70
SC(.75,49-113,30)	5506	-58.1	.66
For All Treatments:			
SC(.75,74-137,15)**	4702	-42.5	.69
SC(.50,74-137,15)**	4796	-37.0	.66
SC(.75,49-113,15)**	4678	-26.4	.61
SC(.50,49-113,15)**	4737	-23.8	.60
SC(.50,74-137,30)**	4682	-37.9	.59
SC(.37,74-137,15)**	4868	-35.5	.59
SC(.37,74-137,30)**	4727	-36.2	.58
SC(.75,74-137,30)**	4614	-40.2	.57

**Highly Significant at 1%; *Significant at 5%

Table 25 Average Values of C, for Threshold, Period and Depth for Two Irrigation Types. Values of C were Taken from the Relationship Yield = K * C * Parameter, the Linear Regression of Yield with Selected Stress Parameters. Dry Season, Brasilia, 1973.

	Regularly Scheduled Treatments[1]	Year-Simulation Treatments[2]	All Treatments[3]
Threshold (Bars)			
.37	31.6	53.3	30.0
.50	30.7	52.5	30.3
.75	33.6	59.3	33.3
Period (days) after planting)			
49-113	24.8	55.5	25.2
63-126	30.9	55.4	27.5
74-137	38.5	54.3	38.2
Depth (cm)			
15	32.4	*	31.8
30	31.5	55.1	30.8

[1] Average of 14 Stress Count Parameters with R^2 Values from .42 to .69.

[2] Average of 9 Stress Count Parameters with R^2 Values from .66 to .98.

[3] Average of 14 Stress Count Parameters with R^2 Values from .66 to .89.

* R^2 Values Low and Not Significant.

od, 74-137 days, from 2-3 weeks before full tasseling to 6-7 weeks thereafter, was the most critical. This tendency is not apparent on the year-simulation treatments because water stress was imposed on those treatments generally between 60 and 90 days after planting. For the regularly scheduled treatments, stress periods extended up to day 109. For the variety of corn used in these experiments, the effect of an early stress may affect maturity date more than yield.

4. There is little apparent difference in effect upon yield as measured by SC at the 15- vs the 30-cm depth. This cannot be explained. In the field, a stress at 30 cm would mean an even greater soil-water stress at 15 cm. Therefore one should expect that a given stress at 30 cm would be more detrimental than the same stress at 15 cm.

5. A day of stress for regularly scheduled treatments resulted in a yield loss of approximately 32 kg/ha for each day that the threshold stress was exceeded; for year-simulation treatments, the figure was 55 kg/ha. Thus, the impact of a stress is 72% greater for year-simulation than for regularly scheduled treat-

ments. In view of conclusion 4, above, this does not appear to be a depth effect. (All of the C values for year-simulation treatments were determined at 30 cm, whereas C values for regularly scheduled treatments were from both 15- and 30-cm depths.) Instead, the field evidence would indicate that the detrimental effect of a stress upon yield will be greater when the stress has not been repetitively imposed. It may be further hypothesized that several stress cycles lead to a type of hardening, which in some way prepares the crop for at least some yield in the face of subsequent droughts. Conversely, this suggests that a single strong veranico in the wet season may have a detrimental effect upon yield out of proportion to the results suggested by the cyclic stress patterns from regularly scheduled treatments. Support for this field evidence may be found in the literature. McCree (1974), working on sorghum grown under controlled conditions, has reported differences in stomatal resistance due to conditioning with repeated stress cycles. His results show that when stress is imposed on plants having no history of stress, stomates will close at lower leaf water potentials than will stomates in plants conditioned to repeated stress cycles. This evidence is in the right direction to explain why year-simulation treatments (or rainfed treatments) may be more sensitive to a stress than regularly scheduled treatments.

6. For both types of irrigations, nearly 70% of the yield variation may be explained by simply counting the number of days in which soil-water stress at 15 cm exceeded .75 bars, or 68% soil-water depletion, for the period 74-137 days after planting.

The analyses of the yield-water-stress relationships for the wet season experiments were not as definitive as for the dry season. It was an unusually wet rainy season. Large soil-water deficits did not materialize, nor were differences in yields due to water treatments as wide ranging as would have been desired. The degree of linear correlation between yield and the stress parameters was a reflection of the narrow range in yields. The best correlations occurred when there was ample variation in yield; when the range in yield was limited, correlations were the poorest. This is illustrated in figure 20, where the absolute value of

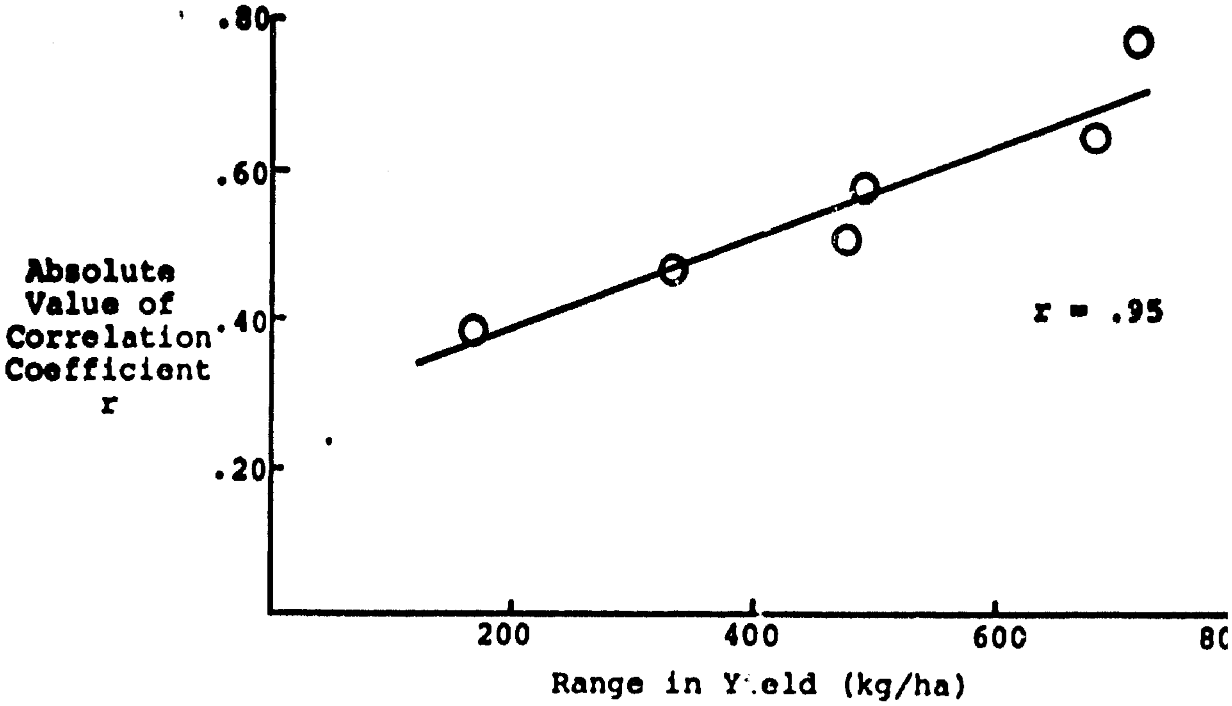

Figure 20 Relation of Correlation Coefficient r, and Range in Co
Yield for Wet Season Experiments. Greater Spread in
Yield Resulted in Improved Correlation Statistics.

r, the correlation statistic, has been graphed on the ordinate and the range in yield has been plotted on the abcissa. This has been done for each of the three experiments and for deep and shallow incorporations, ie. for 6 pairs of values. The result is an excellent correlation between the two parameters, with r = .95.

Unfortunately, data cannot be combined and analyzed across all three experiments or across incorporation types for a single experiment. In the former case, yields vary greatly between experiments as a result of factors other than stress (ie., disease). In the latter case, shallow and deep treatments create markedly different rooting patterns which as a consequence have different patterns of stress build up and which together, nullify correlations. For example, shallow treatments have relatively few roots at 30 cm and therefore stress at this depth generally remains low for these treatments and is not well correlated with yield. Only stress at 15 cm on shallow treatments provides a good correlation with yield. Stress at 30 cm on deep treatments was well correlated with yield whereas stress at 15 cm was not well correlated. Therefore, when deep and shallow treatments are combined for yield-stress relationships, correlations are very low.

In spite of these difficulties, the following conclusions may be drawn with respect to the yield-water-stress relationship in the wet season:

1. The stress count parameters generally gave better correlations with yield than did ADS.
2. Yields were negatively correlated with soil-water stress.
3. For Experiments I, II, and III, the best correlation coefficients (r values) between yield and the stress count parameters were -.64, -.57, and -.77, respectively.
4. Quadratic regression models for yield and the stress parameters gave best R^2 values of .48, .31 and .61 for Experiments I - III, respectively. These are little improvement over the linear case.
5. Different patterns of rooting have precluded the use of a single stress depth for both deep and shallow incorporations. Moreover, no single stress parameter (for threshold, time and depth) could be singled out as having universal application under the two patterns of rooting and the uncontrolled timing of water-short periods.

6. Wet season correlation statistics are lower than similar dry season values.
7. Up to 59% of yield variability may be accounted for by using water stress parameters alone during the wet season. If stress parameters are combined with other crop or soil measurements into a 2-variable model, the explicative power of the equations increase greatly. For example, 86% of the yield variability in deep treatments in Experiment I may be explained using a linear combination of stress and plant height.

Yield - Water Response Functions

In the dry season, production increases of 1.2 ton/ha can be attributed to increased water adequacy as measured by shortened irrigation intervals. For regularly scheduled irrigation treatments, the yield - water response function is presented in figure 21. Yields decreased by 38% as the irrigation interval was increased from 3 to 7 to 14 days. The correlation between yield and irrigation interval was significant at the .02 level. For these treatments, yield was also significantly correlated with water parameters such as amount of water applied ($r = .83$), length of longest dry spell ($r = .89$), and various measures of soil-water stress.

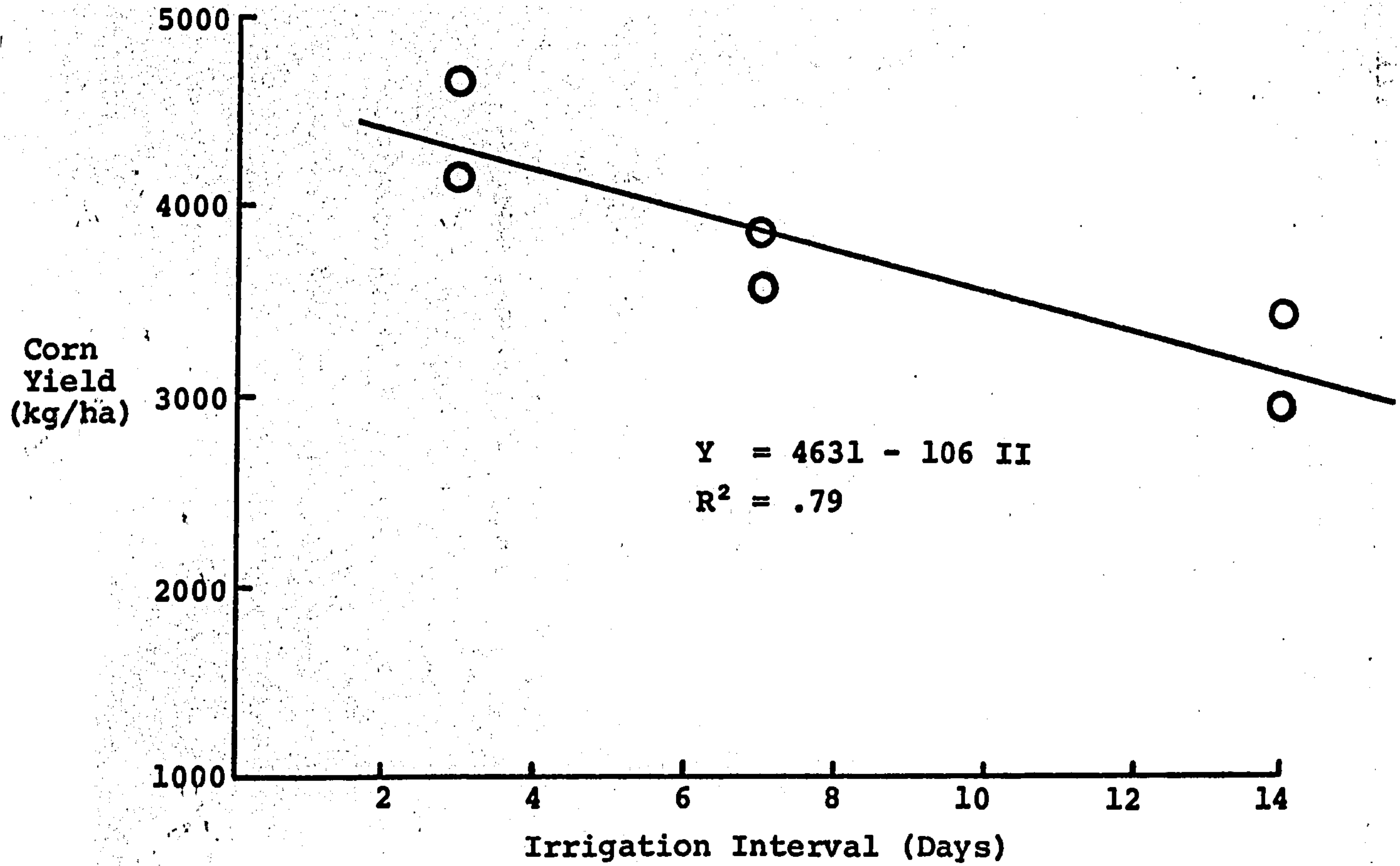

Figure 21 Yield of Shelled Corn (at 15.5% Moisture) versus Length of Irrigation Interval for Regularly Scheduled Irrigation Treatments. Dry Season, Brasilia, 1973.

