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Weather-Crop Yield Relationships in Drought-Prone Countries of Sub-Saharan Africa

Final Report

July 1979

WEATHER-CROP YIELD RELATIONSHIPS IN DROUGHT-PRONE COUNTRIES OF SUB-SAHARAN AFRICA: FINAL REPORT

to

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Office of Foreign Disaster Assistance
Washington, D.C.

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Center for Environmental Assessment Services
Climatic Impact Assessment Division - Models Branch

and

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Finally, those individuals who provided significant information and data for this report are listed in Chapter VI.

EXECUTIVE SUMMARY

WEATHER-CROP YIELD RELATIONSHIPS IN DROUGHT-PRONE COUNTRIES OF SUB-SAHARAN AFRICA: FINAL REPORT

The objectives of this US/AID/OFDA sponsored project include: 1) the development of a meteorological data set to systematically study the climate and its relationship to drought/food production problems in sub-Saharan Africa, and 2) the development of agroclimatic techniques, including climate/crop yield models, historical yield indices and crop calendars, which can be utilized operationally for input into an early-warning assessment program for subsistence food crops in these developing countries.

The climate of the central African region, south of the Sahara Desert, is characterized by relatively well-defined, alternating wet and dry seasons. The frequency, intensity and duration of rainfall are primary controlling factors in agricultural production in the semiarid regions. The seasonal rainfall distribution regulates the agricultural calendar as most agricultural activities coincide with the summer wet season which is governed by the position of the Intertropical Convergence Zone (ITCZ).

Tropical agriculture has four major environmental constraints which may limit productivity. These constraints are: 1) potential photosynthesis, 2) soil fertility, 3) pests and diseases, and 4) water deficits. These factors are discussed in general terms to provide the framework for a discussion of specific subsistence food crops grown in the semiarid regions of Central Africa. Background information on the Sahelian

rangelands, including vegetation and vegetative deteorioration, and livestock and their migratory patterns, are also presented.

Agroclimatic Techniques

Three agroclimatic techniques were used depending upon the amount and quality of available meteorological and agronomic data. The traditional linear regression approach utilizes the historic data bases for crop yield and climatic, or derived agroclimatic, variables to obtain an equation which best explains the variation in yield. This approach was used for subsistence food crops grown in Senegal, Niger, northern Nigeria and Sudan. Specific crops include millet/sorghum, cowpeas, corn (maize), groundnuts and sesame. The coefficient of determination, R^2, or explained variance, ranged between 0.53 and 0.76 for all models using a single predictor variable.

The predictor variable used in model development was the crop moisture ratio (CMR), defined as the ratio of precipitation to potential evapotranspiration. This ratio was determined for successive stages of crop development (i.e., planting, vegetative, reproductive and late). In spite of its simplicity, there was a good relationship between crop yield and CMR for both the vegetative and reproductive stages for millet/sorghum grown in Senegal, Niger, Sudan and Upper Volta. Distinct regional patterns were found in these relationships for the various countries which reflect the moisture availability during these growth stages.

In the absence of historic crop yield data for a region of interest, analogue models developed for similar climatic and agronomic conditions were applied to provide indicators of relative yield estimates. Recognizing

the limitations (i.e., no quantitative yield data, the requirement of similarity of conditions) this approach for the area of study was considered feasible to assess the condition of the crop.

An analogue model was developed for millet grown in Mali using two established climate/crop yield models. The Senegal vegetative model and the Niger reproductive model were used with Mali meteorological data to provide qualitative estimates of Mali millet yields.

Although the magnitude of rainfall fluctuations is much greater for Mauritania than for Senegal (coefficient of variation: 71% for Mauritania and 35% for Senegal), both seasonal patterns exhibit similar tendencies. The similarity of climatic conditions provides an indicator for estimating crop conditions in Mauritania using the Senegal model.

The third approach for assessing crop production in the sub-Saharan area is provided by analyzing long-term records of meteorological data associated with the crop calendar information to develop a yield index for each year. This was done for Senegal, Niger, Sudan, Mali, Chad and Upper Volta. Comparisons of yield estimates and yield indices indicated good relationships for Senegal, Niger and Sudan. The yield indices are expressed in terms of percentile rankings of the crop moisture ratio for both the vegetative and reproductive stages. The results indicate that this qualitative technique of estimating crop conditions during successive stages provides a feasible method of crop assessment using meteorological data and reliable crop calendar information.

Although it was found that moisture availability is the dominating factor in crop production, the influence of political, military, economic and other social events impacted on production in specific years.

An agroclimatic analysis of Kenya/Tanzania was performed to provide the framework for future investigations of climate-agriculture relationships in drought-prone countries of Africa, south of the equator. Preliminary results are reviewed. A qualitative analysis of historical yield indices during the growing seasons are presented to provide insight into recent agroclimatic conditions in Kenya/Tanzania.

Rangeland Index

Results of the development of climatic indices for assessment of rangeland conditions are presented for four regions of the northern Sahel. Because of data limitations, percentile rankings of cumulative precipitation have been determined to provide qualitative information on grasslands used for livestock grazing. Quantifying vegetative information and/or carrying capacity for these rangelands is an important component of this work that needs to be pursued.

Precipitation Analysis

A precipitation analysis for the period 1968-1975 was made for 813 stations in 11 western and central countries throughout sub-Saharan Africa. The isohyetal analysis for each year clearly demonstrated the adverse climatic conditions for agricultural production activities.

In Nigeria, the analysis of long-term rainfall series for a comprehensive set of recording stations was completed. The purpose of this analysis is to examine the regional comparisons of rainfall patterns in the northern Sahelian zone with those of more humid tropical zones

to the south. The objective is to provide a better understanding of possible mechanisms of rainfall variation in the semiarid region of West Africa. The results indicate a relatively strong relationship between the position of the ITCZ and regional rainfall patterns.

Crop Calendars

Information on crop regions and growing seasons was gathered throughout the entire period of the project. This information was assembled by country to provide estimated fixed crop calendar information on important subsistence food crops. The fixed calendar refers to normal growing conditions. This calendar must be adjusted according to seasonal rainfall patterns. This information along with maps of generalized crops regions can be used for operational assessment purposes.

Proposed Operational Assessment Program for Central Africa

The agroclimatic techniques presented in this report can be used to provide readily usable qualitative information on potential crop yields with "real-time" monthly meteorological data for weather-crop impact statements. If a complete data set is not available for all stations used in a specific model, an initial assessment can be made, and "revised" assessments made when more complete data become available. These assessments should be used to complement other sources of information such as field observations, sampling surveys, agricultural attache reports and AID Mission sources.

Concluding Remarks

The results of this project demonstrate the feasibility of using climatic and agronomic data for operational assessment of crop conditions in the drought-prone countries of sub-Saharan Africa. It is recommended that: 1) Follow-on work include the testing and evaluation of all models when and if qualified yield data are acquired and accurate appraisals of actual field conditions by knowledgeable persons are made. Where feasible, revised yield estimates from countries of interest should be used for independent testing of the regression models; 2) Assembled crop calendar information in this report be verified and improved, if possible; 3) Vegetative information and/or carrying capacities of the rangeland regions be quantified. The modification of existing rangeland models, developed in high technology regions, may be one possibility for refinement of the rangeland analysis. A further recommendation would be to study the feasibility of satellite data to support rangeland assessments.

The objectives of this project were met. A comprehensive meteorological data set for sub-Saharan Africa, north of the equator, is published in a separate report. These data represent an exhaustive search for meteorological data from sources both in the United States and in Africa. The data were checked for control of data quality. In some instances, questionable data were found. Agroclimatic techniques were developed which can be utilized in an early-warning assessment program.

WEATHER-CROP YIELD RELATIONSHIPS IN DROUGHT-PRONE COUNTRIES OF SUB-SAHARAN AFRICA

		Page
	LIST OF TABLES	i
	LIST OF FIGURES	ii
I.	INTRODUCTION	1
II.	BACKGROUND	4
	A. Climate	4
	1. General	4
	2. Impact of Recent Meteorological Drought	7
	B. Tropical Agriculture	9
	1. General	9
	2. Specific Crops Grown in Central Africa	12
	3. The Importance of Crop Calendars	17
	C. Sahelian Rangelands	19
	1. Vegetation	19
	2. Vegetative Deterioration	22
	3. Livestock	23
	4. Migratory Patterns	25
	D. Plant-Water Relationships	26
III.	METHODOLOGY	34
	A. Data Requirements	34
	1. Reporting Procedures	35
	2. Specific Data Problems	36
	B. Regional Overview	37
	C. Modeling Techniques	39
	1. Traditional Linear Regression Approach	39
	2. Analogue Model Approach	45
	3. Historical Yield Indices	46
	D. Crop Moisture Ratio	47

10

Page

IV. RESULTS AND DISCUSSION 59

A. General. 59

B. Precipitation Analysis: 1968-1975 60

C. Climate-Crop Yield Models. 74

D. Analogue Models. 105

E. Historical Yield Indices 110

F. Rangeland Indices. 118

G. Special Studies. 129

1. Kenya/Tanzania Agroclimatic Survey 130
2. Nigeria: Long-Term Rainfall Analysis. 140

H. Crop Calendars 150

I. Proposed Operational Assessment Program for Central Africa 157

1. Background 157
2. Operational Utility of the Weather/Crop Yield Relationships in Central Africa. 159

V. SUMMARY. 163

VI. DATA SOURCES 166

A. Meteorological Data. 166

B. Agricultural Data. 169

C. Regional Surveys 170

References 172

Appendix I: Listings of National Reporting Stations

Appendix II: Listings of National Monthly Rainfall Data by Station ID

Appendix III: Listings of WMO Mean Monthly Temperature and Total Monthly Precipitation Data by Year

LIST OF TABLES

Table		Page
3.1	Dates of Independence and Military Coups for Selected African Countries.	38
3.2	Chronological List of Major Events in Select African Countries	40
4.1	Weather-Crop Yield Models for Central Africa.	75
4.2	Nigeria Rainfall Stations Grouped by Region	143
4.3	Nigeria Annual Rainfall, Percentage Departures from Normal (1927-1976)	147
4.4	Estimated Fixed Crop Calendar Information for Cereal Crops/Pulses/Oil Crops	156
4.5	List of World Meteorological Organization (WMO) Stations.	167

12

LIST OF FIGURES

Figure		Page
2.1	Recent trends in Sahelian countries (Mauritania, Senegal, Mali, Upper Volta, Niger and Chad) taken from Winstanley (1976): A) Percent of normal (1931-1960) May-September rainfall in the Sahel; B) Comparison of total food production for the World, in general, and the Sahel; C) Total estimated number of livestock in the Sahel; and D) Population of the Sahel.	8
2.2	Normal isohyet patterns and ecological zones of West Africa taken from Matlock and Cockrum (1974).	21
3.1	Typical seasonal rainfall and potential evapotranspiration patterns during the wet season in Sub-Saharan Africa	49
3.2	Crop moisture requirements expressed in terms of the ratio of actual evapotranspiration to potential evapotranspiration for successive growth stages of a cereal crop (e.g., millet, sorghum and maize).	51
3.3	Average monthly rainfall patterns for Upper Volta, Senegal, Niger and Sudan	53
3.4	Average monthly potential evapotranspiration patterns for Upper Volta, Senegal, Niger and Sudan	54
3.5	Relationship between millet crop yield and crop moisture ratio (CMR) for the vegetative growth stage in Upper Volta, Sudan, Senegal and Niger	55
3.6	Same as Figure 3.5 for the reproductive growth stage.	56
4.1	Map of West African countries in which regional precipitation data were obtained and analyzed.	61
4.2	Map of West Africa depicting the wide variation in the 300-400 mm isohyet zone between 1958 and 1973	63

13

LIST OF FIGURES (cont.)

Figure		Page
4.3	Annual rainfall patterns expressed in terms of percentage departures from normal for West Africa in 1968. Hatched areas indicate greater than 30% below normal. Normal 300 mm, 500 mm and 900 mm isohyets are included.	65
4.4	Same as Figure 4.3 in 1969	66
4.5	Same as Figure 4.3 in 1970	67
4.6	Same as Figure 4.3 in 1971	68
4.7	Same as Figure 4.3 in 1972	69
4.8	Same as Figure 4.3 in 1973	70
4.9	Same as Figure 4.3 in 1974	71
4.10	Same as Figure 4.3 in 1975	72
4.11	Map of Senegal depicting major agricultural regions and 500 mm and 1600 mm isohyets.	78
4.12	Senegal rice model. Independent data for 1975 and 1976 were obtained from the West African Rice Development Association (WARDA), Monrovia, Liberia. Yield estimates for 1977 and 1978 are also included. . . .	80
4.13	Comparison of fluctuations in annual millet yields (top) and growth stage precipitation (bottom) for both the vegetative and reproductive (flower) stages in Senegal.	82
4.14	Senegal millet model with yield estimates for 1974 through 1978.	83
4.15	Senegal groundnut model with yield estimates for 1975 through 1978.	85
4.16	Senegal cowpeas model with yield estimates for 1975 through 1977.	86
4.17	Senegal corn model with yield estimates for 1974 through 1977	88

14

LIST OF FIGURES (cont.)

Figure		Page
4.18	Senegal/The Gambia regional millet model with yield estimates for 1975 through 1978.	89
4.19	Senegal/The Gambia regional rice model with yield estimates for 1975 through 1977.	90
4.20	Map of Niger depicting major agricultural regions and 500 mm and 700 mm isohyets	91
4.21	Comparison of fluctuations in annual millet yields (top) and growth stage precipitation (bottom) for both the vegetative and reproductive growth stages in Niger.	93
4.22	Same as Figure 4.21 for sorghum.	94
4.23	Niger millet model with yield estimates for 1975 through 1977	95
4.24	Niger sorghum model with yield estimates for 1975 through 1977	96
4.25	Comparison of acreage planted to groundnuts and millet in Niger from 1961 to 1976.	97
4.26	Comparison of fluctuations in annual millet yields (top) and growth stage precipitation (bottom) for both the vegetative and reproductive (flower) stages in Sudan	99
4.27	Sudan millet model with yield estimates for 1976 and 1977	100
4.28	Sudan sorghum model with yield estimates for 1976 and 1977	101
4.29	Sudan sesame model with yield estimates for 1976 and 1977	102
4.30	Nigeria sorghum model with yield estimates for 1976 and 1977.	104
4.31	Mali analogue model using the Senegal vegetative model and Niger reproductive (flower) model to generate indicators of relative millet yield estimates.	107

15

LIST OF FIGURES (cont.)

Figure		Page
4.32	Comparison of total rainfall (cm) for July and August between Senegal and southern Mauritania	109
4.33	Historical yield indices, expressed in terms of percentile rankings of the crop moisture ratio (CMR), for both the vegetative stage (top) and the reproductive stage (bottom) of millet grown in Senegal. The numbers on the right-hand side represent the following: 1, well-above normal; 2, above normal; 3, near-normal; 4, below normal; and 5, well-below normal	112
4.34	Same as Figure 4.33 for millet grown in Niger.	113
4.35	Same as Figure 4.33 for millet grown in Sudan.	114
4.36	Same as Figure 4.33 for millet grown in Mali	115
4.37	Same as Figure 4.33 for millet grown in Chad	116
4.38	Same as Figure 4.33 for sorghum grown in Upper Volta.	117
4.39	Regional divisions of the Sahelian rangelands.	120
4.40	Precipitation normals for Regions One and Two for 1951-1977.	122
4.41	Precipitation normals for Regions Three and Four for 1951-1977.	123
4.42	Historical rangeland indices expressed in terms of percentile rankings of the following variables: 1) cumulative January through September precipitation; 2) combined August through October precipitation; 3) cumulative January through October precipitation; and 4) annual precipitation for Region One.	124
4.43	Same as Figure 4.42 for the variables: 1) cumulative January through August precipitation; 2) cumulative January through September precipitation; and 3) annual precipitation for Region Two	126

16

LIST OF FIGURES (cont.)

Figure		Page
4.44	Same as Figure 4.42 for the variables: 1) cumulative January through August precipitation; 2) combined July and August precipitation; and 3) annual precipitation for Region Three	127
4.45	Same as Figure 4.44 for Region Four.	128
4.46	Map of Kenya/Tanzania showing the complex topographic and agroclimatic features of the area. Normal seasonal rainfall distributions are shown for various regions as well as the 500 mm and 1,000 mm isohyets. . . .	131
4.47	Historical yield indices expressed in terms of percentile rankings of the crop moisture ratio (CMR) for both the early period (top) and the late period (bottom) for cereals grown during the primary growing season in the Central Region of Kenya.	134
4.48	Same as Figure 4.47 for cereals grown during the secondary growing season in the Central Region of Kenya.	135
4.49	Same as Figure 4.47 for cereals grown during the primary season in the Coastal Region of Kenya/ Tanzania	136
4.50	Same as Figure 4.47 for cereals grown during the secondary growing season in the Coastal Region of Kenya/Tanzania	137
4.51	Same as Figure 4.47 for cereals grown in the Tabora Region of Tanzania	138
4.52	Same as Figure 4.47 for cereals grown in the Ruvuma Region of Tanzania	139
4.53	Map of Nigeria showing the normal seasonal rainfall distribution for the North, Central, Southwest, and Southeast regions as well as the normal 500 mm, 700 mm, 900 mm, and 1100 mm isohyets	142
4.54	Annual rainfall series for the period 1927-1976 for the North, Central, Southwest, and Southeast regions of Nigeria	145

17

LIST OF FIGURES (cont.)

Figure		Page
4.55	Regional maps of Senegal, Mauritania, Mali, and Upper Volta (top), and Niger, northern Nigeria, and Chad (bottom) showing the predominant regions of cereal/ cash crop production	151
4.56	Regional maps of Sudan (left) and Ethiopia and Somalia (right) showing the predominant regions of cereal/ cash crop production	152
4.57	Regional maps of Zambia (left) and Kenya and Tanzania (right) showing the predominant regions of cereal crop production	153

18

CHAPTER I

INTRODUCTION

Over half of the world's population lives in the tropical regions of the world. The majority of these people are engaged in agricultural production activities. Tropical agriculture is largely controlled by climatic conditions which are generally unfavorable for high crop yields. Nieuwolt (1977) presents a discussion of the climatology of tropical regions. Among the adverse climatic factors, rainfall is the principal controlling element in agriculture. The total amount of rainfall determines the type of crops grown in specific regions. The seasonal distribution of rainfall regulates the crop calendars. Finally, rainfall variability is responsible for fluctuations in crop production.

In Africa there has been a dramatic downward trend in levels of food self-sufficiency over the last 15-year period. The decline in agricultural production has been a reflection of both a general decline in total annual rainfall patterns as well as large year-to-year fluctuations in rainfall. The lower rainfall totals of the most recent decade have had a catastrophic impact on the economies and social structures of these countries. The impact of drought has been compounded by population increases.

The drought-prone countries of Central Africa extend across the full width of the continent between the latitudes of 10 and 20 degrees N. This region is bordered on the north by the Sahara Desert. In East Africa rainfall-deficient zones extend southward toward the equator. The entire region of limited and variable rainfall is referred to as Central

Africa in the text. Agriculture in these regions depends upon the limited and highly variable rainfall during the summer growing season.

Human activity and food production patterns have adapted to the seasonal rainfall patterns. Both sedentary farmers and seminomadic herdsmen have attempted to exist in a delicate balance with this marginal climatic regime. The severity and extent of prolonged drought conditions during the recent decade as well as human mismanagement of the land have both resulted in sharp decreases in the level of agricultural production. Subsistence farmers have been forced to extend cultivation into the more marginal lands in an attempt to feed the increasing population. The resulting competition between seminomadic herdsmen and sedentary farmers for these marginal lands has resulted in degradation of the land. Overgrazing on the fringes of the Sahara Desert has further intensified desertification. Thus, the impact of highly variable rainfall patterns on agricultural activities is not only reflected in terms of severe fluctuations in crop yield but also in terms of broad socioeconomic implications.

For these reasons, the Center for Environmental Assessment Services (CEAS/NOAA), in cooperation with the University of Missouri Atmospheric Science Department, has undertaken a project for the Agency of International Development (AID/OFDA) to study the yearly variability in crop yields based upon monthly meteorological data, and utilizing several agroclimatic techniques.

The objectives of this US/AID/OFDA sponsored project, "Weather-Crop Yield Relationships in Drought-Prone Countries of Sub-Saharan Africa", include:

- the development of a meteorological data base to systematically study the climate and its relation to drought/food production problems and

- the development of agroclimatic techniques, including climate/crop yield models, historical yield indices and crop calendars, which can be utilized on an operational basis for input into a systematic early-warning assessment program for subsistence food crops in these countries.

The purpose of the final report is to summarize the results of the project.

CHAPTER II

BACKGROUND

A. Climate

1. General

The climate of the central African region south of the Sahara Desert is characterized by relatively well-defined, alternating dry and humid seasons. The seasonal rainfall distribution regulates the agricultural calendar of the region. Most agricultural production activity coincides with the summer rainy season which is governed by the position of the Intertropical Convergence Zone (ITCZ). The ITCZ represents the boundary between the hot, dry Sahara air of anticyclonic origin moving south and the cooler, moister maritime air moving north. The summer position of the ITCZ fluctuates greatly both aperiodically and diurnally (Trewartha, 1961). Typically, rainfall is sporadic in frequency, duration and location. Consequently, rainfall variability is a main factor responsible for fluctuations in crop yields.

There is a clear tendency for a zone of maximum rainfall to follow the overhead position of the sun with a delay of about one month (Nieuwolt, 1977). This tendency is particularly well developed over East Africa where the seasonal movements of the ITCZ are large. The movement of the ITCZ is less clear in West Africa. For example, the differential heating between the ocean and the continent along the west African coast delays the southward retreat of the ITCZ so that the rainfall distribution during the wet season in Senegal and the Gambia is often anomalous to the rainfall pattern in countries further inland,

22

(Davy et al., 1976). The seasonal distribution shows a definite zonal pattern, with a double maxima near the equator and a single maximum at latitudes greater than 10 degrees during the period when the sun occupies a relatively high position in the sky (Griffiths, 1972). The zonal rainfall pattern is disrupted rather sharply in the highlands of East Africa, however. Topography has a marked influence on rainfall in this region (Johnson, 1962). The climate of East Africa is further complicated by the presence of a number of large lakes which influence local precipitation patterns (Vowinckel and Orvig, 1979).