In spite of varied patterns of irrigations to simulate rainfalls, yields were relatively constant for all year-simulation treatments. Statistical measures of yield - water response functions were not significant when these treatments were analyzed alone. Therefore, these treatments have been combined with the regularly scheduled treatments to provide data for the yield - water response function presented in figure 22. That figure relates yield from all dry season plots to mm of water applied in the treatments, ie. before the rains began. A quadratic response function has been assumed. This implies: (1) yields decrease greatly when water applications are less than 450 mm; (2) under the established fertility constraints, no gain in yield may be expected for water applications in excess of 840 mm. The quadratic equation has an R^2 of .64 and the parameter is statistically significant. For the range 450-850 mm of water applied, a linear correlation was also statistically significant with an R^2 of .58. Other water parameters having significant correlations with yield included ET ($r = .62$) and various water stress parameters.

Although yield was well correlated with various measures of water adequacy the factors listed below combined to limit full expression of the water variable.

1. Hard rains in late September brought an early

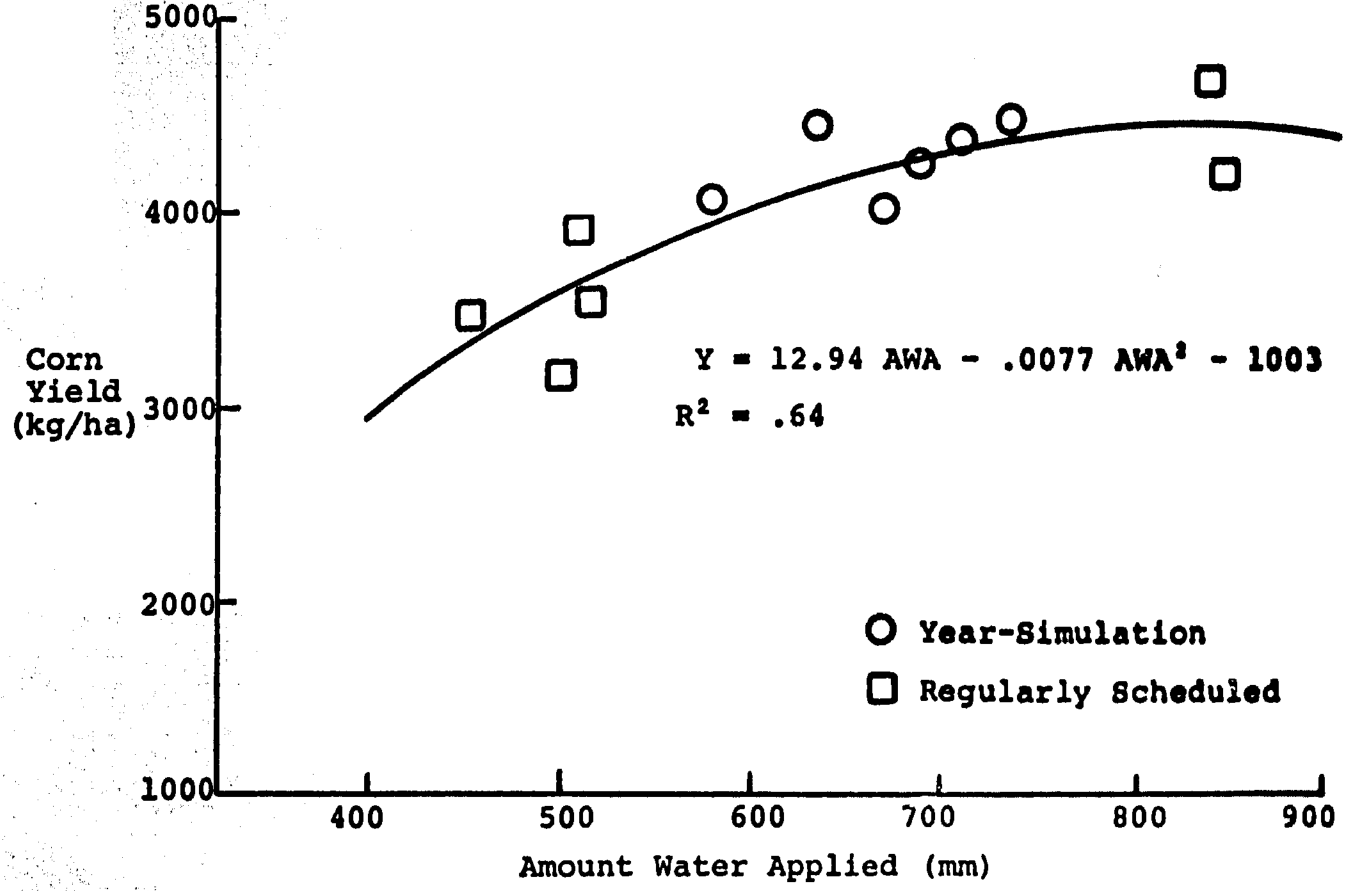

Figure 22 Yield of Shelled Corn (at 15.5% Moisture) versus Amount of Water Applied before Onset of Rainy Season (Day 109). Dry Season, Brasilia, 1973.

cessation to the dry season. Water conditions beyond day 109 were identical for all treatments.

2. The corn variety, Cargill 111, a local hybrid, is one of the best producers under Cerrado conditions. Its good performance over the years is probably due to resistance to veranicos. The variety takes long to mature and has an unusually long period of tasseling and silking, the timing of which were affected by the water treatments. This is a form of plant adaptation which would permit this variety to take advantage of later more favorable water conditions. A variety of shorter duration, more specific in its reproductive stages would have had less ability to adjust to adverse water conditions.
3. Fertilizer phosphorus levels were inadequate.
4. Visual nitrogen deficiency symptons were evident in the 3-day treatment. Although water was adequate in that treatment, the frequent irrigations apparently leached nitrate from the root zone.
5. Liming was not adequate for complete neutralization of the aluminum. This may have placed a limitation on root development and on water

and nutrient uptake.

6. Insufficient magnesium was supplied. This may have reduced early growth but it is not likely to have caused significant yield differences.
7. Potassium may have been deficient. This will be discussed in more detail in Chapter VII.

Given in figure 23 are the yield - water response functions for the three wet season experiments. The dependent variable, yield, has been plotted against the independent variable "longest dry spell", which was the basis on which wet season irrigation treatments were triggered. As described in Chapter IV, irrigation treatments served to restrict dry periods to no more than the longest dry spell. However, rainfalls resupplied soil moisture at intervals less than the longest dry spell. Thus, this parameter differs from irrigation interval in that the latter implies a fixed interval between irrigations.

The following conclusions may be drawn from the three graphs in figure 23.

1. Deep treatments were superior to shallow treatments. Since response to deep and shallow treatments was generally parallel over the full range in water treatments in Experiments I and II, one may conclude that there was no interaction between water treatments and lime-

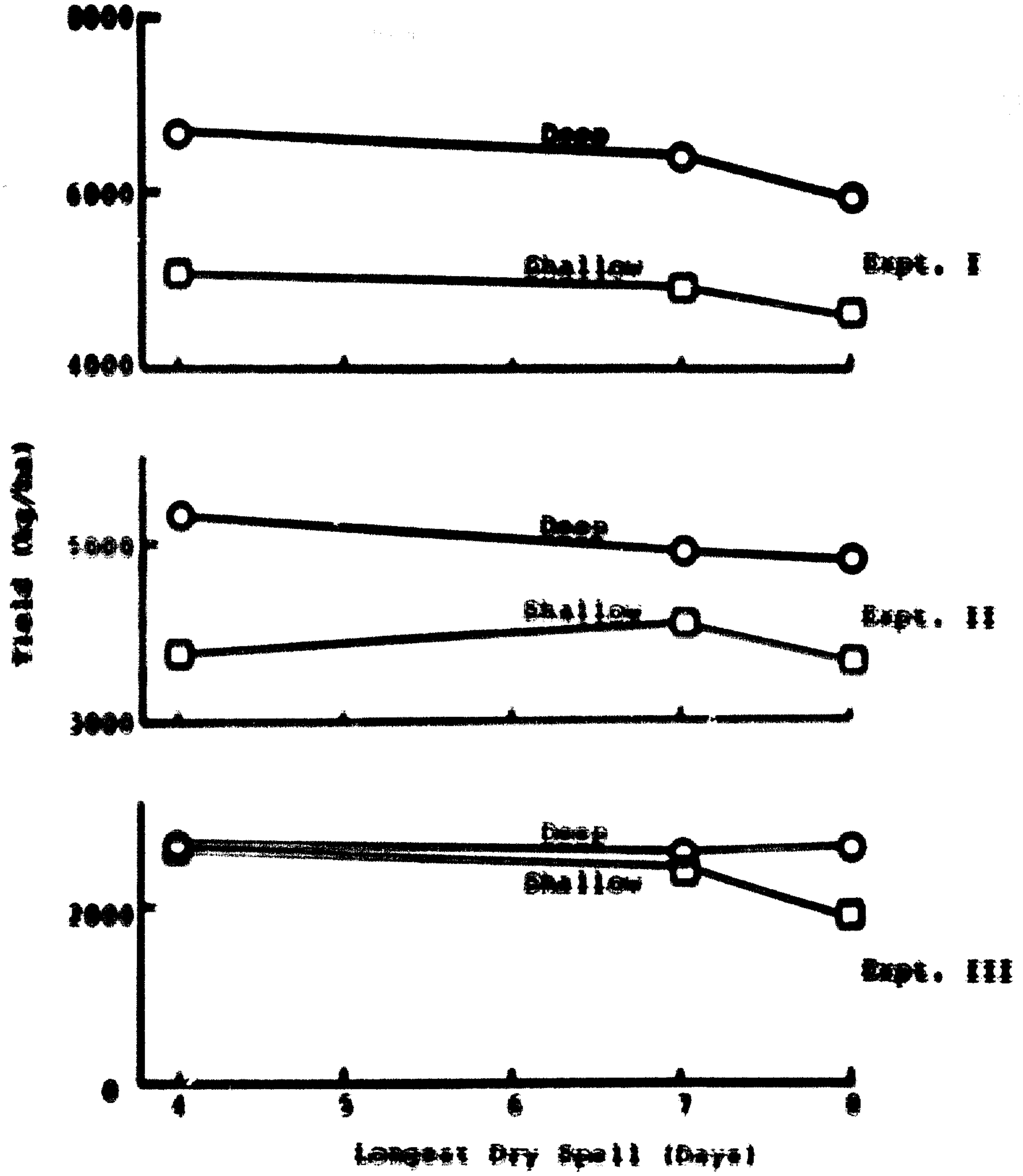

Figure 23 Yield of Shelled Corn (at 15.5% moisture) as a Function of the Longest Dry Spell for 3 Experiments During the Wet Season 1973-74.

stone incorporation treatments. These results are discussed in detail in Chapter VII.

2. Although design variables in Experiments I, II and III were identical, yields decreased greatly in going from Experiment I to II to III. This will be discussed in Chapter VI.
3. The loss in yield in going from 7 to 8 days without rain in Experiment I was approximately 1/2 ton/ha or 10%. This is a result of a single irrigation. Additional irrigations resulted in only modest yield gains. This implies that during wet season veranicos, water should be resupplied through irrigations perhaps every 7 days. This would depend upon actual weather, soil and crop conditions during the veranico.