The duration of the rainy season has a strong influence on the vegetation and controls the agricultural growing season. In the vast region of Central Africa stretching from about 10° to almost 20°N and from the Atlantic Ocean in the west to the Ethiopian highlands in the east, the most common feature of climate is the gradual decrease in both the length of the rainy season and the total amount of rainfall with latitude. The length of the wet season decreases from about five months at 10°N to two or three months at 18°N. The total annual rainfall correspondingly decreases from over 1,000 mm in the south to less than 200 mm in the north.

In July and August the ITCZ is at its most northerly position, at about 15-20°N. Southwesterly winds invade the continent. The air masses associated with these winds are warm and humid. Rainfall amounts are greatest during this period in the northern regions. From September to November, the ITCZ moves southward, usually in an irregular fashion. The rainy season ends during September in the north and during October in the south. From October to June, the region of Central Africa

located north of the equatorial zone is largely under the influence of northeasterly trade winds. These winds are associated with dry, continental air masses which often carry dust from the desert regions. These hot, dry winds are often referred to as the 'harmattan' in many parts of West Africa (Nieuwolt, 1977). This is the dry season in sub-Sahara Africa north of the equator.

As noted, latitudinal differences in climate, which are governed by the seasonal migration of the ITCZ, are of considerable magnitude. The ITCZ also differs strongly in longitude. In the western part of tropical Africa the ITCZ hardly ever moves south of the equator, while in the east it may reach latitudes around 20°S. A primary reason for the different migratory pattern of the ITCZ between the eastern and western parts of tropical Africa is the contrast in sea surface temperatures (Nieuwolt, 1977).

In the east, the Mozambique Channel has surface water temperatures around 23-27°C, whereas in the west the Atlantic Ocean, cooled by the Benguela Current, has surface temperatures around 16-18°C. The difference in water surface temperatures influences the air masses which move from the oceans over the continent. The cooling effect of the Benguela Current keeps the ITCZ from moving southward during the southern hemisphere summer on the western side of equatorial Africa. As a result, both the duration of the rainy season and the mean annual rainfall decrease not only with distance southward from the equator, but also from east to west along the equatorial zone.

In East Africa, areas close to the equator have two wet seasons--April through May and October through November. This seasonal pattern

prevails between approximately 5°N and 4°S. Over most of the area, the April-May wet season brings more rainfall because the ITCZ is usually very broad and moves slowly northward. This season is referred to as "the long rains". The October-November wet season is called "the short rains" because the ITCZ generally moves faster on its southward journey, particularly in the east.

Further away from the equator (latitudes greater than 4°S), one rainfall season prevails beginning usually in December and ending in April. Rainfall variability over East Africa is high, not only in total amount but also in the time of arrival. During March and April the ITCZ begins its migration northward resulting in a dry season from May to November in Africa south of the equator. This region is influenced by southeasterly trade winds during this period.

2. Impact of Recent Meteorological Drought

Short-term climatic fluctuations can have a serious disruptive effect on the interdependency between nomadic and sedentary agricultural economies. The impact of climatic anomalies on subsistence agriculture has been demonstrated in the last decade. Central Africa has suffered a number of exceptionally dry years since the mid-1960's. Glantz (1977) noted that in 1973 there were more than 100,000 human deaths, and up to 40% of the livestock died in the Sahel as a result of the drought.

The climate in the Sahel-Sudan region is marginal for crop production and pastoralism. Persistent drought extending over entire countries has a disastrous effect on national economies. Figures 2.1 a, b, c, and d present recent trends in rainfall, food production, livestock and

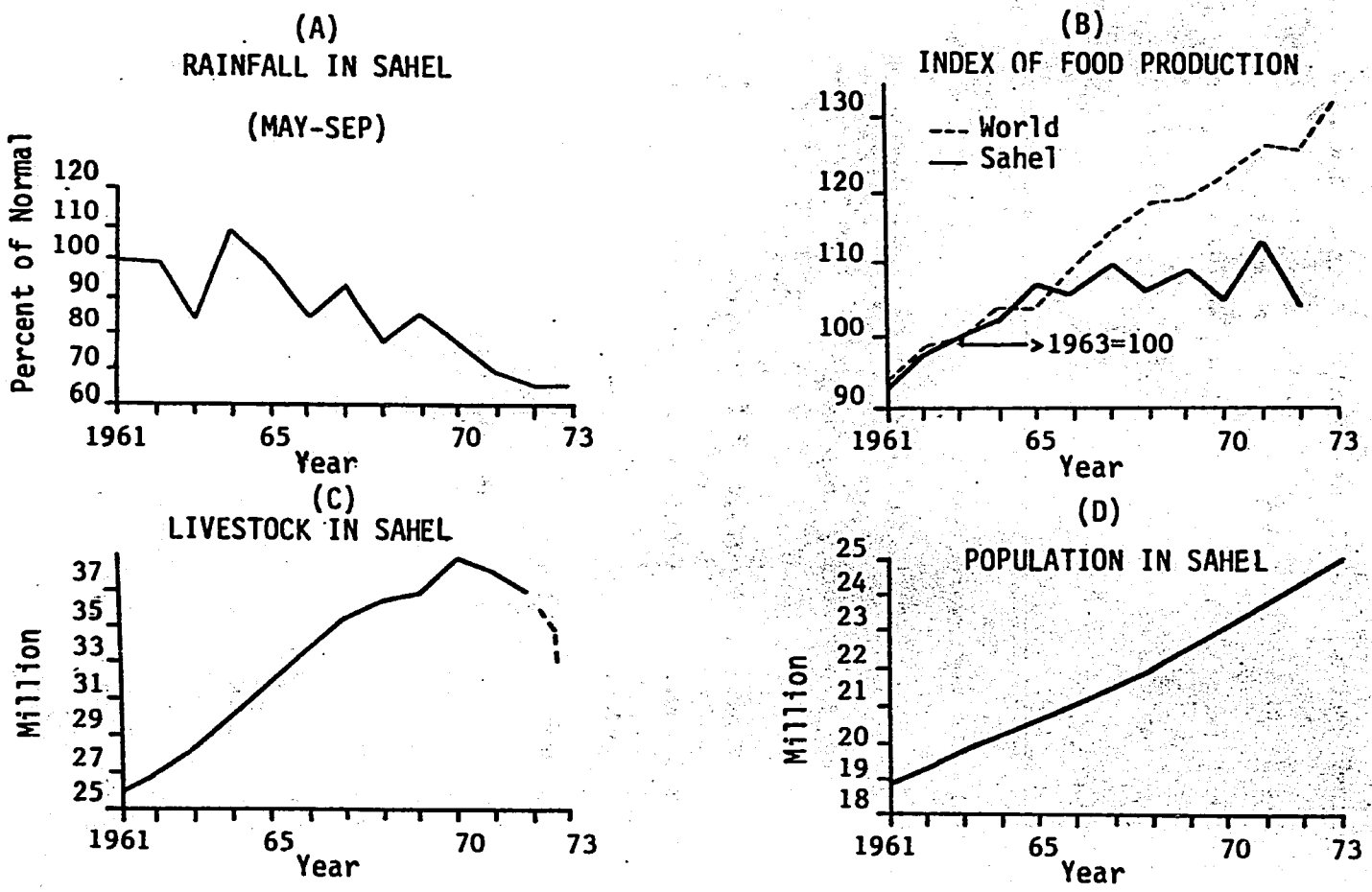

Figure 2.1. Recent trends in Sahelian countries (Mauritania, Senegal, Mali, Upper Volta, Niger, and Chad) taken from Winstanley (1976): A) Percent of normal (1931-1960) May-September rainfall in the Sahel; B) Comparison of total food production for the world, in general, and the Sahel; C) Total estimated number of livestock in the Sahel; and D) Population of the Sahel.

population, respectively, in the Sahelian countries (after Winstanley, 1976). Beginning in the mid-1960's annual rainfall showed a decreasing trend and large yearly fluctuations (Figure 2.1 a). The index of food production (Figure 2.1 b) leveled off and also began to fluctuate considerably. This increased variability corresponded with the beginning of the prolonged drought period. With continued water shortages and a general degradation of the environment resulting in overgrazing, livestock losses increased significantly after 1970 (Figure 2.1 c).

The impact of the prolonged drought was compounded by the continued population increase throughout this period (Figure 2.1 d). As a result, severe food shortages were caused by the prolonged period of deficit rainfall. The severity of the meteorological drought and its impact on food production in central Africa will be demonstrated in this report.

B. Tropical Agriculture

1. General

Agriculture is the dominant economic activity in the tropical regions of the world. In spite of the great labor input, however, the tropics are noted for low agricultural productivity. For example, the yield potential of cereal crops grown in the tropics is substantially lower than that of crops grown in the temperate zone. The low agricultural productivity has been attributed primarily to four major constraints of the physical environment (Chang, 1977). These constraints include: 1) potential photosynthesis as determined by the radiation and thermal regimes; 2) soil fertility; 3) pests and diseases; and 4) water deficit.

Agricultural production activity corresponds primarily with the wet season. During this period, solar radiation intensity is relatively low, day length is much shorter than in higher latitudes (e.g., summer growing season in northern latitudes) and temperatures, particularly minimum temperatures at night, are high. These factors contribute to lower rates of photosynthesis in the tropics compared to those in the temperate zone. Consequently, the yield potential is relatively low for most cereals and other subsistence crops in the tropics due, in part, to the radiation and thermal regimes.

Most tropical soils are low in fertility. Liberal and proper application of fertilizers is essential for maintenance of soil fertility. However, tropical countries consume only about 10 percent of the world's total fertilizers; the lowest application rate per hectare of cropland is found in Africa. The cost of fertilizers is not the only factor that limits their use in the tropics. The sporadic and heavy showers which are characteristic of the wet season tend to wash away fertilizers. Further, the effectiveness of fertilization may also be limited by drought. As a result, the effect of technology on agricultural production has been minimal and proper management procedures to maintain soil fertility have been difficult to practice.

In fact, the transfer of technology may not have the expected benefits when applied to subsistence agriculture in tropical Africa. Although traditional techniques do limit the productive capacity of the cropping system, these farming methods may have helped maintain an equilibrium between the farmer and the environment. Such farming techniques may have an important role in this particular type of agricultural system found in semiarid regions of Africa.

For example, mixed cropping provides a means of extending the vegetative cover for a longer period of time thereby reducing the potential adverse effects of soil erosion by wind and rain and soil heating. Mixed cropping also reduces the risk of single-crop failure due to parasite infestation. Denshering, the practice of burning crop residues in the soil, has been shown to improve crop yields.

Pests and diseases are also major problems for agriculture in the tropics. The environmental conditions of the tropics are favorable for the multiplication of a wide variety of pests, insects and diseases which have caused substantial reductions in crop yield. For example, in many countries in Africa, the Quelea grain-eating bird causes severe losses in sorghum and millet production. Locust infestations often ruin crops grown in the agricultural region of East-Central Africa. The locust problem has been addressed by Muller (1976). Specific crops such as cowpeas are plagued by insect pests and several leaf diseases.

Finally, the efficiency of water use for the production of organic matter is low in the tropics. Stanhill (1960) found that the water use efficiency, defined as the ratio of photosynthesis rate to evapotranspiration rate, was two or three times higher for grass grown in the temperate zone than in the tropics. Photosynthesis is a function of solar radiation (photosynthetically active radiation) whereas evapotranspiration is a function of net radiation. Net radiation is the difference between total upward and downward radiation fluxes. It is a measure of the energy available at the ground surface to drive the processes of evaporation, air and soil heat flux and other smaller energy-consuming processes (Rosenberg, 1974).