Results from all three experiments have been pooled to provide data for the generalized response function of figure 24. The dependent variable, relative yield, is the actual yield for a particular water treatment divided by the best yield for that experiment and incorporation type. A quadratic response surface has been fitted to the data. The R^2 is .33. Results are not significant because the well distributed rains restricted the longest dry spell in each experiment, (for the non-irrigated or control treatments), to but 8 days. The response

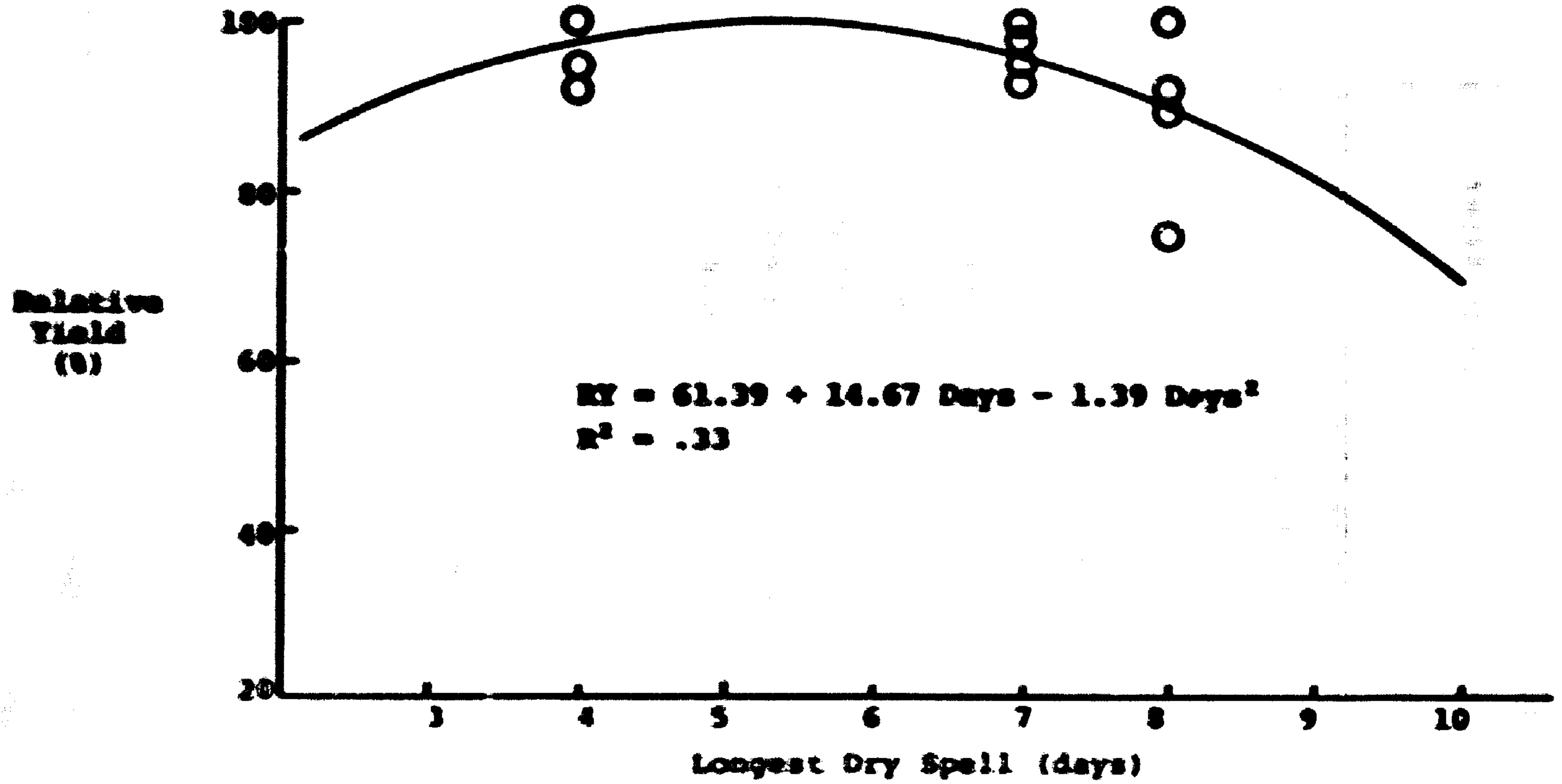

Figure 24 Relative Yield of Shelled Corn Versus Longest Dry Spell for Data Pooled from Three 1973-74 Wet Season Water Experiments.

surface predicts that maximum yields occur at 5 days. Relative yields decline from 100% at 5 days to 96%, 90% and 69% of the maximum at 7, 8 and 10 days, respectively. Over this narrow dry-spell range, this response surface would appear to provide a reasonable estimate of yield reductions caused by veranicos.

Summary and Conclusions

1. Basic soil-water-plant relationships were similarly operative for simulated "rainfed" and "arid irrigation" water management regimes.
2. Although recovery from visual wilting was practically immediate following an irrigation, treatments undergoing severe moisture stress failed to use water in a normal manner for three days after the irrigation. Evapotranspiration rates for those treatments were only 66% of treatments not stressed prior to the irrigation. Water extraction patterns with depth indicated root inactivation in the top part of the root zone.
3. Yield was well correlated with soil-water stress in the dry season, less so in the wet season. Correlations were as high as -.98 in the dry season and -.77 in the wet season.

4. For the fertility constraints of the dry season experiment, top yields in the absence of water stress were estimated at 4.7 ton/ha.
5. One-half bar, or 60% soil-water depletion, may be considered a critical level above which yields are increasingly reduced.
6. A day of soil-water stress will result in yield decreases of 32-55 kg/ha/day for the range in water stress in the dry season experiment.
7. The impact of a stress was greater for year-simulation than for regularly scheduled treatments. This suggests that an internal mechanism exists, analogous to hardening, for preparing a crop for repeated drought periods.
8. Dry season yields were well correlated with irrigation interval and amount of water applied.
9. Wet season yields were only weakly affected by veranicos of up to 8 days.

CHAPTER VI

CROP WATER USE, WATER REQUIREMENTS, AND THE POTENTIAL FOR DRY SEASON PRODUCTION

Introduction

Utilization of agronomic data requires base level measurements of climatic and soil conditions under which the crop was grown. These were presented in detail in Chapters II and III. How a crop responds to the climatic variables has value in making results more generally applicable. For agriculture in the developmental stages, these data have value in planning for future development.

In this chapter, functional relationships will be presented to relate evapotranspiration to the various climatic parameters measured during the growing season. Data will be presented on crop water use, and an estimate will be made of the water requirements for dry season irrigated cropping. Lastly, the potential for cropping in the dry versus the wet season will be discussed.

Results

Crop Evapotranspiration and Climatic Factors

For the dry season, field instrumentation was adequate to determine changes in soil-water storage. Using equations presented in Chapter III, changes in storage were separated into crop ET and internal drainage (deep percolation). Because of the onset of the rainy season it was impossible to accurately calculate ET using tensiometers and blocks after day 109.

To establish functional relationships between ET and the meteorological parameters, dry season treatments were divided into two groups:

1. Well watered treatments - Regularly scheduled irrigation treatments with an irrigation interval of 3 days, and treatments from a phosphorus experiment where the irrigation interval was approximately 5 days and where soil-water tensions at 15 cm never exceeded 1/2 bar;
2. Poorly watered treatments - Regularly scheduled irrigation treatments with irrigation intervals of 7 or 14 days.

For the poorly watered treatments, soil-water conditions rather than climatic ones exercised the dominant effect upon ET. For these treatments, the correlations of ET with climatic factors were low and not significant. Consequently, the following discussion will focus on ET from well watered treatments only.

For the period 36-108 days after planting, daily values of ET were correlated with daily values of pan evaporation, solar radiation, maximum temperature, minimum temperature, accumulated wind and average relative humidity. Highly significant correlations were obtained for ET and the following parameters: Maximum temperature ($r = .69$), pan evaporation ($r = .67$), relative humidity ($r = -.50$), minimum temperature ($r = .48$) and solar radiation ($r = .47$). Correlation with wind was lacking. Regression models were run for ET and these climatic factors. For a well watered, dry season corn crop in the Brasilia area, the two variable model, Crop ET = .505 max. temp.** + .642 Pan Evap.** - 13.3, can be used to predict ET.[1] The model has an R^2 coefficient of .58 and a coefficient of variation of 29%. The addition of other variables did not markedly improve the fit.

During the period from 36-69 days after planting, plant height and crop cover increased greatly. Marked increases occurred in ET. Progressive increases also occurred in maximum temperature, pan evaporation and solar radiation, while decreases occurred in relative humidity. These parallel changes, in ET and in the weather, may possibly void the general application of the relationship for ET presented above. Therefore, analyses were performed for the period 70-108 days after planting, during which the only climatic factor showing

[1] ** = Highly significant correlation at 0.01 level.

an increase with time was maximum temperature. It is during this period that ET was near the maximum. Parameters with highly significant correlations with ET were pan evaporation ($r = .72$), solar radiation ($r = .68$), relative humidity ($r = -.65$) and maximum temperature ($r = .48$); minimum temperature and wind were not significant.[1] Crop ET may be determined from pan evaporation and solar radiation using:

$$\text{Crop ET} = .527\ \text{Pan Evap}^{**} + .00628\ \text{Solar}^{**} + .435.$$

This equation has an R^2 of .57 and a coefficient of variation of 18%. Since solar radiation data normally would not be available, the one variable model,

$$\text{Crop ET} = .77\ \text{Pan Evap}^{**} + 1.45,$$

has usefulness. This equation has an R^2 of .52 and a coefficient of variation of 18.8%. Data from a class A pan may be used with this equation to predict crop ET for a well watered crop in the period 70-108 days, (late vegetative to reproductive stage). For this period, the best fit equation without the intercept term was:

$$\text{Crop ET} = .96\ \text{Pan Evap}.$$

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[1] Correlation coefficients are equal to or better than those reported by Drinkwater and Janes (1957) who correlated measured potential evapotranspiration of Kentucky Bluegrass with climatic factors. In that study, 7-day correlations gave the following results: pan evaporation - $r = .68$; solar radiation - $r = .43$; average temperature - $r = .40$; insolation - $r = .60$.

Coefficients in the two equations above are similar to values reported by Tanner, (1967).

Statistical coefficients, r and R^2, for the equations presented in this section may be considered good from three standpoints:

1. These coefficients are for equations which relate ET and the climatic factors directly without use of formulas such as Penman's or Thornthwaite's. Use of climatic data with Penman's equation to estimate evapotranspiration would have improved the statistics.
2. The calculation of ET was made indirectly and was based upon changes in soil-water storage on inference from tensiometers and blocks.
3. Correlations were presented only for daily data. When data were grouped into 4, 7, 10 or 14 day intervals, correlation coefficients improved. However, level of significance declined because of fewer data points.