Theoretically, with the relatively low intensity of solar radiation in the tropics, greater amounts of water would be required to produce the same water use efficiency, or, in other words, to produce the same crop yield. Water deficits, defined as the difference between the effective rainfall and potential evapotranspiration, are large in the tropics. There are large areas of cropland in tropical Africa, for example, where annual water deficits are comparable to those of deserts in the temperate zone (Chang, 1977). In some areas of the tropics irrigation has lessened the severity of water deficits during the growing season. However, in Africa, less than 5 percent of the cultivated land is irrigated (Chang, 1977). The potential for future irrigation acreage is not only dependent upon the availability of water but also upon economic feasibility. Water deficit, due to the lack of sufficient rainfall, is the most limiting factor for crop growth in the sub-Saharan region of Africa (Salter and Goode, 1967; Winstanley, 1977). Marginal cropland areas with relatively low rainfall concentrated into a short wet season are the most drought prone.

All of these environmental constraints reduce the potential yield of crops grown in the agricultural regions south of the Sahara Desert. Moreover, large yearly fluctuations in crop yield are characteristic of this climatic regime.

2. Specific Crops Grown in Central Africa

The specific crops that are grown in the drought-prone region of Central Africa, south of the Sahara Desert, can be divided into two groups: 1) the subsistence food crops and 2) the cash crops. The

subsistence crops include such cereals as millet, sorghum, maize and, to a lesser extent, rice. Cowpeas are an important annual legume crop which provide food for both human and animal consumption. Groundnuts are a major cash crop throughout the region. In addition, sesame is an important oil crop in Sudan.

In the aggregate, the ratio of food to cash crop acreage is 7-10 to 1 (Becker, 1974). The only exceptions might be in Senegal and Sudan where the acreage is more evenly divided between subsistence food production and export cash crops. The northern-most limit of all these agricultural crops, under rain-fed conditions, is roughly the isohyet for 350 mm annual rainfall.

Cropping patterns have followed a traditional format. Agricultural surveys of the Sahel-Sudan region of Africa have indicated that 45-50 percent of agriculturally-used land is planted exclusively with cereals. Another 45 percent is planted with cereals in combination with cowpeas and groundnuts or other cash crops (Becker, 1977; Arnon, 1972; Murdock, 1960).

A brief discussion of the major crops grown in Central Africa follows.

a. Millet and Sorghum

Bulrush or pearl millet is grown throughout the entire region and is the dominant crop in the Sahel. Millet is usually planted to coincide with the wet season. In fact, the length of the growing season for millet is dictated by the length of the wet season. It ranges from the short-cycle 95 day variety to the long-cycle 150 day variety. Thus, the varieties of millet are well adapted to the needs of subsistence agriculture in a

particular climatic zone. Millets are the earliest maturing and most drought-resistant of the cereal grain crops.

All types of millet can endure drought periods of two to three weeks (Arnon, 1972). The crop is especially drought-resistant before flowering. However, severe moisture stress during the reproductive stage can have a disastrous effect on yield. Heavy rains during the flowering stage may interfere with fertilization and also cause reduced yields.

Sorghum is not as drought-resistant as millet. Therefore its northern limit of cultivation in Central Africa, north of the equator, is further south than that of millet. Sorghum provides a major source of food for a large portion of the population in the semi-arid regions of Africa. In fact, it has been considered to be the leading crop of the continent as a whole (Murdock, 1960). Sorghum, like millet, does have the ability to withstand severe drought lasting up to fourteen days during the vegetative stage without serious injury to the plant (Glover, 1959).

b. Rice

Rice is the second most widely grown cereal in the world. It is primarily grown in regions where annual rainfall is 1000 mm or more. In the Sahel region of Central Africa, therefore, significant rice production is concentrated only in specific regions, including the Casamance Region of Senegal and along the Niger River in Mali and Niger. The length of the growing season for rice varies from 90 to 260 days.

The rice crop requires high temperatures, ample light and adequate moisture for optimum productivity. Rice needs an adequate water supply

32

during its initial and early stages of growth. Sunlight becomes increasingly important as the plant develops. The panicle differentiation stage marks the beginning of the critical light-requiring period which lasts until maturity (Arnon, 1972). However, if the crop dries out too quickly during the maturation stage yields will be reduced. Therefore, timing of rainfall is critical if the crop is grown under rainfed conditions.

c. Cowpeas

In Africa cowpeas are an important pulse crop grown particularly in regions of low rainfall. Not only do they provide a high protein food, but they also offer a means of improving the nitrogen fertility status of the soil. Cowpeas are a drought-resistant crop; however, moisture deficiencies have an adverse effect mainly on vegetative growth while seed production is less affected.

Cowpeas are grown almost exclusively as a ground cover crop together with millet and sorghum. The growth of cowpeas remains retarded until the cereals are harvested (Arnon, 1972).

d. Groundnuts

Groundnuts are a major cash crop throughout Central Africa. Until the recent prolonged drought period, Senegal was ranked as the 5th leading exporter of groundnuts. Abundant sunshine is essential throughout the growing season for both plant growth and fruit production (Yao, 1973). Groundnuts bear fruit below the ground surface. The plant is considered to be drought-resistant during vegetative growth, but drought during fruit production is harmful.

The plant does not use much soil moisture in the first six to eight weeks after planting. However, water availability becomes crucial, particularly in the upper inches of the soil during the period of pod and seed development. During the final weeks before maturation only a small amount of water is needed for fruit development. If available moisture in the topsoil has been near zero for more than six to ten consecutive days, groundnut production will be reduced (Yao, 1973).

e. Sesame

Sesame is one of the important oil crops of traditional agriculture in dry climates. It is grown widely in Sudan, a major exporting country. The sesame crop has high heat and light requirements and is sensitive to low temperatures. Growth and fruiting are favored by temperatures around 27°C (Arnon, 1972). The plant is very drought-resistant. A minimum of 400 mm of rainfall is sufficient to support the dryland crop. Sesame grows better on sandy rather than heavier clay soils, probably because of its sensitivity to excess soil moisture.

The sesame crop has a short growing season. Flowering begins about four weeks after seedling emergence. The seeds mature about 60-70 days after flowering.

f. Maize

Maize is grown where the mean temperature is greater than 19°C and where the average night time temperature remains above 13°C. Excessively high temperatures and low air humidity at the time of pollination, however, have adverse effects on pollination and fertilization. The critical high temperature affecting yields appears to be 32°C. Maize generally requires sufficient moisture to wet the soil to field capacity down to the root

depth before planting and a minimum rainfall of 375 mm during the growing season (Arnon, 1972). Thus, the combined effects of high temperature and low precipitation are major factors in limiting the areas devoted to rain-fed maize in the Central African region.

Maize is more drought-resistant in the early stages of growth after seedling emergence. Peak requirements for moisture occur during the reproductive stage. Moisture deficiency during this stage will seriously affect yield. Maize cannot tolerate extended periods of drought like sorghum and millet. As a result, although emphasis on maize production has increased during the recent decades, yields have been highly variable due to the large seasonal fluctuations in climate.

3. The Importance of Crop Calendars

Seasonal climatic fluctuations regulate the agricultural calendar within specific regions. Under rainfed conditions in semiarid regions, crop development is particularly sensitive to moisture conditions as noted in the general review of the specific crops. Crop yields are, therefore, directly related to rainfall patterns throughout the growing season (Koli,1970). Thus, crop calendar information is essential in the crop-weather analysis. The Foreign Agricultural Service of the USDA has summarized general planting dates and harvesting periods for major crops grown in specific regions of Africa. The WMO has also provided a generalized agroclimatological survey of the Sudano-Sahelian zone of West Africa (Special Environmental Report No. 9, WMO No. 459).

The influence of the sowing date on crop yield has been found to be particularly important for crops grown in Central Africa. The planting

date is dictated by the onset of the wet season. Akehurst and Sreedharan (1965) reported that if sowing is delayed by two weeks after the optimum date in tropical Africa, drought may reduce the yield by as much as 50 percent. Koli (1970; 1973) and Dogget (1970) also estimated that sorghum and maize yield losses, respectively, were as high as 40 percent when plantings were either two weeks too early or two weeks too late relative to the optimum planting dates.

Several field studies have been carried out in Central Africa to determine the influence of sowing date on the yield of sorghum, millet and maize (Koli, 1973; Ganry, 1973; and, Dogget, 1973; Jones and Stokinger, 1973; respectively). Different high-yielding and low-yielding varieties were tested. Results showed that, in general, delayed planting significantly reduced yields, especially for higher yielding varieties. The reduction in yields was attributed to conditions during the flowering stage of crop development. Observations showed that the time from sowing to flowering decreased with delay in planting date. The growth period decreased by one to two weeks with every two-week delay in planting for sorghum (Koli, 1973).

Ganry (1973) provided a plausible explanation for the significant decrease in millet yield with delayed planting by studying the biological activity of the soil, characteristic of the Sahelian zone. During the dry season there is an accumulation of carbon, not metabolized by the lethal effect of the dessication on the soil microflora during the dry season. The first rains trigger "explosive" biological activity in the soil which does not exceed 20 days. During this period of intense but short-lived activity the seedling grows in a strong biologically favorable

soil environment due to the accumulation of soil nitrogen. If sowing is delayed until after the overall biological activity becomes weak, the rapid decline in accumulated soil nitrogen may significantly reduce crop yields. This hypothesis has been partly confirmed by Ganry (1973) from experimental study.

Once the seedling has emerged, the period of photosynthetic accumulation becomes crucial for crop growth and development. This period of active growth is highly dependent upon favorable environmental conditions throughout the growing season, particularly with regard to moisture availability. Thus, timing is critical. Subsistence agriculture is not only dependent upon the amount of rainfall during the wet season but also upon the onset of significant rains at the beginning of the crop season and the seasonal distribution of rainfall.

With the aid of the sources listed in Chapter VI, we have been able to document crop calendar information for specific crops grown throughout Central Africa. Basic knowledge of general planting and harvesting dates, length of crop growing seasons and phenological information is essential for crop-weather analysis. The acquisition of this qualitative agricultural information has been a significant component in the project. Specific crop calendars will be discussed in the results section.

C. Sahelian Rangelands

1. Vegetation

The Sahel is characterized by a gradient of vegetation types, ranging from sparse, stubby annual grasses in the north to more uniform, tall grasses in the south, with increasing densities of shrubs and trees

from north to south. The vegetative zones correspond roughly to the normal precipitation zones as indicated in Figure 2.2. In order to survive in this harsh environment, grasses are required to reseed, compete with weeds, resist diseases and insect destruction, and produce dry matter under adverse conditions. Most of the Sahelian grasses are ephemeral so that they mature quickly and produce seed at the end of the year to provide growth for the following year.

The northern grasses are generally short, about 40 cm high, and are interspersed with short scrubby bush. The drier parts of the Sahel support four types of plants: annuals such as cheat grass that only grows when there is water; shrubs that become dormant before wilting occurs; succulents such as euphorbias and cacti that store water in their tissues; and microflora such as mosses, lichens, and bluegreen algae that are dormant in the soils but respond quickly to cool or wet weather (Odum, 1963). The central and southern Sahel is scattered with acacia and other thorny narrow-leafed trees and bush. In the far south the trees are taller, and there are more broad-leafed deciduous plants, with grasses growing to about 80 cm in height.

Whether a plant germinates or not is highly dependent upon the first rains. After the first wetting of the soil, the germination proceeds very quickly and, due to a mineralization flush, young plants are well provided with nitrogen so that they can grow if soil water is not the limiting factor. Quite often more than one germination flush is needed to get any sustained growth (Stroosnijder, 1977).

The growth cycle of plants in the rangeland areas is very short. Plants of Eragrostit pilosa and Mollugo cerviana grow from seeds to

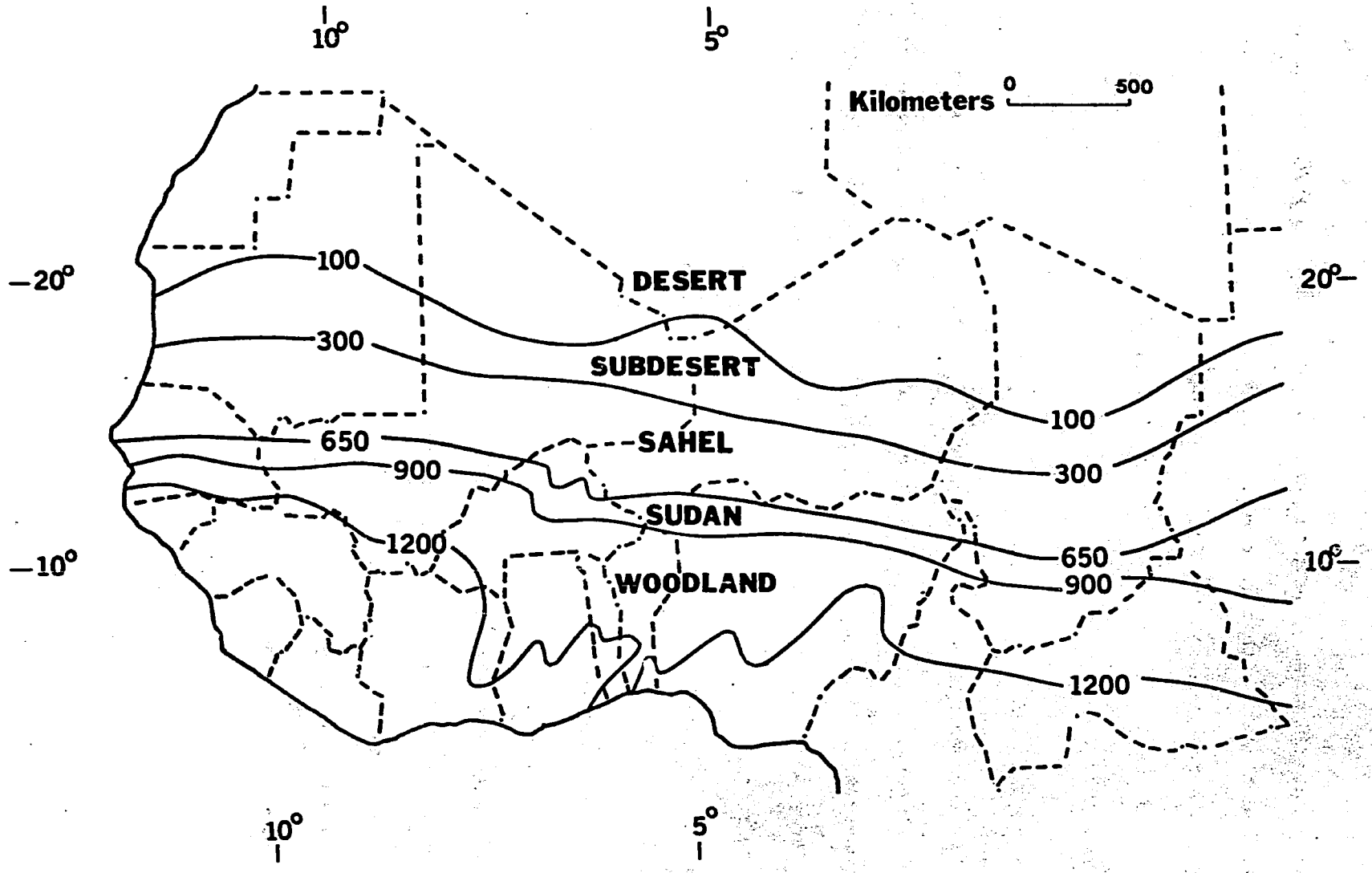

Figure 2.2. Normal isohyet patterns and ecological zones of West Africa taken from Matlock and Cockrum (1974).

flowers within 30 days. The gama grass Bouteloua aristidoides germinates, emerges and flowers within four weeks. Boerhoavia repens, a grass located on the southern fringe of the Sahara, has been observed to germinate, flower, and sow its seeds in the space of eight days (Cloudlsey-Thompson, 1977).

2. Vegetative Deterioration

The encroachment of the Sahara Desert southward has been largely due to the destruction of the ecological balance by human mismanagement. The process of forage and soil degradation caused by human negligence is called desertification. For a rangeland to be self-sustaining year after year, grasses must have 50 percent of volume by weight left at the end of the rainy season (Bell, 1973). Overgrazing is the single greatest cause of desertification not only in Africa but in all parts of the world.

Grasses need to store reserves at the end of the rainy period in order to survive the sequential dry season. Studies have shown that by cutting grasses too short and too late in the season, the chance of survival is greatly reduced. Defoliation of grasses greatly reduces their ability to take up water (Arnon, 1972). In a study conducted by Weaver (1950), the detrimental effects of overgrazing were two-fold: first, dry weight of the tops of weakened plants (overgrazed) were 32 to 84 percent less than plants with fair or good vigor and second, the new roots of weakened plants were shorter and less branched, with dry weights 28 to 94 percent less than the plants with good vigor.

It is estimated that as a result of poor management, the bulk of the rangelands produce less than half their potential yields. With

decreases in vegetation, there is an increase in weedy invaders that are generally unpalatable, some even poisonous (Terhune, 1978).

In a model developed by Picardi (1974) only a three year time constant was needed for overgrazing to result in severe vegetative deterioration. That is, in three consecutive years of overgrazing, almost 70 percent of the vegetation is destroyed. Soil erosion has a time constant of six years. Regeneration, on the other hand, is much slower, taking 20 years to regain two-thirds of the vegetation and 80 years to restore the soil to two-thirds its original condition (Odum, 1971; Kassas, 1970).

3. Livestock

Livestock production is maintained by three distinct groups: 1) the nomads who raise camels and goats and remain in the grazing areas north of the 300 mm isohyet lines; 2) the transhumant herdsman who raise predominantly cattle and sheep and migrate within the 200 to 600 mm precipitation zone; and 3) the semi-sedentary pastoralist who maintains crops and livestock in the 600 to 800 mm zone (Matlock and Cockrum, 1974; Davey et al., 1976). Goats and camels can thrive on areas overgrazed by sheep because they have the capability to utilize browse, or woody and spiny vegetation.

Cattle herds in the northern Sahel are generally comprised of Zebu cattle that have become well adapted through centuries of breeding and natural selection. They have more stamina for traveling long distances and greater resistance to the diseases and parasites of the dry tropics than do the European breeds (Glantz, 1976). They eat poorer quality

pasture, grow slower, have a longer interval between calvings, and reach maturity in seven years. In the southern Sahel, N'Dama cattle are raised which are resistant to the tsetse fly (May and McLellan, 1968).

Based on a model developed by Picardi (1974) for livestock raised in the Sahel, a 450 kg cow requires at least 7 kg of dry matter per day to merely maintain itself. Arnon (1972) and Bell (1973) stated that in order for a cow to produce milk or meat it needs between 12 to 18 kg per day. However, these figures may be misleading. Grasses found in the Sahelian rangelands have a low nutrient content compared to the quality of grasses or feed available to modern cattle raising systems. Matlock and Cockrum (1974) discussed the comparison of production systems. They indicated that whereas modern cattle raising systems require only about 8 kg of feed to produce 1 kg of meat, the ratio in the Sahel may be 20 to 1 or even higher.

Maintenance and/or production are determined by the amount of available grassland and the number of livestock per unit area. Because of the variety of animals that are grazed, "animal units" have been defined. Picardi (1974) defines one AU (animal unit) as 450 kg, equivalent to 0.77 camels, 1.67 cattle, 10 sheep, or 10 goats. Another stock unit, the UBT (Unite de Betail Tropical), has been discussed in the literature (see Davy et al., 1976).

Because of the problem of overgrazing and the low rainfall between 1968 and 1977, the carrying capacity of the Sahel has gained much attention. Siefert and Kamrany (1974) suggested a maximum sustainable stocking density for the Sahelian region of 0.047 AU/ha. The allowable carrying capacity, or that at which stock can exist without pasture improvement, was considered to be 0.057 AU/ha by Tyc (Picardi, 1974).

In comparing these ideal stocking densities to the actual population of the Sahel, it becomes evident that overgrazing is occurring. Based upon available figures for the entire Sahel in 1971, it was estimated that there were 12.6 million AU per 260 million ha, or 0.049 AU/ha (Tyc, from Picardi, 1974). In the Tahoua region of Niger there were an estimated 0.055 AU/ha in 1963 compared to 0.084 AU/ha in 1971 (Picardi, 1974). Using these figures, Picardi noted that in 1971 the sustainable stocking density was only 56 percent of the actual observed density. These estimates suggest that severe overgrazing was evident throughout the region. Two antagonistic patterns were developing simultaneously during this period. First, there was the sharp increase in livestock population throughout the 1960's due to increases in human population and a major livestock innoculation program. Second, the onset of drought conditions which began in the mid-1960's reduced the carrying capacity of the grazing lands. Therefore, a larger livestock population was required to graze on relatively less vegetated land. Consequently, severe overgrazing and intensified desertification resulted.

4. Migratory Patterns

Migration is an old and historically well controlled system of herd movement in search of water, food, and salt. In the dry season, the herds remain near points of permanent drinking water in the southern part of the Sahel. After the first rains, the cattle move to areas with fresh, protein rich annuals. In general, transhumance takes place in a south-north direction so that the moving herds follow the germination pattern which is dictated by the onset of the wet season. Thus, the

herds make optimal use of the continuous supply of fresh protein rich annuals. At the end of the rainy season a shortage of drinking water occurs in the remote northern areas and herdsmen bring the cattle back to the wintering places. The protein content of the annuals in these places is so low at the end of the growing season that the cattle cannot survive on this fodder alone, but need legumes, shrubs and trees for their protein balance (Stroosnijder, 1977).

There is nothing random about the migrations of the nomads. For example, the dry season finds the herds as far south as they can go without entering the range of the tsetse fly. There is then almost a symbosis between the nomads and the sedentary farmer. The nomads' cattle graze the stubble of the crops at the same time they fertilize the fields. In return, the nomads receive millet from the farmers. With the first rains, the grass springs up and the herds begin the northward migration. As the wet season p[illegible]hward during late spring and early summer, the catt[illegible]ind in search of new grazing areas (Cloudsley-Thor[illegible] done in Chad found that each group had its own tra[illegible]nerary and did not trespass on the grazing or wa[illegible]other nomadic or sedentary groups through which it must pass (Nelson et al., 1972).

D. Plant-Water Relationships

Water is an essential nutrient for plant growth. Some of the water absorbed by plants is used in photosynthesis. The movement of

44

water through the plant also provides an effective means of transportation for other nutrients to all parts of the plant. In addition, water provides a cooling mechanism for the plant as water vapor is transpired by the stomata of the leaves. The rates of various physiological processes are closely related to the internal water balance of the plant which, in turn, is dependent upon the relative rates of water absorption and water loss (Kramer, 1959).