Crop Evapotranspiration Requirements

The ratio of crop ET to pan evaporation for the dry season crop period of 36-108 days is presented in figure 25. These data are for 10-day averages of pan evaporation and crop ET from well watered treatments. Since the ordinate is dimensionless, the graph reflects changes

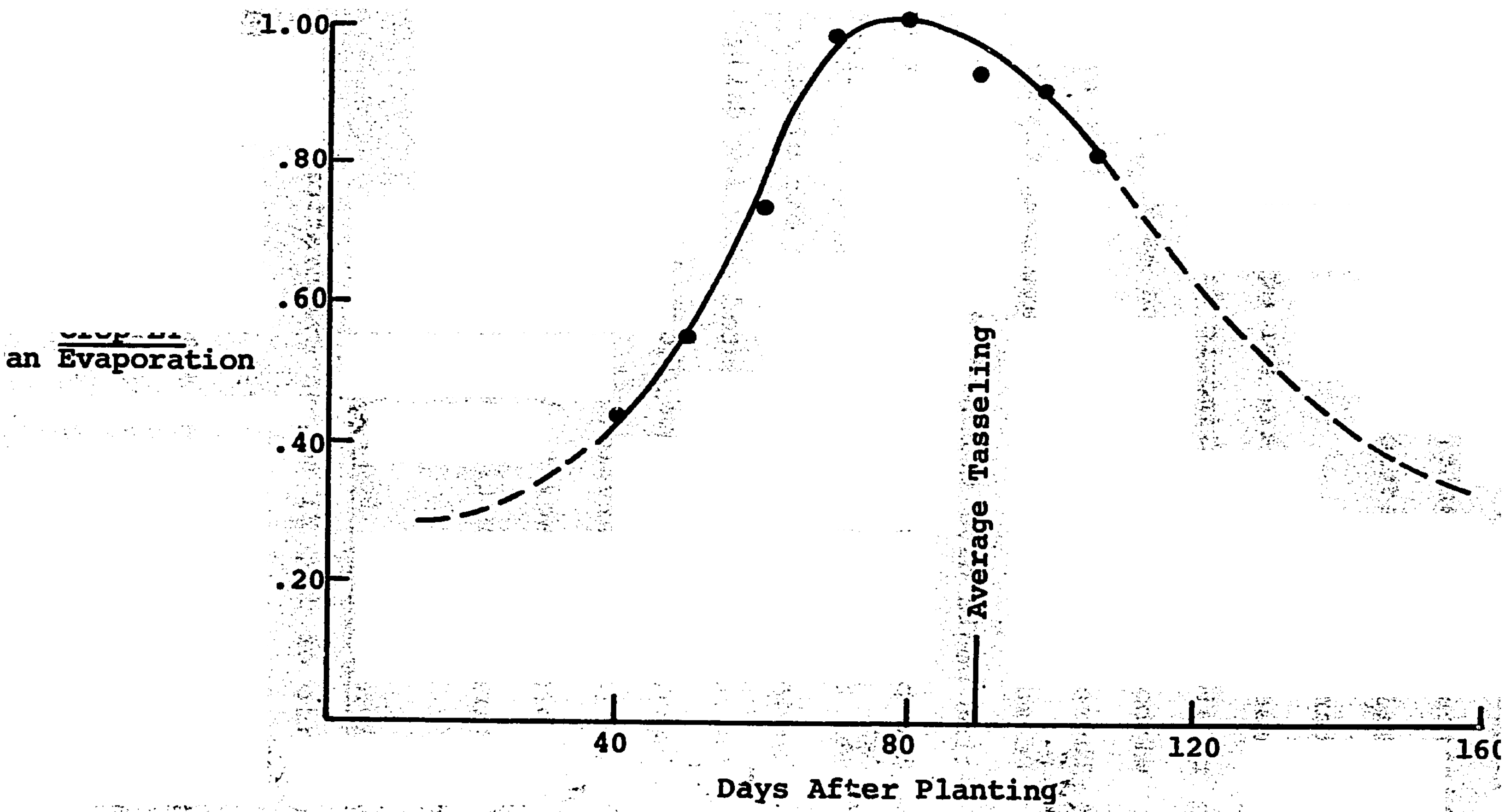

Figure 25 The Dimensionless Ratio of Crop ET to Pan Evaporation for Corn for Well Watered Dry Season Treatments.

in crop ET as influenced by crop stage, but not weather. Peak daily ET, approximating evaporation from a class A pan (7.5 mm/day) occurred during the crop period 65-100 days. This coincides with a 35-day period of rapid vegetative and reproductive growth from three weeks before tasseling to two weeks thereafter. After day 109, the ratio ET to pan evaporation was thought to diminish rapidly as the plants entered the grain filling stage and later senesced. This is indicated by the dashed line. Since ET before 60 days is less than 75% of pan evaporation, the figure suggests that droughts which come early in the crop's development may not be as detrimental as drought after this period.[1] For a wet season crop, this implies that a drought in October or November may not be of great consequence.

Total evapotranspiration was significantly correlated with yield (r = .62). For a well watered, 150-day corn crop, ET was estimated at 550 mm. Poorly watered treatments used an estimated 470 mm over the

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[1] The extent of root proliferation in a young crop is naturally limited. Because of this, a young crop may be thought to be highly susceptible to drought. However, since the plant is still young it may have roots which continue to grow toward the water. Also, the high capillary conductivity of the LVE soil may permit ample flow of water to the limited root system. In general, a young crop needs less water and is better able to rebound from drought than is an older crop.

150 day period.[1]

Seasonal Cropping Comparison

The wet season has been the time of traditional, though limited, cropping in the area, because of the lack of precipitation in the dry season. But other climatic factors also influence the suitability of each season for agricultural purposes. Data for some of these are presented in table 26 which gives data for a 5-month wet and 5-month day season. Notable is, of

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[1] A requirement for 470-550 mm of water is not the design field water requirement but rather the amount required for evaporation and transpiration. For irrigation runs of 8 meters on this soil, average deep percolation losses were approximately 60% of ET. Therefore, greater losses could be expected on longer runs. During the dry season, a certain proportion of ET would be supplied by rains in September and October, which average 180 mm. The dry season field water requirement, supplied through irrigations, was estimated as follows:

ET	510 mm
Deep Percolation	300
Rains	- 180
Dry Season Field Water Requirement	630 mm

The requirement for 630 mm of water is for a rather efficient gravity system which is unlikely to be duplicated in most gravity systems. Further, this estimate does not include other types of system losses, eg. conveyance and application losses which also may be considerable. A sprinkler type irrigation system would be an alternative for keeping losses to a minimum. Proper management of that system would be accomplished by frequent wettings of the shallow root zone, minimizing losses due to deep percolation. Farmers in the nearby Alexandre Gusmão project currently follow practices along these lines.

Table 26 Climatic Data for a Comparison of Wet and Dry Cropping Seasons.

	Wet Season November-March	Dry Season June-October
Precipitation(mm)[1]	1262	196
Min. Temp.(°C)[2]	18.0	14.7
Max. Temp.(°C)[2]	27.4	28.1
Aver. Temp.(°C)[2]	21.9	20.9
Insolation(hrs/day)[2]	5.4	8.7
Solar Radiation (gm-cal/cm²/day)[3]	416	407
Pan Evaporation (mm/day)[3]	5.39	5.78

Sources of Data

[1] Long-term averages of monthly precipitation for the Brasilia area. (Table 1).

[2] 30 years of record for Formosa. (Table 3).

[3] 1973-74 Data from the EEB. (Table 4).

course, the large difference in average precipitation. Average temperatures do not differ greatly. However, dry season minimum temperatures in June and July may be considerably lower, slowing initial crop development and delaying maturity of a dry season crop. Dry season minimum temperatures could be too low for pollination in certain sensitive varieties of rice.

Vegetative growth during the wet season was considerably ahead of dry season growth. For example, a comparison of 60-day old plants not subjected to water stress reveals that wet season plants were approximately 70 cm taller than dry season plants. This may be attributed to the combination of cool temperatures early in the dry season and to higher phosphorus and magnesium applications in the wet season. Also, cloudiness during the wet season may have contributed to increased plant elongation. Tasseling in the wet season was approximately 10 days ahead of tasseling in non-stressed dry season treatments.

Insolation is considerably greater during the dry season but solar radiation does not reflect this, due perhaps to the longer days during the wet season. Shorter days during the dry season may limit production of certain day-length sensitive varieties. Pan evaporation is somewhat greater during the dry season. This is probably an advective effect most pronounced during

August and September. In summation, climatic data suggest that with the exception of precipitation, the two seasons are only moderately different and that with irrigation, production of most crops would not be limited by seasonal climatic differences.

To experimentally test the potential for production in the dry season vs the wet season, a dry season experiment was established with soil fertility and moisture conditions identical to those in an experiment at the EEB conducted during the wet season 1972-73.[1] Fertilizer additions were identical. Soil test results for pH, aluminum, and calcium + magnesium taken at the conclusion of the experiments were similar. A comparison of rainfalls and irrigations simulating them was given in figure 16. For the crop period 56-109 days, the rainfall pattern of 1972-73 was effectively simulated by the irrigations. After day 109, rains created a better water environment in the dry season experiment. In general, moisture and fertility conditions were well established to make an interseasonal production comparison.

Yields for these two experiments and for a third wet season are presented in table 27. Differences be-

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[1] The author is indebted to Enrique Gonzales E., North Carolina State University, for permission to use data from his experiment.

Table 27 Yield of Shelled Corn (at 15.5% Moisture) for a Comparison of Wet and Dry Cropping Seasons at the EEB, Brasilia.

Season	Fertility[1]	Yield(kg/ha)
72-73 Wet	1	4400
73 Dry	1	4266
73-74 Wet	2	5417
"	2	4353
"	2	2445

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[1] 1 = 100 N, 300 P_2O_5, 100 K_2O, 4T Lime, Zn, B, Mo
2 = 140 N, 500 P_2O_5, 100 K_2O, 4T Lime, Zn, B, Mo, Mg.

tween seasons, as reflected in yields, were minor. This confirms the results from the climatic analysis suggesting no limitation to irrigated production in the dry

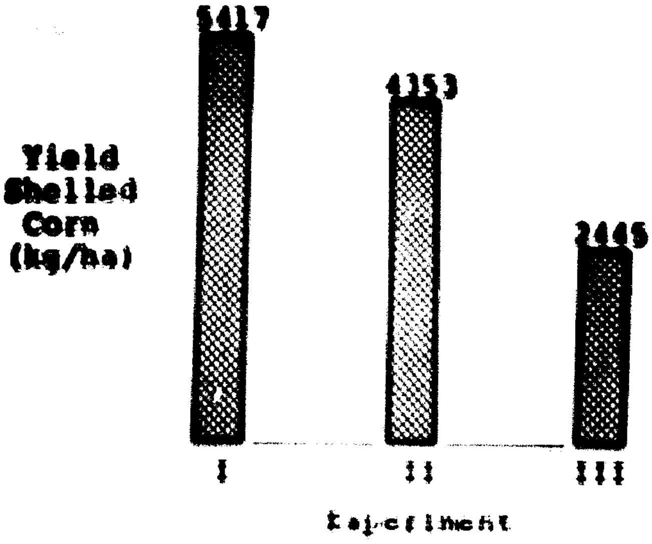

Figure 26 Average Yields from 3 Experiments at the EEB in the Wet Season 1973-74. In Each Experiment, Water Conditions were Similar and Fertility Conditions Identical.

season. Other yield data from various experiments at the EEB suggest that production potential in the dry season is greater than in the wet season. (Personal communication with Ady da Silva.) Data in table 37 and figure 26 show wet season production to be highly variable and on the average no better than production in the dry season of 1973, in spite of superior fertility and water conditions in the wet season experiments.

Yield reductions in going from Experiment I to Experiments II and III are striking. Average yields in Experiments II and III were 80% and 45% respectively of Experiment I yields. This occurred in spite of identical conditions of soils, fertility levels and water treatments. The variable production was not due to weather factors per se, but rather to disease and insect problems which may have been climatologically induced.[1]

It is not possible to conclude that the dry season production potential is greater because of higher radiation, pan evaporation or other climatic factors. However, one may conclude that the incidence of uncontrolled variables, including disease, insects and unexpected drought, is greater during the wet season. For this

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[1] The lesson from a comparison of these experiments is clear. To do an effective job of agricultural production (or research) in a humid tropical climate, considerable attention must be paid to the full complement of factors which go into the production process. To focus simply on water or fertility practices alone will by no means insure high levels of production especially where uncontrolled variables are operative. Further, it may be speculated that disease and insects will become more serious problems as the region is more intensively cultivated. Currently, farmers on the nearby Alexandre Gusmão project acknowledge a preference for dry season production to avoid such problems on vegetable crops.

reason, the potential for irrigated production in the dry season is greater thah for the wet season under rainfed conditions.

Summary and Conclusions

1. For the dry season, crop ET was highly significantly correlated with climatic measurements, in particular, pan evaporation, solar radiation, and relative humidity. Functional relationships were presented between crop ET and the standard meteorological parameters.
2. Crop ET was significantly correlated with yield.
3. Peak crop water use occurred from three weeks before tasseling to two weeks thereafter.
4. Dry season evapotranspiration requirements were estimated at 470-550 mm.
5. Climatic data suggest no significant limitations to irrigated production of most crops in the dry season.
6. There was no conclusive evidence that the dry season crop production potential is greater than the wet season because of higher radiation, pan evaporation, or other climatic factors. However, the incidence of uncontrolled variables such as diseases and insects is

greater in the wet season and consequently the potential for crop production may be considered greater in the dry season.

CHAPTER VII

EFFECTS OF DIFFERENTIAL DEPTHS OF LIMESTONE INCORPORATIONS IN RELATION TO WATER TREATMENTS

Introduction

In Brasilia, Gonzales, in NCSU, (1973) has reported that deep incorporations (0-30 cm) of 4 tons of limestone/ha gave yield increases of up to 20% when compared with shallow incorporations (0-15 cm). He showed that deep incorporations nearly doubled the length of roots per unit soil volume in the zone 15-30 cm when compared with shallow incorporations. It would follow that the more extensive root systems in the deep treatments would permit more water and/or nutrient exploitation, and that one or both of these was the direct cause for the superiority of the deep incorporations.