Determining the water requirements of crops is essential for an understanding of plant-water relationships. It must be realized that plant water requirements are not constant. Both growth and transpiration (i.e., loss of water vapor from the plant through leaves) determine plant water requirements. Transpiration is influenced by the climate surrounding the plant. The rate of water loss is controlled by plant characteristics, and atmospheric and soil environment conditions. Any environmental factor which affects either growth or transpiration will have some effect on the water requirements of the plant.

Peak moisture requirements, critical stages of growth and optimum moisture levels are as important (if not more important!) as total seasonal water use. Most crops have certain key periods of development which require higher water use than other periods. Optimum moisture levels are also influenced by the crop, stage of growth, soil and climatic conditions. Optimum levels of moisture refer to the range required to get optimum yield. Optimum yield means both quantity and quality of the product.

A study of plant-water relationships is incomplete if consideration is not given to the hydrologic cycle. Precipitation and/or irrigation provides moisture to sustain life. A certain fraction of the precipitation

is directly intercepted by the plant canopy and evaporated without reaching the soil surface. Of that precipitation which reaches the surface, part infiltrates into the soil and part runs off, eventually finding its way to a stream. Some also evaporates from the soil surface.

Precipitation is intermittent whereas plants require a continuous supply of water for survival and growth. Thus, the ability of the soil to store usable water between rainfalls is of extreme importance to plant growth. Not all water that infiltrates the soil is usable. The amount of water that enters a soil during a storm depends upon the rate at which the soil can absorb water and the length of time water stands on the soil surface. Water continues to percolate downward in response to gravity even after precipitation ends, however. The rate of deep drainage decreases and becomes negligible over a period of time. The ability of the soil to store water is dependent upon the porosity of the soil. The total pore space of the soil depends upon the structure and texture of the soil (Baver, Gardner and Gardner, 1972). As the water content of the soil decreases, the remaining water is held by increasingly stronger adsorption and capillary forces. Thus, the energy state of soil water is also important.

The water balance of the soil-plant-atmosphere continuum can be described by:

$$P = ET + Q + U + \Delta W$$

P is the precipitation and/or irrigation; ET is the evapotranspiration; Q is the runoff; U is the deep drainage (or percolation) beyond the root zone; and ΔW is the change in soil-water storage. ET is the combined water loss by evaporation from the soil and by transpiration from plants.

46

In "A Study of The Caribbean Basin Drought/Food Production Problem: CEAS Final Report", May, 1979, a detailed review of the concepts and terms associated with the water budgeting techniques designed for agroclimatic analysis is presented. The following discussion is presented to focus attention on the agroclimatic approach designed specifically for the central African region, south of the Sahara Desert.

Crop water requirements can be expressed in terms of potential evapotranspiration (PET). PET is defined as the amount of water that would evaporate from an extended surface of short green crop which fully shades the ground, exerts little or negligible resistance to the flow of water, and is always well supplied with water (Rosenberg, 1974). Actual water needs of specific crops or actual evapotranspiration (ET), may differ from PET depending upon the type of crop, its stage in the growing cycle and the development of leaves, and the density of the plant cover. However, both PET and ET are controlled by the same meteorological factors (temperature, humidity, windspeed, and radiation).

ET represents the amount of water used by the plant in its growth functions. This moisture supply is not obtained directly from precipitation. Moisture is drawn up through the plant from the root zone of the soil. Thus, an estimate of actual ET is based upon the availability of soil moisture. Soil moisture computations are dependent upon the water holding capacity of the soil which varies with type of soil and root zone depth of the vegetation. Thornthwaite and Mather (1957) noted that local conditions might also differ widely. The error in computation of the maximum water holding capacity is particularly important in climates with pronounced wet and dry season characteristics of the tropics (Nieuwolt, 1977).

Hall and Dancette (1978) addressed an important point with regard to soil moisture considerations. The amount of moisture stored in a soil, typical of the Sahelian zone during the wet season, depends heavily on farming practices. For example, water may be conserved in the soil through effective weed removal after the crop is harvested.

Hall et al. also compared crop water use and soil moisture for different crop varieties. Greater crop water use and large fluctuations in soil moisture reserves were observed for longer cycle millet as compared to shorter cycle millet in a region with average annual rainfall of 502 mm. The authors concluded that shorter cycle crops with partial fallow help maintain consistency in soil moisture reserves in regions of highly variable rainfall patterns.

The amount of moisture available to the plant during its growth cycle is often quite different from the water supplied by rainfall. A proportion of rainfall is lost by surface runoff and not available to the vegetation. In the tropics where rainfall intensities are often quite high, runoff can be considerable. Runoff is extremely difficult to estimate, however.

The effect of crop water use on deep drainage, or percolation, is related to the ET rate and the soil depth (Reicosky, Doty and Campbell, 1977). As ET increases with increasing vegetative cover, soil water content will rapidly decrease until drainage becomes negligible if an additional supply of rainfall is not provided. Conversely, with frequent rains and large ET rates, less water will be available for deep drainage due to the high water demand of the crop, particularly during the vegetative stage. Reicosky et al. found that the subsurface drainage component of the

48

water balance equation was relatively small compared to the ET component for non-stressed millet grown in a sandy loam soil. The subsurface drainage did contribute as much as 34 percent of the water loss by ET for stressed crop conditions with a prolonged period of no rainfall.

With this background of the water balance of vegetation grown in the semi-arid tropics, emphasis was placed on evapotranspiration as a direct function of precipitation since accurate estimates of the other terms in the water balance equation were extremely difficult to compute. This assumption was found to be reasonable for the crop-weather analysis in Central Africa for the following reasons.

First, the crop growing season corresponds with the wet season. Before the onset of the rains, there is little pre-season moisture available for planting. Therefore, planting must wait until the first meaningful rains. From emergence through the vegetative growth stage, crop water requirements increase to meet the needs for proper growth and development. For crops planted at the beginning of the wet season, the amount of rainfall increases as the crop advances through the vegetative stage. At flowering, peak crop moisture requirements are normally met by maximum rainfall. During the maturation stage, rainfall decreases as the wet season comes to an end. Thus, precipitation is directly proportional to ET.

Second, if a surplus of rainfall over water needs occurs during a particular month, a portion of this surplus may be stored in the soil for use during the next month. The actual amount of water stored will vary with soil type and depth of the vegetative root zone. However, the surplus moisture is a function of rainfall. Conversely, a deficit rainfall

will reduce the amount available for soil moisture storage during a particular growth stage. Finally, since rainfall variability is high in the semi-arid region of Central Africa, surface runoff and deep drainage may be difficult to estimate accurately.

With these considerations, an estimate of the actual crop water use under rainfed conditions can be approximated by the supply of moisture available to the crop from precipitation. Rainfed agriculture predominates in Central Africa since less than five percent of all agricultural land is irrigated (Chang, 1977).

In the drought-prone region of Central Africa, rainfall is the most limiting factor for agricultural production. Some studies have been carried out to assess the actual water requirements of crops grown in this region. Hall and Dancette (1978) found that, under rainfed conditions in Senegal, a short-cycle millet crop (75 day growing season) used about 315 mm, whereas a longer-cycle crop (90 day growing season) used over 400 mm. Cowpeas (76 day growing season) used 315 mm. Kassam and Kowal (1975) found that the pattern of crop water requirements for millet was well-matched to the pattern of crop water availability in northern Nigeria. Crop water use during 85 days from sowing to harvest was 330 mm.

Slatyer (1955) reported on the comparison of 3 crops (cotton, peanuts and grain sorghum) during a period of severe moisture stress. Studies indicated that grain sorghum showed remarkable adaptation to conditions of moisture stress by having the best root system of the three crops and the most effective internal control over transpiration

(or water loss). The peanut plants were intermediate in reaction to moisture stress, and cotton plants were the least adapted to conditions of moisture stress.

Too much water can be just as harmful to plants as too little. The maximum moisture which can be tolerated varies with different species and with stage of crop development. An excess of moisture during the flowering stage, for example, interferes with fertilization and may result in delayed flowering, poor seed setting, and lower quality seed (Arnon, 1972).

To be well adapted a crop should exhibit a vegetation rhythm in harmony with the climatic rhythm (Wilsie, 1962). Optimum conditions correspond to a type of climate in which the various phases of development proceed under changing conditions with the advance of the season. Different requirements for the four principal crop stages--seedling growth, vegetation growth, reproduction and maturation--require different intensities of temperature and light as well as moisture. In Central Africa, however, the response of crops to moisture availability at different stages of crop growth is of primary importance.

CHAPTER III

METHODOLOGY

A. Data Requirements

An investigation of agricultural practices and data availability was made for each country considered for agroclimatic analysis. The determination of agronomic data quality and subsistence cropping practices were major tasks in this study. These tasks were accomplished through various means including an extensive literature search for documentation of specific agricultural information, interviews with officials of various U.S. and international agencies (e.g., USAID, USDA, NOAA, World Bank, FAO), contact with university professors familiar with local agronomic and/or local climatic patterns in various countries, and communications with research institutes and local government officials within these countries. In addition, a trip to several African countries was necessary to establish contacts, obtain quantitative meteorological and agronomic data, and interview numerous qualified personnel for firsthand information concerning local agronomic practices, crop calendars and climatic conditions.

Considerable effort was also made to determine regions within a country where specific crops are grown. This is extremely important because there are large north-south gradients in rainfall within countries. The major crop regions must, therefore, be identified so that climatic data from WMO reporting stations within the major crop

52

growing regions can be aggregated for analysis. This approach provides the most representative agroclimatic analysis for specific crops.

1. Reporting Procedures

Before considering the methodology in greater detail, it is important to address the problem of data quality, particularly with regard to agricultural data. Many, if not all, of the countries under investigation have not had systematic crop reporting systems. At best, some statistics may be assembled by an agency of the federal government from sample surveys. These surveys provide some indication of production activities. Therefore, most statistics represent rough approximations of aggregate production and acreage. However, as long as data collection procedures do not undergo major changes, these statistics do provide indicators of yearly fluctuations in crop yields.

As an example of this type of problem, a crop data base was developed for Upper Volta. Becker (1974) noted that data collection procedures had major changes implemented throughout the ten year period from 1961 to 1970. This problem was compounded by the fact that the data base was compiled from four separate sources which results in four possible "biases in the reporting system". After initial crop-weather analysis, it was concluded that these data must be considered suspect and no further work on model development utilizing this data base was carried out.

All meteorological and agricultural data bases were checked very carefully for quality and consistency. When deemed adequate, the agricultural data base was used in model development with the purpose of providing estimates of yearly fluctuations in yield based upon crop

season weather data. If the data base was suspect, then other methods were attempted to provide qualitative information on crop conditions based upon meteorological data and crop calendar information.

2. Specific Data Problems

The most drought prone countries are situation in a zone between the arid region of the Sahara Desert in the north and the humid region of tropical Africa to the south. In the humid zones closer to the equator high annual rainfall during a longer wet season is a characteristic feature of the climate. Although rainfall variability is high in the humid zones, a comparison of variation between rainfall data sets in semiarid and humid zones shows even higher relative variability in the semiarid drought-prone regions.

Relative rainfall variability is emphasized because several African nations had to be eliminated from the analysis due to data problems. Most of these countries were located in the more humid zones. They include Guinea-Bissau, Guinea, Sierra Leone, Liberia, Ivory Coast, and Ghana. Meteorological data bases were incomplete and/or of poor quality for these countries as well as for Cape Verde Islands, Ethiopia, and Somalia. Without these complete data sets no meaningful analysis could be performed.