The purpose of this chapter is to present experimental results which pertain to differential depths of limestone incorporation in relation to water treatments. The effect of limestone incorporation depths in relation to water utilization patterns will be discussed. Conclusions will be drawn as to the reasons for the observed benefits from deep liming.

Results

Deep vs Shallow Incorporations

In the dry season, the mean yield for deep treatments (3956 kg/ha) was nearly identical to the mean yield from shallow treatments (4026 kg/ha). Soil test information is helpful in explaining why results did not show the benefits from the deep incorporation which had been demonstrated earlier by Gonzales and which were to be confirmed in the subsequent results from wet season water experiments. At the conclusion of the experiment, soil samples from each plot were taken from depths of 0-22.5 cm and 22.5-45 cm. Since tensiometer and block placement gave water utilization from 0-22.5 cm and 22.5-45 cm, these depths were selected for sampling. These depths did not correspond exactly with the nominal incorporation depths, but nevertheless analyses were expected to demonstrate the effectiveness of the incorporation treatments for creating differential rooting environments. Samples were analyzed for pH, aluminum and calcium + magnesium; the results are presented in table 28. Results indicate virtually no differences between deep and shallow incorporations as measured by pH, aluminum, calcium + magnesium or percent aluminum saturation. For some unexplained reason, the variation in depth of incorporation of limestone which was desired

Table 28 Soil pH, Exchangeable Al, Exchangeable Ca + Mg and Percentage Al Saturation for Unlimed Soil and for Deep and Shallow Limestone Incorporations in the Dry Season 1973 Water Experiment.

Treatment	Depth (cm)	pH (in water 1:1)	Exchangeable Al(meq/100g)[3]	Exchangeable Ca+Mg(meq/100g)[4]	Al Saturation (%)
Not Limed[1]	0-15	4.55	1.14	0.35	77
	15-30	4.61	1.09	0.31	78
	30-45	4.69	0.91	0.22	81
Shallow[2] (0-15 cm Incorporation)	0-22.5	5.23	0.33	2.37	12
	22.5-45	4.87	0.70	0.96	42
Deep[2] (0-30 cm Incorporation)	0-22.5	5.20	0.40	1.94	17
	22.5-45	4.90	0.71	0.93	43

[1] Sampled Prior to Planting in May 1973.
[2] Sampled after Harvest in December 1973.
[3] Replacement with 1 N KCl and titration with NaOH.
[4] Replacement with 1 N KCl and titration with EDTA.

Results from the wet season experiments were more definitive and clearly show the beneficial effects upon yield from deep limestone incorporations. Yield data are presented in table 29 and were graphed in figure 23. For Experiments I and II, yield increases due only to depth of incorporation averaged 1.4 ton/ha, or 32%. For each pair of irrigation treatments in Experiments I and II, and for all water treatments combined, highly significant differences were obtained. For Experiment III, in which yields were severely depressed by disease, average yield increases due to deep incorporations were still significant.

The direct effect from incorporation differences is reflected in soil test results given in table 29. Unlike the dry season, clear differences between the incorporations were established. For shallow incorporations, percent aluminum saturations with depth were 4%, 45%, and 55%, whereas for deep incorporations percent aluminum saturations were more uniform, 26%, 22%, 28% respectively. These aluminum saturations were still higher than desired but similar to what Soares et al. (1973) report for aluminum neutralization on this soil for a 4 ton/ha application of limestone. For shallow treatments, pH and Ca + Mg were higher in the zone 0-15 cm than for deep treatments. Below 15 cm, the deep incorporations showed higher values for pH and for Ca + Mg. From these analy-

Table 29 Yield of Shelled Corn (at 15.5% Moisture) by Irrigation Treatment for Wet Season 1973-74 Water Experiments

Irrigation Treatment	Yield (kg/ha) Limestone Incorporation Shallow	 Deep
Experiment I		
4-Day	5067	6640
7-Day	4949	6403
Not Irrigated	4592	5961
Experiment II		
4-Day	3757	5321
7-Day	4094	4947
Not Irrigated	3761	4830
Experiment III		
4-Day	2623	2642
7-Day	2498	2621
Not Irrigated	1976	2789

ses we may conclude the following:

1) Nominal incorporation types, deep and shallow, were in fact achieved as evidenced by differences in pH, Ca + Mg and Al;
2) The shallow incorporation treatment resulted in a very favorable rooting environment in the zone 0-15 cm and a very unfavorable environment in the zone 15-45 cm. From a chemical standpoint, the deep treatment resulted in a relatively uniform soil profile to 45 cm. This uniformity would permit more uniform corn root exploration with increasing depth in the profile.

Root densities were not determined directly. Rather an indication of root activity was obtained by comparing soil-water stress readings at 30 cm for the 2 depths of incorporation. Average daily stress and stress count at 30 cm are higher for deep incorporations than for shallow incorporations which indicates that for deep incorporations more water is being removed from the 30 cm zone, this a result of an active root zone in this region. In contrast, shallow treatments evidenced lower stress at 30 cm, hence less water being removed from this zone and therefore less root activity in that region.

The soil test results present a strong and plausible picture of the differential effects of the incorporations.

They do not however explain why deep incorporations are superior to shallow ones. Two hypotheses are proposed, both associated with the larger crop root system of deep incorporations:

1) Better utilization of soil-water, especially when water is a limiting factor.
2) Better crop nutrition because of:
    a) Increased utilization of soil nutrients which are deeply located and associated with more moist soil conditions. This would be particularly true of nutrients either supplied from the limestone itself, or for the mobile nutrients, N and K, since these nutrients would be distributed throughout the zone 0-45 cm. Other nutrients, P, Zn, etc. were applied after the limestone and were presumably confined to the top 15 cm of the root zone.
    b) Decreased aluminum toxicity with depth. Aluminum does more than simply restrict rooting and general ionic uptake. High aluminum concentrations in plants have been shown to have an adverse metabolic effect on certain crops (Foy and Brown, 1963).

The evidence from wet season Experiments I and II negates the hypothesis of yield differences caused by better water utilization as a result of deep incorporations. In 4-day irrigation treatments, soil-water tensions were kept at approximately 0.2 bars for both deep and shallow incorporations. In other words, water was in no way limiting growth, and one cannot attribute the 1.6 ton/ha in yield increases from deep incorporations to increased water availability. If deep incorporations enabled better water utilization, that advantage would have been equalized in 4-day treatments, and deep and shallow incorporations would have had similar yields. Yield differences between incorporations are relatively constant for all irrigation treatments in Experiments I and II. If improved water utilization was the result of deep incorporations, poorly watered treatments should show the best gains from deep incorporations; this was not the case. Deep treatments made the largest gains from increasing water availability. For example, in going from 8-day to 4-day water treatments in Experiment I, deep treatments gained 679 kg/ha and shallow treatments gained 475 kg/ha. In Experiment II, deep treatments gained 491 kg/ha while shallow treatments yielded approximately the same over all water treatments. Apparently, deep treatments had a nutritional advantage erences between 4-day treatments in Experiment III, conclusions from that experiment should be subordinated to results from I and II because of the disease problem previously described.

To gain insight into crop nutritional status, ear leaf sampling was made on all experiments at silking stage. Analyses were performed for N, P, K, Ca, Mg, Na, An, Mn, Fe, Cu, B, and Al for all experiments; S was determined only for Experiment I. Mean concentrations of these elements by incorporations are given in table 30.

Elemental concentrations have been compared with similar data in Jones (1967) and Chapman (1966). N, P, K and Mg concentrations were on the low side; all other elements analyzed appeared to be present in adequate but not toxic amounts. Although leaf aluminum levels were high to excessive (Jones, 1967) there is no evidence that leaf aluminum had a detrimental effect upon yield. Neither was leaf aluminum a cause for the differences between deep and shallow incorporations.

Correlations between ear leaf concentrations of the elements and yield were run, but no correlations were obtained which could be interpreted as cause and effect between the elemental concentrations and yield. In general, calcium and magnesium were negatively corre-

Table 30 Concentrations of Various Elements in the Corn Ear Leaves at Silking for Two Depths of Incorporation of Limestone and for Three Experiments, Wet Season 1973-74.

Element	Experiment I Shallow	Experiment I Deep	Experiment II Shallow	Experiment II Deep	Experiment III Shallow	Experiment III Deep
N(%)	2.14	2.17	2.03	2.10	2.23	2.38
P(%)	0.18	0.17	0.11	0.11	0.11	0.14
K(%)	1.20	1.42	0.98	1.01	0.88	1.32
Ca(%)	0.95	0.78	0.76	0.63	0.34	0.47
Mg(%)	0.24	0.19	0.19	0.16	0.10	0.12
K/(Ca+Mg)	0.46	0.68	0.48	0.65	1.05	1.01
Na(ppm)	29	26	34	31	29	38
Zn(ppm)	24	25	16	18	14	20
Mn(ppm)	51	51	43	42	38	47
Fe(ppm)	116	111	77	73	69	93
Cu(ppm)	7.6	7.2	4.0	4.1	2.8	4.9
B(ppm)	13	12	13	12	10	12
Al(ppm)	393	381	167	156	192	211
S(%)	0.177	0.185				
Yield(kg/ha)	4728	6335	3843	5033	2269	2684

Uptake and utilization of potassium have been shown to be influenced by concentrations of calcium and magnesium, and vice versa.[1] The ratio, (meq leaf K)/(meq leaf Ca + meq leaf Mg), was calculated and used as an index to yield. For Experiment I, this ratio is plotted against yield in figure 27. The ratio was highly significantly correlated with yield, but the scattering of data points within incorporation types suggests that other factors, not yet known, will be required to account for yield differences between deep and shallow incorporations.

In Experiment III, visual symptoms, confirmed by test foliar applications of magnesium, revealed deficiency of this element in deep treatments but not in shallow treatments. This may be explained by relatively high concentrations of calcium and potassium in deep treatments in this experiment which likely interfered with magnesium nutrition in the plants. Although it is possible that ionic imbalances may have been responsible for observed yield differences between deep and shallow incorporations, the evidence is not conclusive on this matter.

Uptake of the mobile elements, nitrogen and potas-

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[1] For a discussion of the subject of potassium interactions with other cations see Chapters XVI and XVII in Kilmer, et al. 1968.

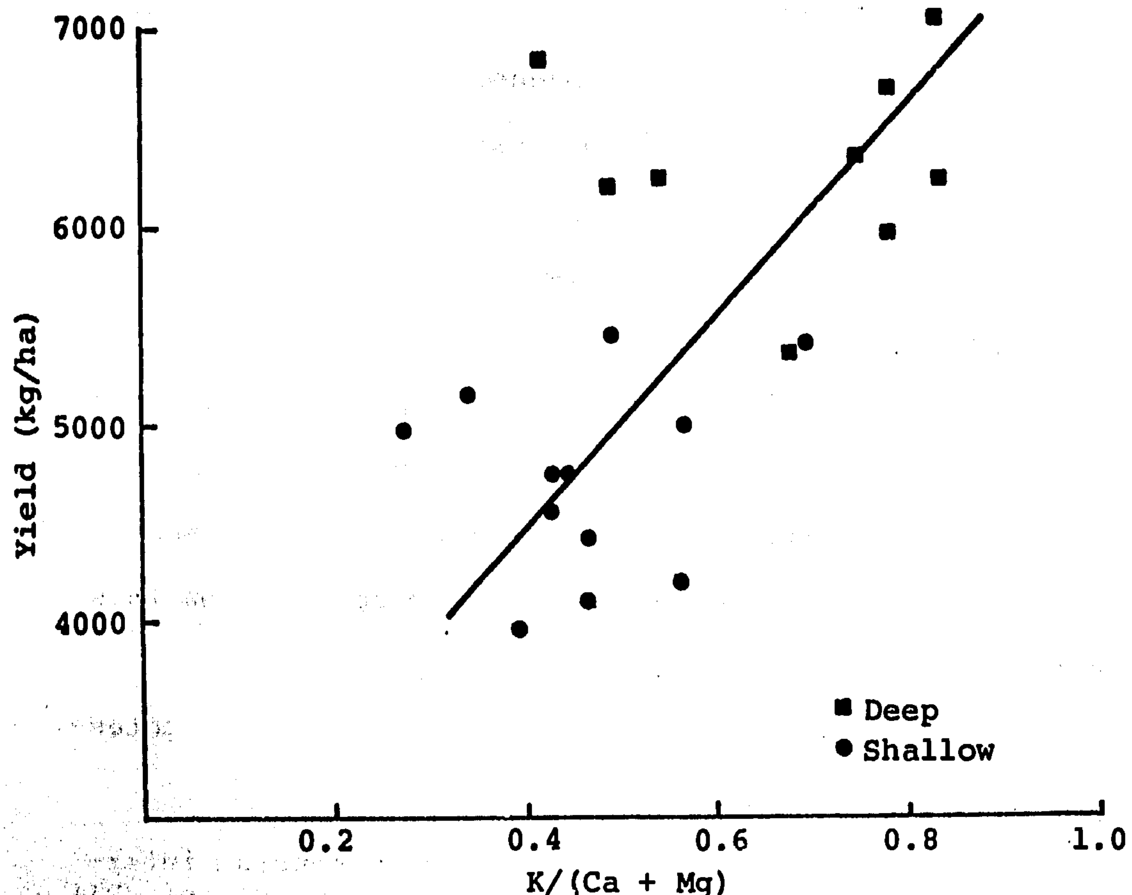

Figure 27 Yield of Corn vs Ratio of Potassium to Calcium Plus Magnesium, for Deep and Shallow Incorpora-

sium, was higher in deep treatments. This suggests that deep treatments may have profited from a larger root system which tapped nitrogen and potassium in the zone 15-45 cm.[1]