Ethiopia and Somalia have been involved not only in a border war but also in internal strife which also creates an element of uncertainty in the data, when reported. Chad has also experienced a long period of civil strife which not only affects the quality of data

flow but also disrupts all facets of the economy. These problems are addressed further in the next sub-section.

B. Regional Overview

Non-weather factors may play a dominant role in agricultural production activities. Such events, in total, are considered as random "noise" in crop model development. These events include political, social, economic or military activities which may influence productivity and cause fluctuations in crop yields in addition to the variability related to climate.

A notable feature of African politics is the rapid change which has occurred since the 1950's. Before 1956 only Ethiopia and Liberia were politically independent in sub-Saharan Africa. By 1965 there were 31 independent states. The transition from the colonial era to self-rule did not necessarily lead to political stability, however, as indicated in Table 3.1 which lists the dates of independence, successful military coups and unsuccessful coups or mutinies.

It is often difficult to speculate on the degree of impact that an event may have on agriculture. In fact, some events may have positive effects on the farmer in his decision to improve yield. For example, following the prolonged drought period which began in 1968, official producer prices for important subsistence crops increased in response to the general food shortages. As a reaction there were increased crop acreages (Becker, 1974; Berg, 1977). If weather conditions were favorable during the crop season, yields increased. However, if adverse weather conditions prevailed, yields decreased.

The prolonged drought of the recent decade in many parts of Africa has caused many hardships for the inhabitants. The impact of this

TABLE 3.1

Dates of Independence and Military Coups
For Selected African Countries

COUNTRY	DATE OF INDEPENDENCE	DATES OF SUCCESSFUL COUPS	DATES OF UNSUCCESSFUL ARMY COUPS OR MUTINIES
Benin	1960	October 1963; November 1965; December 1965	February 1972; January 1975
Cameroon	1960		
Central African Republic	1960	January 1966	November 1974
Chad	1960	April, 1975	
Ethiopia	Not under colonial rule	September 1974	December 1960
The Gambia	1965		
Ghana	1957	February 1966; January 1972	
Ivory Coast	1960		
Kenya	1963		1964
Mali	1960	November 1968	
Mauritania	1960		
Niger	1960	April 1974; April 1975; March 1976	December 1963
Nigeria	1960	January 1966; July 1966; July 1975	February 1976
Senegal	1960		
Somali Republic	1960	October 1969	
Sudan	1956	1958; 1969; July 1971	September 1975
Tanzania	1961	January 1964	
Togo	1960	January 1963; January 1967	
Upper Volta	1960	January 1966; February 1974	
Zambia	1964		

natural disaster may be felt for many years. The situation has been further complicated during the mid-1970's by the economic instability resulting from the energy crisis. One major effect of the increased price for petroleum would be a reduction in the availability of fertilizers (technology) necessary to improve crop yields in these drought-stricken countries.

A chronological list of events that are hypothesized as having a potential economic impact on subsistence crop production in various sub-Saharan countries is summarized in Table 3.2. This list is not necessarily complete but does represent a synopsis of events which have been documented in the literature (Bienen, 1978; Rivkin, 1969). This list also includes surveys of data bases from The New York Times (1969 - June 18, 1979), the Public Affairs Information Service (1976 - present), Commonwealth Agriculture Bureaux (1972 - present), and National Agriculture Library (1970 - present).

C. Modeling Techniques

Meteorological and agricultural data sources are provided in Chapter VI. The data were used as input for several different agro-climatic techniques. The modeling technique used in a particular area depended heavily on the amount and quality of the available agronomic data.

1. Traditional Linear Regression Model Approach

In this approach one or several variables are related to crop responses such as yield. The independent variables included such weather or climate factors as temperature or precipitation or some de-

TABLE 3.2

Chronological List of Major Events in Select African Countries

YEAR	COUNTRY	EVENT
1960	Ethiopia:	Rebels staged an unsuccessful coup in December.
	Mali:	Mali embargoed all trade with Senegal in June due to conflicts over internal and external policies.
1962	Chad:	In January a ban was placed on all political parties except the southern-based Progressive Party of Chad.
	Mauritania:	Raids were conducted by Moroccan-supported guerrillas; excessive violence and terrorism led to an invocation of the Franco-Mauritanian defense agreement on internal security.
	Nigeria:	Political crisis in May begins with the collapse of the regional government resulting in mass riots and a Federally declared state of emergency.
	Senegal:	An attempted coup in December is defeated by the majority of Senegal's army.
1963	Chad:	The adoption of a new constitution advocating a strong presidential form of government led to bloody riots at Fort-Lamy and Am-Timan; a nationwide state of emergency was declared in September.
	Niger:	Unsuccessful military coup in December was followed by a year of political unrest and led to an unsuccessful attempt to assassinate the President in April 1965.
	Ethiopia:	Border war between the Ethiopian and Somali armed forces during 1963-64.
1964	Nigeria:	A general strike occurred in which over 800,000 persons left their jobs, and violence occurred in the streets. There was a mass decline in public respect for authority during 1964-65.

TABLE 3.2 (cont.)

YEAR	COUNTRY	EVENT
1964 (cont.)	Sudan:	Resentment against military rule led to a ten-day general strike with five days of continuous rioting. Attacks continued leading to guerrilla warfare which had engulfed the south by 1964. Civil War from 1955-1972.
	Tanzania:	After a coup in January followed by an army mutiny, Zanzibar and Tanganyika merged in April to form the United Republic of Tanzania.
1965	Chad:	Unrest continued with open revolt against the government. From 1965-1970, large parts of Chad were under the control of rebels.
	Upper Volta:	Mass demonstrations and a general strike among trade unions preceded the January 3, 1966, resignation of President Yameogo after a bloodless military coup.
	Nigeria:	With widespread violence in October, and two coups in 1966, the Nigerian Civil War began with an attack on the self-proclaimed Republic of Biafra and lasted until 1970. Subsistence food production was destroyed, agricultural trade was disrupted, and transport facilities were diverted to war use.
1966	Chad:	Farmers revolted against high taxation in June. An armed rebellion occurred near the Chad-Sudan border in 1967 with continuous power struggles involving Chad in a Civil War from 1959-1971.
1967	Sudan/ Ethiopia:	The Red Locust were particularly threatening to crops from 1967 through 1969.
	Senegal:	A second attempt was made to assassinate President Senghor and mass demonstrations, states of emergency, and strikes occurred from May 1968 until March 1973. After a government decree in 1960 provided for an association of farmers in reorganized local marketing cooperatives, and, after the licenses of most private traders had expired by 1967, the official cooperative-marketing system collected 98 percent of the recorded groundnut crop in the 1967 season as compared

TABLE 3.2 (cont.)

YEAR	COUNTRY	EVENT
1964 (cont.)	Sudan:	Resentment against military rule led to a ten-day general strike with five days of continuous rioting. Attacks continued leading to guerrilla warfare which had engulfed the south by 1964. Civil War from 1955-1972.
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TABLE 3.2 (cont.)

YEAR	COUNTRY	EVENT
1974 (cont.)	Mali/ Upper Volta:	Border clashes between Mali and Upper Volta.
	Upper Volta:	A coup returned the nation to full military rule. Political tensions had been developing for several months due to a power struggle between the deposed Premier and Assembly President.
1974-75	Sahelian Countries:	Large official producer price rises for main subsistence crops occurred throughout the entire Sahelian region after stable or falling prices during most of the period 1960-1974.
1974	Niger/Mali:	Mali accuses Niger of preventing the return of thousands of nomads who took refuge in Niger to escape the famine and drought.
1975	Sudan:	Unsatisfactory urban conditions, lack of transport plus the oil crisis caused riots in 1974 and preceded the September 1975 coup.
1976	Senegal:	Billions of rats destroyed more than 40 percent of food crops in Senegal as of June 1976, and constituted a serious threat to all Sahel areas.
1977	Tanzania:	Tanzania closed the border with Kenya in April.
	Somalia:	The Western Somali Liberation Front occupied most of Ogaden, Ethiopia in their War of Liberation.
	Sudan:	Plans were made to drain excess waters of the Nile and irrigate some 3.7 million acres.
	Zambia:	The country was on the verge of economic collapse. By June 1978 the nation was highly vulnerable to Rhodesian raids.
1978	Ethiopia/ Somalia:	Desert Locust caused what was potentially East Africa's biggest crop disaster, especially in Northeast Ethiopia and Northwest Somalia.

rived agrometeorological variable such as an index of atmospheric moisture stress or the soil moisture regime.

The traditional linear regression technique utilizes the historic data bases for crop yield and average monthly temperature and total monthly precipitation as well as crop calendar information. Only those meteorological, or predictor, variables which are available from data transmitted over the World Meteorological Organization's Global Telecommunications System were used in model development. This constraint was necessary to ensure the desired potential for operational use of these established climate/crop yield relationships.

The statistical models have the form:

$$\hat{y} = \hat{\beta}_o + \sum_{i=1}^{N} \hat{\beta}_i X_i$$

where $\hat{y}$ is the predicted yield,

$\hat{\beta}_o$ is the estimated regression constant, and

$\hat{\beta}_i$ is the ith least square estimate of the coefficient for the ith predictor variable, X_i.

In addition to meteorological variability related to crop yield, technological change such as increased fertilizer application or improved genetic quality of seed must be considered. Another factor which must be considered is random 'noise' (McQuigg, 1975). Random noise in crop weather models is the result of random events not specifically included in the model.

In the development of crop yield models in the drought-prone countries of Central Africa, technology was found to be an insignificant factor. Random noise was, however, a very important factor

62

as indicated in the discussion of Section III.B. Since the historical agricultural data bases were relatively small, only a single agrometeorological predictor variable was used in model development (Section III.D.)

The meteorological data were screened carefully to identify missing and suspect data. After these data sets were checked for quality control, they were ready for agroclimatic analysis and model development. In selecting the predictor variable the aim was to obtain an equation which best explained the relative variation in yield for assessment purposes.

In many of the countries lack of quality crop data prevented regression model development. Two other methods were employed under these circumstances.

2. Analogue Model Approach

The second method is the analogue modeling approach. In the absence of historic crop yield data or with inadequate data for a region of interest, existing models developed for similar climatic and agronomic conditions were applied to provide indicators of relative yield estimates using the meteorological data from the country under study. Recognizing the limitations imposed upon the analogue technique (i.e., no quantitative yield data, the requirement of similarity of conditions), this approach may be used as a tool to assess the condition of the crop and provide qualitative estimates of potential yield fluctuations based upon the meteorological and crop calendar information.

It is necessary to emphasize similarity of conditions (i.e., climatic conditions, crop calendar patterns) for application of this approach. Climatic conditions include not only annual rainfall amounts but also the seasonal distribution of rainfall. Crop calendar patterns include planting dates for specific crops and lengths of growing seasons. Preferably, the region under consideration for the analogue method should be in proximity to the 'reference' region. This may reduce some of the problems posed by local agricultural practices and by local climatic patterns which may not be identified on a larger scale.

When a region has been selected for application of the analogue technique, the meteorological data is provided as input with the established model using the regression coefficients developed in the reference country to provide qualitative estimates of the variation in yield.