Limestone Incorporations and Water Use with Depth

Deep and shallow limestone treatments from dry season experiments showed no differences in patterns of water utilization with depth. That the nominal incorporation treatments showed no differences is not surprising in light of the soil test results. What is unusual is the water extraction pattern itself, figure 28, which shows that 84% of crop water use occurs from the top 45 cm of the profile. For corn on the LVE soil, on which these experiments were conducted, effective water use is confined to the top 60 cm of the profile. This is in marked contrast to water extraction patterns reported

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[1] Further work should be done, particularly with regard to potassium and magnesium nutrition. Determinations should be made of soil potassium and its distribution in the soil profile. Since this element is very mobile and likely to be leached from the root zone due to its inability to be exchanged or fixed in this soil which has a low cation exchange capacity and an absence of 2:1 clays, consideration should be given to sidedressings of potassium as crop growth progresses.

It is further recommended that ear leaf sampling be done three or more times during the growing season to relate when ionic uptake occurred to plant growth.

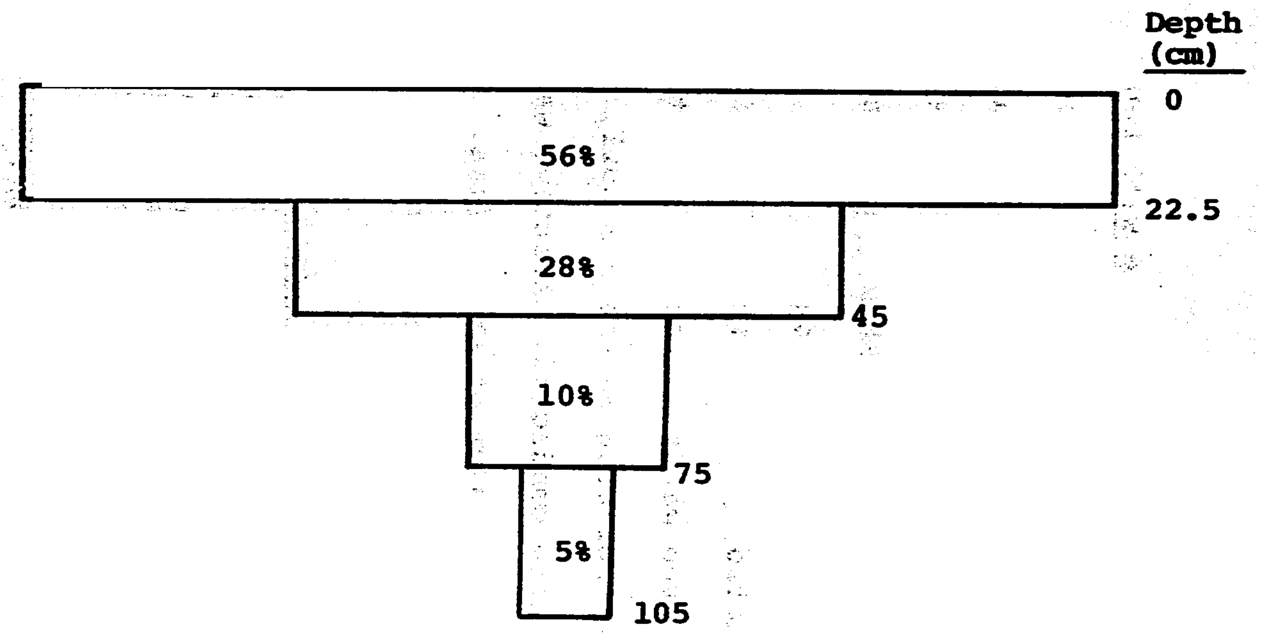

Figure 28 Percentage Water Extraction by Depth for Corn on the LVE Soil, Dry Season, Brasilia.

for corn on soils with less aluminum saturation. Fischbach and Somerhalder (1972) in Nebraska, and Russell and Danielson (1956) in Illinois, report soil-water utilization by corn to a depth of 150 cm, or more.

Since nominal incorporation treatments were not in fact achieved, analysis of water extraction patterns was made after separating treatments into two groups on the basis of soil test results. The four treatments with the lowest percentage aluminum saturation from 22.5-45 cm were placed in one group, those four with the highest percentage aluminum saturation were placed in a second group. Results are presented in table 31.

Table 31 Water Extraction with Depth for Two Groups of Treatments Representing Low and High Percentage Aluminum Saturation from 22.5-45 cm.

	Water Extraction (%)	
Depth(cm)	Low Al Saturation	High Al Saturation
0-22.5	57	52
22.5-45	28	32
45-75	9	10
75-105	6	6
	100	100
Mean Al Saturation (22.5-45 cm)	34%	55%

The comparison of water extraction patterns for the two groups reveals no differences between the two groups and no substantial difference from the pattern of figure 28.

Although Gonzales, in NCSU, (1973) has shown that the effect of deep incorporation of lime is to increase root proliferation with depth there is no evidence from the dry season data to support the conclusion that the enlarged root system enabled the crop to change its pattern of water extraction. This however may be said to conflict with visual evidence that plants grown on deep limed soil will withstand wilting for 2-3 days after wilting has occurred on shallow limed treatments. There can be little doubt that this is a water effect. The answer may be that small amounts of water, not sufficient to change the overall pattern of water extraction, might be temporarily adequate to keep plants from wilting. Further, the high capillary conductivity values reported for this soil would act to minimize extraction pattern differences between treatments. Further studies are recommended to aid in understanding this apparent anomaly.

Summary and Conclusions

1. Deep incorporations of limestone (0-30 cm) out yielded shallow incorporations (0-15 cm) by 1.6 ton/ha or 30% across all water treatments.
2. Water and nutritional hypotheses were proposed to account for differences between incorporation types.

3. At average soil-water tensions of 0.2 bars in both incorporation types, yield differences between deep and shallow incorporations were 1.6 ton/ha. At low soil-water tensions, this is evidence to negate the hypothesis that yield differences were due to increased water availability. Under more limiting soil-water conditions, deep treatments would likely benefit from the effect of a larger crop root system and its ability to extract water from deeper depths.
4. Soil-water extraction was effectively confined to the top 60 cm of the soil profile, with almost 85% of the water use occurring from the top 45 cm of the profile.
5. Deep and shallow incorporation types had similar patterns of water extraction. Soil-water extraction appeared to be independent of percentage aluminum saturation. However, this is not supported by visual observations of wilting.
6. Analyses were reported for 13 elements in the corn ear leaves in an effort to determine whether yield differences could be attributed to nutrition.
7. There is evidence that deep liming had a beneficial nutritional effect especially in terms

of potassium nutrition. However, it is not likely that this element alone will account for observed yield differences.

CHAPTER VIII

LACK OF WATER CONTROL AND ITS EFFECT ON AGRICULTURAL PRODUCTION

Introduction

The question of profitability of supplemental irrigation in rainfed environments has been studied by workers such as Asopa and Swanson (1969), Reutlinger and Seagraves (1962) and Allen and Lambert (1971), among others. Their common approach is the use of historical weather records in combination with crop production records to assess the benefits from the supplemental irrigation capability. Unique to the Brasilia situation is the fact that a productive agriculture does not yet exist in the region, yet the same question is being asked. However, the question of supplemental irrigation is not simply, will it be profitable, but more importantly will it be required for agricultural development of the region.

The research information presented in Chapters II and III describes the critical importance of water for agricultural production in Central Brazil. This information, together with results from Chapters V, VI and VII provides understanding into the manner in which water affects the production process. The purpose of this chapter is to put that research information into a framework which can be useful in assessing the need for irrigation in Central Brazil. The focus will be on determining that need in the wet season, for if it can be established that an irrigation capability is justified for that season, then the same system will of course be used and will pay dividends in the dry season.[1]

Methodology

Determination will be made of long term average yield losses for corn in the absence of a functioning and well managed irrigation system. These losses, less the cost of developing and using the water resource, may be considered the benefits from improved water management in the wet season.

$$\boxed{\begin{array}{c}\text{Benefits from}\\ \text{Improved Wet}\\ \text{Season Water}\\ \text{Management}\end{array}} = \boxed{\begin{array}{c}\text{Value of}\\ \text{Yield Losses}\end{array}} - \boxed{\begin{array}{c}\text{Cost of}\\ \text{Developing}\\ \text{And Using the}\\ \text{Water Resource}\end{array}}$$

For two reasons, no attempt will be made to attach a monetary value to the elements of the equation. First, the losses/costs may be expected to vary greatly in time

[1] The question of water availability in the dry season will not be discussed in this dissertation. Pruntel (1975) has concluded that there is sufficient water to irrigate from 5 - 10% of the Federal District in the dry season.

and space. Secondly, social costs and benefits would need to be assessed and reduced to like monetary terms for inclusion in the equation. Therefore, the requirement for the developed water resource will be gaged only in terms of the predicted long term effects of droughts upon yields.

The probability distribution function for the parameter, longest dry spell, presented in Chapter II, will be combined with crop response data from yield-water response functions, developed in Chapter V, to assess the need for wet season irrigation in Central Brazil. The parameter, longest dry spell, has been used both for rainfall probabilty analysis and as the basis for triggering water treatments in Experiments I - III. This parameter was the basis for the treatment differences and therefore has actual physical significance.

The use of longest dry spell is a simplifying approach to a difficult problem, ie. how to deal with various combinations of drought severity and duration and their effect upon yield. This approach is not without limitations since possible combinations of dry and wet spells in a five-month period are almost infinite. Dry spell effects upon crops are further complicated by the following:

1. Impacts of dry periods are not independent

events. Suppose one n-day dry period was followed by one wet day and then by another m-day dry period. This might be more damaging than the two dry periods more widely spaced. Such was the case in 1970-71 when there occurred dry spells of 13 and 16 days separated only by 6 mm of precipitation. That year, the corn crop at the Experiment Station was lost.

2. The effects of dry-day sequences are only indirectly related to crop yield through soil-water stress and thence plant-water stress. But, as was pointed out in Chapter V, soil-water stress is not always a good index to water effects upon yield.
3. Other atmospheric factors beside rainfall have not been considered. For example, a 10-day dry spell under generally overcast conditions may not be as detrimental as a 10-day dry period when radiant energy is higher.
4. The relation in time between dry spell occurrences and critical crop stage is of utmost importance for a crop such as corn. A dry spell of 10 days at silking may be

in the crop's growth or immediately prior to harvest.

Yield-Water Response Functions

Results from the three wet season experiments have been presented in figure 24. This is a generalized response function in that it pools yield data from all three experiments and from both deep and shallow incorporations. The dependent variable is relative yield (the yield for a particular water treatment divided by the best yield for that experiment and incorporation type). Use of the dimensionless parameter, relative yield, can permit extrapolation of these results to a wider range of soils, fertility levels, disease conditions, etc. These factors and others may vary greatly under different management practices and it is only through a relative yield determination that the results for water response reported herein may be more generally applied. The independent variable, longest dry spell, was the irrigation criteria used in those experiments.

The experimental data did not cover the full range of yield response to increasing drought. Therefore, possible extremes in the yield-water response function have been extrapolated in figure 29.

1. Response Surface 1 (RS-1) predicts that ther will be no yield of corn after a 14-day

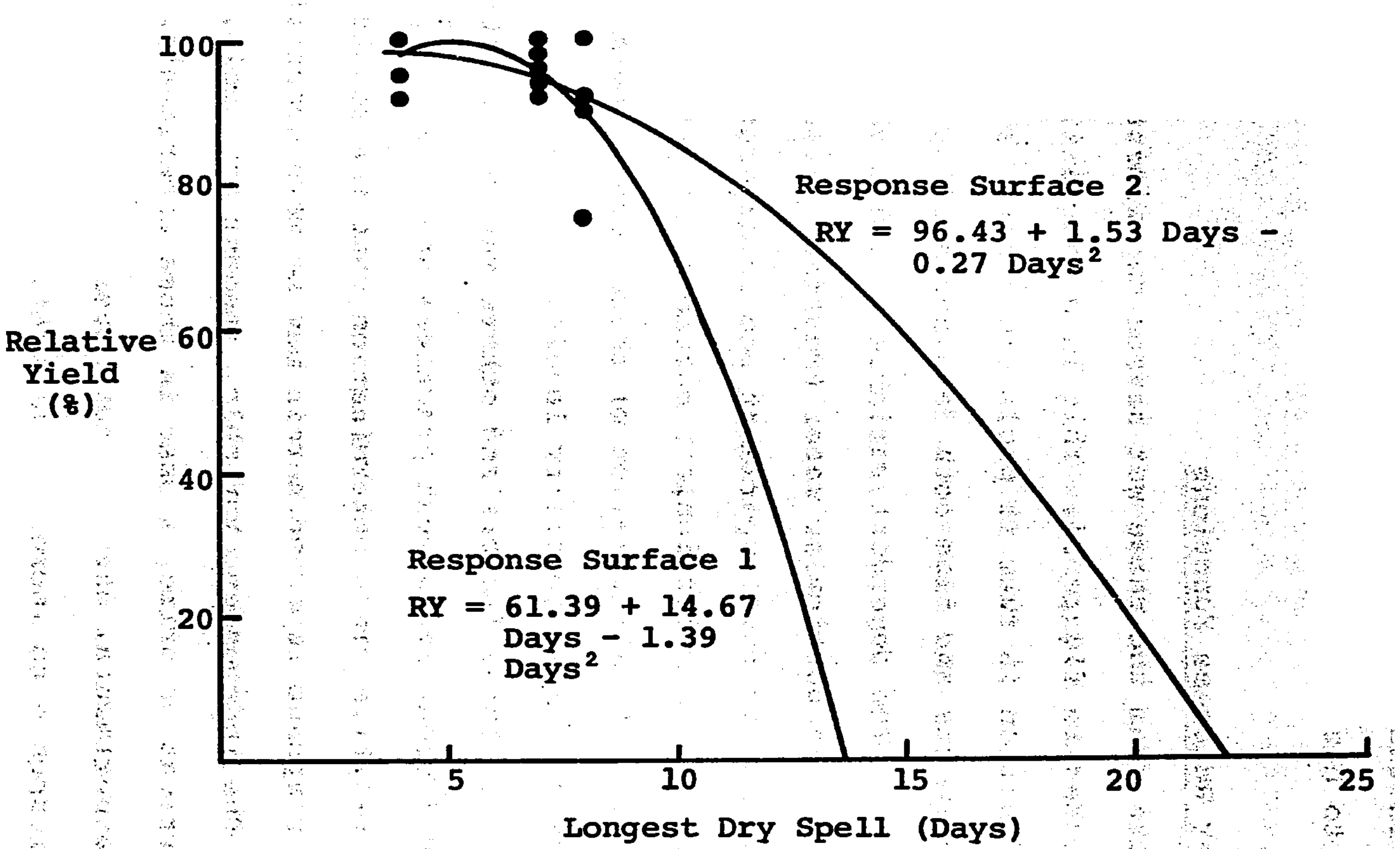

Figure 29 Relative Yield of Corn vs Longest Dry Spell. Response Surfaces 1 and 2 Represent Low and High Yield Models for the Effect of Dry Spells Upon Yield.

drought. (Maximum impact model)

2. Response Surface 2 (RS-2) predicts that there will be no yield of corn after a 22-day drought. (Minimum impact model)

RS-1 was drawn from data from all three experiments and incorporation types fitted to a 2nd degree polynomial. Experimental data beyond an 8-day drought are lacking; the 14-day, zero yield prediction is a projection of the curve to more severe drought conditions. Since there were yields for 14-day treatments during the dry season, one may conclude that RS-1 overestimates yield losses.

RS-2 was drawn from data from the same experiments together with the condition that only after a 22-day dry spell will yields be so adversely affected by the lack of rain that the crop will be lost. This condition is based upon actual crop data and weather records for 1968-69. Since the 1968-69 crop may have been lost before the full 22 days elapsed, RS-2 represents a conservative estimate of losses due to lack of rain.[1] The two response surfaces therefore bracket the range in crop response to drought for corn which will be likely

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[1] A 22-day drought immediately prior to harvest will not have the impact that the same length of dry spell will have earlier in the crop. On the other hand, it has been pointed out that two dry spells of durations shorter than 22 days can also result in no yield.

under Cerrado conditions and erratic rainfall distributions.

A comparison of yield projections from RS-2 with experimental results from the dry season reveals that 7 days without rain will be associated with a relative yield of 84% in the dry season and 94% in the wet season. Fourteen days without rain leads to a relative yield of 73% in the dry season and 65% in the wet. Thus, dry season results overestimate yield reductions for short droughts and underestimate losses for longer droughts. Crop adaptation to repeated 14-day droughts during the dry season may explain why losses were not greater in the dry season.

Probability Distribution Function for the Longest Dry Spell

The probability distribution function for the longest dry spell was presented in Chapter II. Briefly stated, each of the 42 years of record was characterized by a single longest dry spell. Results were presented in histogram form and a smooth curve was drawn using the log-normal probability distribution function (figure 4). This distribution function has been used to predict the likelihood that in any given wet season the longest dry period will last n days, or longer. For example, there is a 50% chance that in any wet season, the longest dry spell will be 14 days or longer. Cumulative data for longest dry spell probabilities were given in table 5.

Long Term Wet Season Yield Losses of Corn in the Absence of Improved Water Control

To determine expected long term wet season yield losses, probability data for experiencing a dry spell of length n have been combined with production function data describing the effect upon yield of that n-day dry spell. The method of calculating long term yield losses is indicated in table 32. Results reveal that, for the minimum impact projection, long term wet season yields will average only 54% of yields had precipitation been well distributed, or water not otherwise limiting due to a functioning and well managed irrigation system. In other words, with well managed irrigation, these data would indicate that long term wet season corn yields in the Cerrado would nearly double. For the maximim impact projection, long term average yields are estimated at only one quarter of possible yields.

It is important to note that these production function data were obtained from field research conducted at the local experiment station. To what extent are these data applicable to the local farmer and to development in the region? On the positive side one may note

Table 32 Data for Calculating Long-Term Yield Losses for Corn in the Cerrado.

Longest Dry Spell (days)	Probability of Longest Dry Spell[1]	Maximum Impact Model		Minimum Impact Model	
		Relative Yield[2] (%)	Yield Component[4] (%)	Relative Yield[3] (%)	Yield Component[4] (%)
4	.00078	97.83	0.07643	98.25	0.07676
5	.00396	99.99	0.39659	97.36	0.38619
6	.01152	99.37	1.14521	95.93	1.10565
7	.02364	95.97	2.26958	93.97	2.22230
8	.03849	89.79	3.45616	91.46	3.52064
9	.05328	80.83	4.30707	88.42	4.71158
10	.06560	69.09	4.53256	84.83	5.56575
11	.07401	54.57	4.03902	80.71	5.97439
12	.07813	37.27	2.91207	76.05	5.94285
13	.07834	17.19	1.34668	70.86	5.55137
14	.07542			65.12	4.91243
15	.07032			58.85	4.13868
16	.06388			52.03	3.32468
17	.05683			44.68	2.53998
18	.04971			36.79	1.82925
19	.04287			28.37	1.21632
20	.03655			19.40	0.70929
21	.03087			9.89	0.30562
22	.02587			0.14	
23	.02154				
			24.48		54.03

[1] From Log-Normal probability distribution. See figure 4.

[2] 14-day, zero yield projection. See RS-1, figure 29.

[3] 22-day, zero yield projection. See RS-2, figure 29.

[4] (Relative Yield) x (Probability of Longest Dry Spell).

that soils and climate are representative of a much larger area. However, on the Experiment Station, inputs probably were greater and management more intensive than can be expected in the initial stage of regional farm development. While it is difficult to say whether the same percentage yield reduction will occur, the absolute yield reduction probably will be less since the farmer is likely to be operating on a lower response surface. Therefore, he may be less able to economically justify the development of an irrigation capability for the wet season than data from the experiment station would indicate. However, if farmers go to high investment crops, the unstable production conditions caused by the erratic rainfall distribution will place an even higher premium on irrigation. Further, it should not be forgotten that dry season production benefits from irrigation would be over and above those mentioned for the wet season.

General Implications for Agricultural Development

The impact of these potential yield losses on intensive agricultural development is underlined when one considers that intensive farming on the Cerrado will never be inexpensive. Intensive production under conditions of low native fertility will require large capital inputs for fertilizer alone. It is the inability to repay these inputs in the face of widely fluctuating yields which threatens development of an improved, prosperous and stable agriculture.

In spite of the prospect for instability of agricultural production, improved water management will not be adopted unless policy dictates or motivation occurs. Policy options may include subsidization of water development, crop pricing policies and tax incentives, among others. Motivation can occur only if the farmer sees and can realize the benefits from having a developed water resource. This is not likely to occur unless a significant change occurs in the local crop production system, ie. adoption of new varieties/crops and/or changes in the existing cropping pattern.

For the small subsistence farmer who has always operated on a risk-avoidance response surface, this may mean a shift from exclusive production of traditional crops such as corn, rice, beans and mandioca, to a system which includes production of some crops for market, together with purchase of fertilizers, and crop insurance against losses from lack of water, insects and disease. An extreme example would be that portion of the Alexandre Gusmão project which is almost entirely market oriented, with heavy reliance on fertilizers and intensive management. Under that type of production system, improved water management was perceived as a necessity.[1]

Since Cerrado land is cheap, easily mechanizeable, and subject to speculative pressures, it is likely that increasing investments will be made by large investors. Other than discouraging initial investment, the water constraint may not be as critical to this type of developer. If investment in agriculture and production is made mandatory by government policy (as opposed to simply investing in the land), large investors may be able to cope with bad water years by development of the water resources, by mixed cattle and crop production systems, or simply through benefits of size such as reliance upon capital reserves. Additional encouragement for investment should stem from the fact that even if agricultural profits do not fully materialize, the profits from land speculation may be large.

Given the favorable economic climate for production of foodstuffs, together with the impetus for development caused by the new capital city, changes in the existing

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[1] Construction of the water delivery system for the Gusmão project was made only after that project was faltering from failure to integrate water aspects into the agronomic system. In an effort to serve a contiguous project area, water for that project is stored behind a small dam and transported in 37 km of earth canals. Lower cost water systems serving individual farm units are presently operative in the Brasilia area. Similar systems may be encouraged by proper government incentives and expertise.

agricultural structure of the region, to include increased water development, are by no means remote.

Summary and Conclusions

A generalized yield-water response function was developed on the basis of experimental results and the prediction of no yield of corn after 22 successive days without rain. The combination of this response function with wet season rainfall probabilities for n successive days without rain predicts long term average yields of only 54% of possible yields given the capability to irrigate during the wet season. In other words, with irrigation, long term average wet season production of corn would nearly double.

The need for improved water control will become increasingly apparent as farmers move away from traditional crops and toward new cropping systems. Then, improved water control may be required if yields are to be stabilized and costly fertilizer inputs repaid.

Benefits from an irrigation capability in the dry season would be in addition to those mentioned above.

CHAPTER IX

MANAGEMENT OPTIONS AND RESEARCH NEEDS

Introduction

Earlier chapters have described climatic and soil conditions and crop response which make water a limiting factor in the agricultural production system in Brazil's Central Plateau. The water constraint upon development exists not only for the dry season, but for the wet season as well. From a practical standpoint, the figures presented in Chapter II for expected number of multiple wet season dry spells are perhaps the most revealing in terms of their qualitative relationship to risk and agricultural development in the Cerrado. Long wet season dry spells obviously will have an adverse effect upon crop production and investment. Knowing that one may expect an 18-day dry spell, or longer, 2 years in 7 should raise questions in the mind of the planner, the investor or the farmer who contemplates agricultural development of the Cerrado. Under these erratic rainfall distributions, will intensive agriculture be too risky to warrant the investment? What can be done to minimize the risk? This chapter has as its objective the exploration of management options which minimize risk and which deal with the water problems as they exist in the area. Soil and crop management practices to minimize the potential effect of the wet season drought hazard will be discussed. In addition, specific research needs will be identified.

The Problem

What is the water problem? Briefly stated it is as follows: for many crops such as corn rooting is limited by concentrations of aluminum to the top 45 cm of soil. Water and nutrient uptake must therefore occur from a shallow zone of soil. The available water storage in these soils is less than for similar textured temperate zone soils. From May until September there is no rainfall. Wet season rainfall is erratic and research indicates that two weeks or more without rain during the cropping season is not uncommon. Yields will vary greatly from one year to the next. Low native soil fertility and soaring fertilizer prices will mean that agricultural development will be costly. Because of year-to-year variation in rainfall, together with restricted rooting regimes and limited water supplying capacity of the soils, it may be difficult to recover costs in the absence of improved water management practices.

Two general approaches are proposed to minimize the problem stated above. These may be termed "soil management options" and "crop management options" respectively. The former will include irrigation, liming, and fertility management practices. The latter includes options as to crop selection, variety selection, planting dates and cropping sequences.

Soil Management Options

Irrigation

Probably the most obvious solution to lack of water for cropping is to provide it through irrigation. Previous research has shown that even a single irrigation during the wet season can spell the difference between some yield and crop failure. This has already been recognized in practice in the Brasilia area. On the Experiment Station, a low-cost gravity irrigation system has been constructed and it is used regularly both in the dry and the wet seasons to provide water for cropping. Two of the more successful agricultural operations in the area, the Alexandre Gusmão project and the Fazenda San Antonio (John Bateman) have irrigation systems which are used year-round. It may be noted that the Bateman system was constructed at a cost estimated by the author at $50 per hectare.

Irrigation, in conjunction with improved fertility practices, could be a solution to promote regional agricultural development over a wide area of Central Brazil. Slopes are conducive to irrigated cropping and erosion generally is not a problem. However, the high infiltration rates of the soils will make losses in gravity irrigation systoms extremely high. Although there is little concern now for over-irrigation, - except as it causes nutrient and top soil losses, - in time water supply will be a limiting resource and one must recommend against gravity systems. A sprinkler system is viewed as the best irrigation alternative at the present time.

Even during the dry season, water supply is adequate to support significant cropping. Pruntel (1975) has estimated that from 5-10% of the Federal District could be irrigated in the dry season with construction of small impoundments to store the water. This might lead to a type of development of farm units having both intensively cultivated portions on good slopes and proximate to the source of water, together with more extensive cattle type operations on other parts of the property. Research might now be initiated on the viability of this approach as a prototype to Cerrado development. Such research would include technological, economic and sociological components.

Traditionally, Brazilian farmers have not practiced irrigation, and it is not only the resources and hardware which may limit adoption of the irrigation practice, but education and training as well. In the near future it is unlikely that irrigation will be the sole answer to solving Central Brazil's water problems unless substantial investments are made in influencing people to want the water and in training them to use it intelligently. This has been shown to be a difficult proposition even in areas having a long history of reliance upon irrigation.

Liming

Liming will be an integral part of any intensive crop production system in Central Brazil. Liming these soils is, in essence, a soil reclamation process necessary for reducing aluminum concentrations to levels which will permit growth of crops sensitive to the aluminum.

Limestone deposits are widely distributed on the Central Plateau. The material is available in Brasilia at a cost of less than $10 per ton. Applications of 5 ton/ha have been shown to correct the aluminum problem in that immediate area. Preliminary data (Gonzales, personal communication) suggest that maintenance applications will be required with intensive cropping.

During drought, it is likely that some but not all of the benefits from deep limestone incorporations may be attributed to better water availability. Rooting of crops such as corn, soybeans and cotton has been shown to reflect depth of incorporation of the liming material. Crops grown on deep limed soil will withstand wilting longer than crops grown on shallow limed soil. Even under excellent soil moisture conditions, a yield advantage of 1.6 ton/ha was obtained for corn from deep incorporations. This is strong argument for the practices of deep plowing and rotovation even where power is costly. Limestone applied and simply disced into the topsoil will lead to a surficial concentration of roots which may accentuate problems of nutrition and/or water.

In terms of the regional development process the problems of liming are twofold. First, there are logistic problems involved in exploiting and distributing the liming material. Second, there are problems in proper use of the material with power practices designed for deep incorporations. This is a problem which may be met with institutional arrangements such as government sponsored motor pools providing equipment for hire. Such an agency is currently operational in the Federal District.

Fertility Management Practices

The fact that soils of the Central Plateau will require large and costly fertilizer inputs, particularly phosphorus, means that a successful agriculture in the region will require insurance against crop failure from lack of water and from the subsequent inability to pay back fertilizer investments. A reduction in the crop requirement for fertilizers will mean a similar reduction in the necessity for the water component as an insurance factor. This concept is a shift from intensive agriculture requiring costly inputs to an agriculture less dependent upon outside inputs. For the Brasilia area it would appear that farmers are moving away from the low input type of operation and towards intensification of inputs.

Even with this trend efforts can be directed to reducing fertilizer requirements. For example, more efficient placement of phosphorus in combined band and broadcast applications can reduce phosphorus fixation and permit crop uptake of phosphorus even when drought may inactivate portions of the root zone. More efficient use of all fertilizers should be studied and recommendations made as to sources, placement and amounts of fertilizer material and timing of preferred fertility practices.

Wet Land Utilization

In many areas of the Cerrado, localized areas of seepage and/or perennial wetness occur. These areas are often on black soils (Aquox) which may have somewhat better chemical properties than the well drained more extensive Oxisols of the area. In locations where they occur, these areas may be thought of as central to the development of farm units since one may expect production on these soils well into the dry season. One aspect of future research might focus upon production systems for these soils.

Crop Management Options

Crop Selection

Certain crops are able to withstand adverse water and/or aluminum conditions, and can produce well under low native soil fertility. Efforts should be directed to encouraging the introduction of crops which fit into these categories and which are economically acceptable.

Crops such as mangos and mandioca (cassava) are examples of crops which produce well where others will not. Brachiaria is a grass which remains green longer into the dry season than do traditional forages of the area. Research efforts should be directed to understanding why these crops and others are well adapted to Cerrado conditions. Such basic understanding could be of value in presenting breeders with plant "design characteristics" basic to the success of other species.

Varietal Selection

As with crop selection, the problem is one of developing varieties which can withstand drought, root well under high aluminum concentrations, and which can produce well under the low native soil fertility conditions. This is an area where much interest and research is currently underway and breeders in many parts of the world are looking into each of these areas.

In terms of drought tolerance deeper rooted varieties would appear to have an advantage. Even if root systems are not particularly proliferous at depth, a few dispersed roots may be of considerable advantage in view of the high capillary conductivities reported for the Brasilia Oxisol.

Length of time to maturity is a second crop criteria which can be related to drought tolerance. It was pointed out that the variety of corn used in the experiments was long to maturity (140 days) and lacked uniformity in its reproductive habits, ie. tasseling and silking occurred over a long period. These are qualities which permit that corn variety to be relatively tolerant to water stress and to produce some grain yield even under drought conditions. However, in terms of year-round cropping delay in maturity is in essence a loss. This is particularly true in tropical and sub-tropical climates where possibilities exist for more complete use of the environment. If adequate water control can be assured a variety of shorter duration would be recommended. If in the long run irrigation is developed and agricultural water supplies become limiting, the picture may again change. Although crop maturity may be delayed by early lack of water, this may be an acceptable alternative if other priority allocations are to be made for the water.

Planting Dates

Results of the climatic analyses indicate that in most years wet season droughts will affect yields of many crops. Management practices such as an early planting date should be chosen to take advantage of likely rains in November and December and to minimize the potential effect of the wet season drought hazard which can occur with regularity after late December. For example, corn might be planted as early as possible in September or October so that in late December the crop was in the late grain filling stages rather than at tasseling. If good moisture conditions exist early in the season, it would be advisable to plant an early maturing variety with a view to double cropping. As pointed out above, a problem with earlier varieties is that these tend to have a shorter and more time-specific reproductive period which would make these varieties more susceptible to drought should it occur. However, the incidence of drought from mid-November to late December and coinciding with reproduction and grain filling in early corn varieties has been shown to be unusually low. And as will be pointed out in the next section, the drought insurance is the second crop.

A second possible option for corn is a delayed planting date, for example, late November, so that likely veranicos in late December and January would come while the crop was still in the period of vegetative growth. Drought at this stage might not be as injurious as a drought on the crop at a more critical stage. A delayed date of planting should take into consideration other likely dry periods in late March as the dry season approaches.

Cropping Sequences

Certain sequences of crops such as corn followed by beans or sorghum are logical from the standpoint of more fully utilizing the rainy season. Both beans and sorghum are short crops and might be planted in February and harvested in May. Sorghum is accepted as a drought tolerant species. It is also quite susceptible to aluminum toxicity. Research on sorghum varieties less sensitive to the aluminum is in progress in Brazil and results may offer promise. If short varieties of tropical soybeans can be developed which are less affected by photoperiodicity, these might also fit into a desirable cropping sequence.

Earlier maturing varieties have the advantage of permitting double or triple cropping. One advantage is that with two or more crops grown sequentially the likelihood of total crop failure from drought is reduced. A variation on this would be to have several staggered planting dates of a single crop to obtain the same end. A second advantage of two crops is that fertilizer additions, particularly nitrogen and potassium might be more fully recovered if provision is made for farming the same land. Perhaps the principle advantage in shorter varieties and multiple cropping is more complete exploitation of the land and sunlight to produce needed foodstuffs.

This intensive approach to agricultural production is not the one generally taken in locations where land is so abundant. However, because farming in the Cerrado will require base level additions of limestone, phosphorus and other nutrients before significant production can be attained, there will be advantages in exploiting the lands which have received these inputs.

Future Integrated Research

Several potentially productive areas of future research have already been described. These include the following:

1. The investigation of the economic viability of farm units combining both extensive and intensive enterprises including use of irrigation and/or perennially wet areas.
2. Development of fertility management practices which minimize fertilizer requirements and reduce the need for water as insurance against crop loss.
3. Selection of crops/varieties which can better withstand drought and which can produce well under low native fertility conditions.
4. Development of crop production systems which are less vulnerable to wet season drought and which more fully utilize the year-round climatic potential of the area.

Five additional lines of research are suggested:

1. Farmers often comment that second crops do better than the first on Cerrado soils, or that rice is the only first crop for opening up new land. No one at present is studying the microbiologic factors and transformations implicit in these observations. A practically oriented microbiologic study would be valuble in defining what is the effect of microbiologi-

cal action upon nutrient transformations. This study would be especially timely in view of the worldwide pressures upon fertilizer supply.

2. In the tropical environment disease and insect control is especially crucial when year-round cropping is practiced. A year and a half of continuous cropping has resulted in a marked increase in crop losses due to insects and disease. Efforts at chemical control have not been adequate. Field research, consistent with sound ecological practices, needs to be initiated on methods of prevention and control of insects and disease before these factors become widespread problems.

3. Studies need to be made on tillage management on Cerrado soils. Possible topics of interest and importance would include:
   a. Methods of land clearing, eg. burning.
   b. Should crop residues be returned to the land?
   c. Can soil-water properties (water storage) be improved by mechanical operations?
   d. Should minimum tillage be practiced?
   e. Can compaction be a problem on these soils?

4. During the wet season 1973-74, water management research was initiated to determine water response functions for corn and the effect of veranicos on yield. This research was only partially successful inasmuch as the range of water treatments was limited due to well distributed rains. This work needs to be continued, perhaps with other crops, so that yield-water response functions may be more adequately defined. These may then be combined with veranico probabilities already developed for the area to provide an estimate of risk and expected wet season production.
5. The soils on the Alexandre Gusmão project are Oxisols similar to those at the Experiment Station. Crop production there is representative of what might occur in larger areas of the Cerrado given the intensive inputs of water, fertilizers and management. A study of this project should be made to understand the production system which has evolved in the few years since the project was initiated. An important facet of that study would focus on sociological questions, for there appears to be a disparity in production between farms operated by Brazilians

of Japanese ancestry and those operated by native Brazilians. Are different value systems operative, or are the differences caused by differences in accessibility to markets, credit and technology? An understanding of these and other questions may aid in eliminating potential constraints to expansion of Cerrado development.

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