3. Yield Indices

In regions where the analogue modeling technique is not deemed appropriate a third approach is used to provide a qualitative assessment of the condition of the crop at successive growth stages. An historical index for crop yield can be provided by analyzing long-term records of meteorological data associated with the crop growing season. Crop calendar information is essential in this analysis to provide agronomic meaning to the results. The climatic analysis must be oriented towards key phases of crop development. During certain phases, a climatic varible may become a limiting factor for growth processes. These phenological events may impact heavily on the overall crop yield.

The yield indices developed from this analysis of long-term data are ranked over the entire period to determine conditions of the crop relative to conditions associated with near-normal meteorological conditions. This procedure provides the basis for objective analysis of crop conditions at successive growth stages based upon meteorological data and crop calendar information only.

D. The Crop Moisture Ratio

The predictor variable used in model development requires careful attention. The effect of the weather's contribution is identified in the selection of the variable which shows the most statistically significant contribution to the final yield estimates. The weather variable must also show agronomic significance based upon phenological and physiological considerations.

Research has been conducted on plant water requirements. Yao (1969) introduced the R-index which is a measure of plant water supply in relation to plant water requirements, or a ratio of actual to potential evapotranspiration. The computation of actual evapotranspiration includes consideration of soil moisture storage. Sakamoto (1978) discussed the Z-index which represents the monthly moisture anomaly based upon water balance computations and is derived from the difference between observed precipitation and the "climatically appropriate" precipitation. This difference is then weighted by an average supply and demand coefficient which varies with the local climate. Sakamoto presented model results using the Z-index as the predictor variable for estimation of wheat yield.

The Food and Agriculture Organization (FAO) has paid considerable attention to the crop moisture requirements of crops grown specifically

in the Sahelian region of Africa. Doorenbos and Pruitt (1975) discussed the guidelines for crop water requirements in terms of crop coefficients which relate the potential evapotranspiration to crop evapotranspiration at successive growth stages. Crop coefficients, which consider crop characteristics, time of planting and length of growing season, were developed for different crops. Frere and Popov (1978) have discussed an operational program for monitoring crop conditions in the Sahelian region based upon these crop coefficients. Crop calendar is essential in this analysis procedure. Davy, Mattei, and Solomon (1976) presented a generalized agrometeorological study of the Sahelian region which was divided into rainfall zones.

Based upon these studies, and with the acquisition of specific crop calendar information for the various crops grown in Central Africa, the moisture availability of the crops at successive growth stages was found to be adequately represented by the crop moisture ratio.

The crop moisture ratio (CMR) was developed as a predictor variable for the regression models. The CMR is defined as the ratio of precipitation to potential evapotranspiration (PET). It is a measure of water supply to demand under rain-fed conditions for successive growth stages of specific crops. From water balance considerations, the actual crop moisture use, or evapotranspiration, is directly related to the amount of precipitation during the wet season (see Section II.D.). Figure 3.1 shows the typical rainfall and potential evapotranspiration (PET) patterns in the Sahel. PET is determined by the Thornthwaite method (Thornthwaite, 1948).

Available Moisture

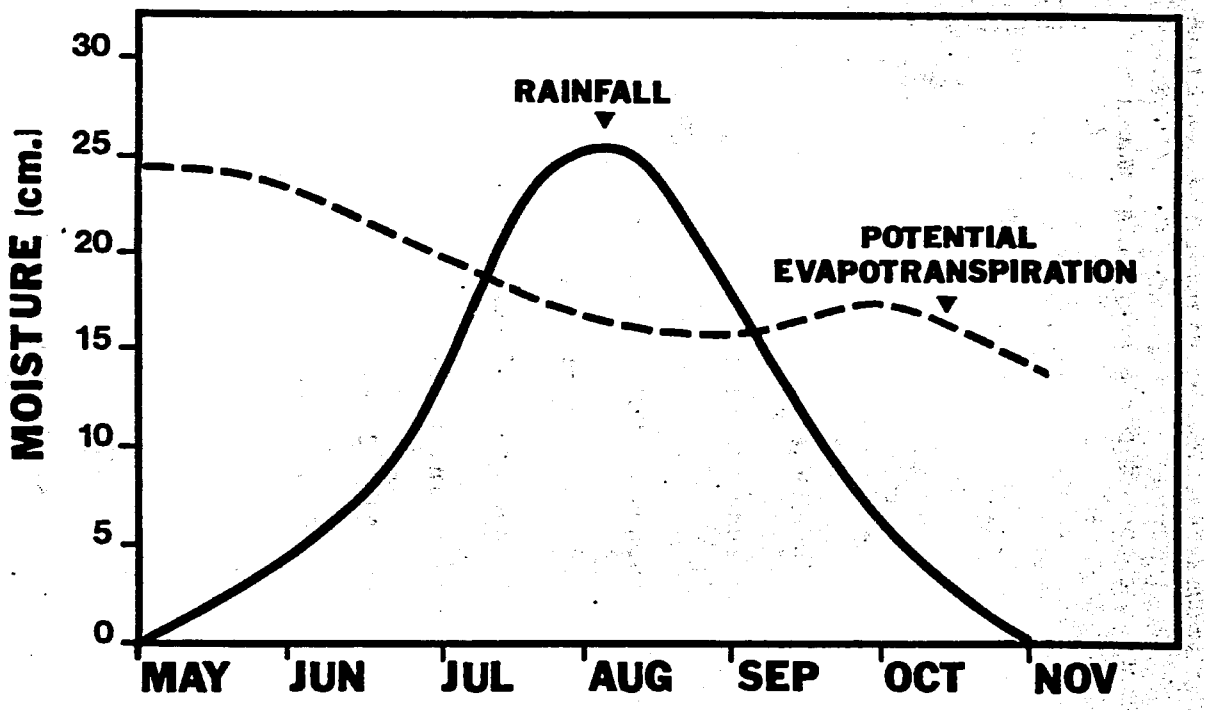


Figure 3.1. Typical seasonal rainfall and potential evapotranspiration patterns during the wet season in Sub-Saharan Africa.

To estimate potential evapotranspiration by this method, mean monthly temperature and latitude must be known. The first step in the computation is to compute a heat index (I) which is the summation of monthly heat index values, each a function of the monthly mean temperature. PET is then computed for a particular month by:

$$PET = 1.6\ (10T/I)^{a}$$

where T = mean monthly temperature in ^{o}C,

I = heat index (defined above), and

a = cubic function of I.

Finally, these monthly values of PET are adjusted for possible hours of sunlight corresponding to the appropriate latitude.

Figure 3.2 presents the crop moisture requirements based upon FAO guidelines and crop calendar information, for cereals (i.e., millet and sorghum) during four successive growth stages: planting, vegetative, reproductive (flowering) and late (maturation). The shape of the curve in Figure 3.2, representing the crop moisture requirements at successive growth stages, resembles the shape of the curve derived from the CMR in Figure 3.1.

To account for soil moisture storage indirectly, the CMR includes precipitation and PET from the last month prior to the growth stage under consideration. For example, if the millet crop reaches the flowering stage in September, August is included in the computations of the CMR for the reproductive stage to account for stored soil moisture.

Crop Moisture Requirements

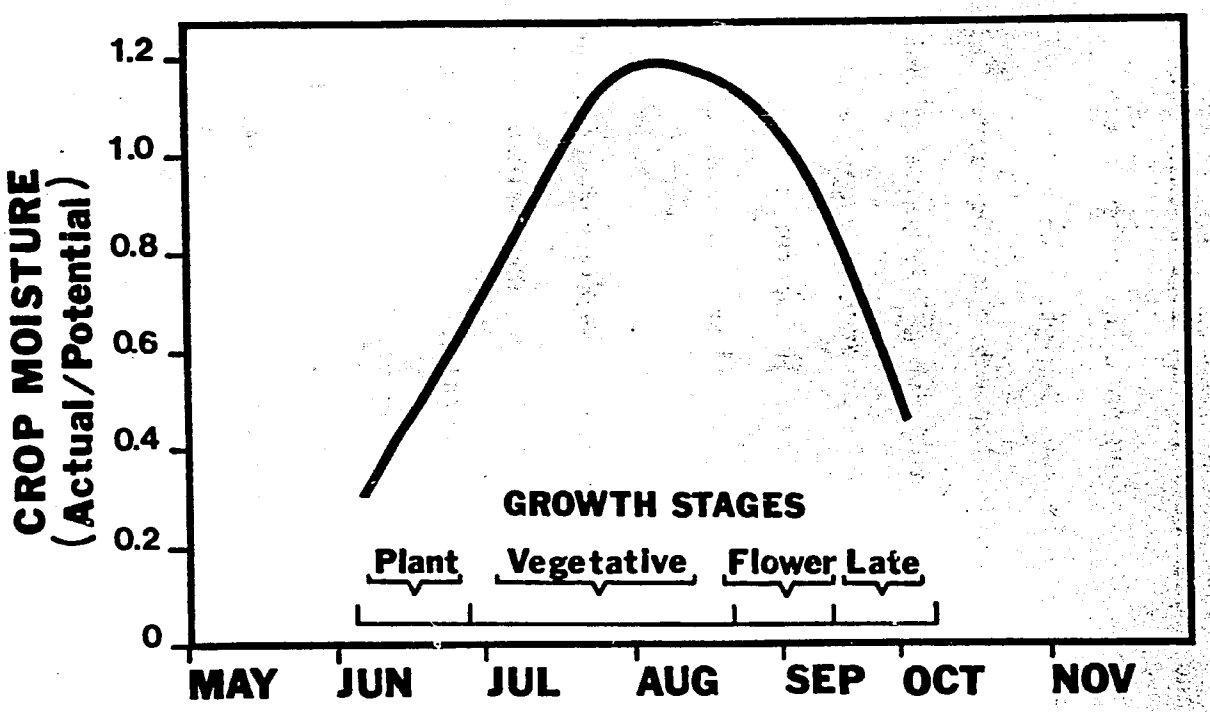


Figure 3.2. Crop moisture requirements, expressed in terms of the ratio of actual evapotranspiration to potential evapotranspiration for successive growth stages of a cereal crop (e.g., millet, sorghum, maize).

Figure 3.3 presents the average monthly rainfall patterns for four countries: Senegal, Niger, Upper Volta, and Sudan. Three points need to be emphasized. First, the duration of the wet season varies, with the longest wet season found in Upper Volta and the shortest in Sudan. Second, monthly amounts vary, with Upper Volta receiving the highest monthly amounts and Sudan receiving the lowest monthly amounts. Finally, Senegal and Niger exhibit similar patterns except for Senegal during the latter part of the wet season; Senegal received greater monthly amounts than Upper Volta during September and October. This anomalous rainfall during the late season in Senegal is probably due to the southwestward retreat of the ITCZ rather than a more southward retreat of the wet season. Further, Senegal is located on the west coast of Central Africa and, as a result, maritime or coastal effects might enhance late season rainfall.

Figure 3.4 presents the average monthly potential evapotranspiration patterns for the four countries. PET values were computed from the Thornthwaite method. According to this approach PET is a function of temperature and day length. The similarity in PET patterns between all four countries reflects the relatively small variability in mean temperature and day length throughout the region.

The relationship between crop yield and CMR for successive growth stages was examined. Using millet yield estimates obtained for Senegal, Niger, Sudan, and Upper Volta, empirical relationships for both the vegetative and reproductive stages are presented in Figures 3.5 and 3.6, respectively. Crop yield data for Upper Volta were included in this analysis even though there is some question as to the quality of the agricultural data (see Section III.A.). The largest scatter was ob-

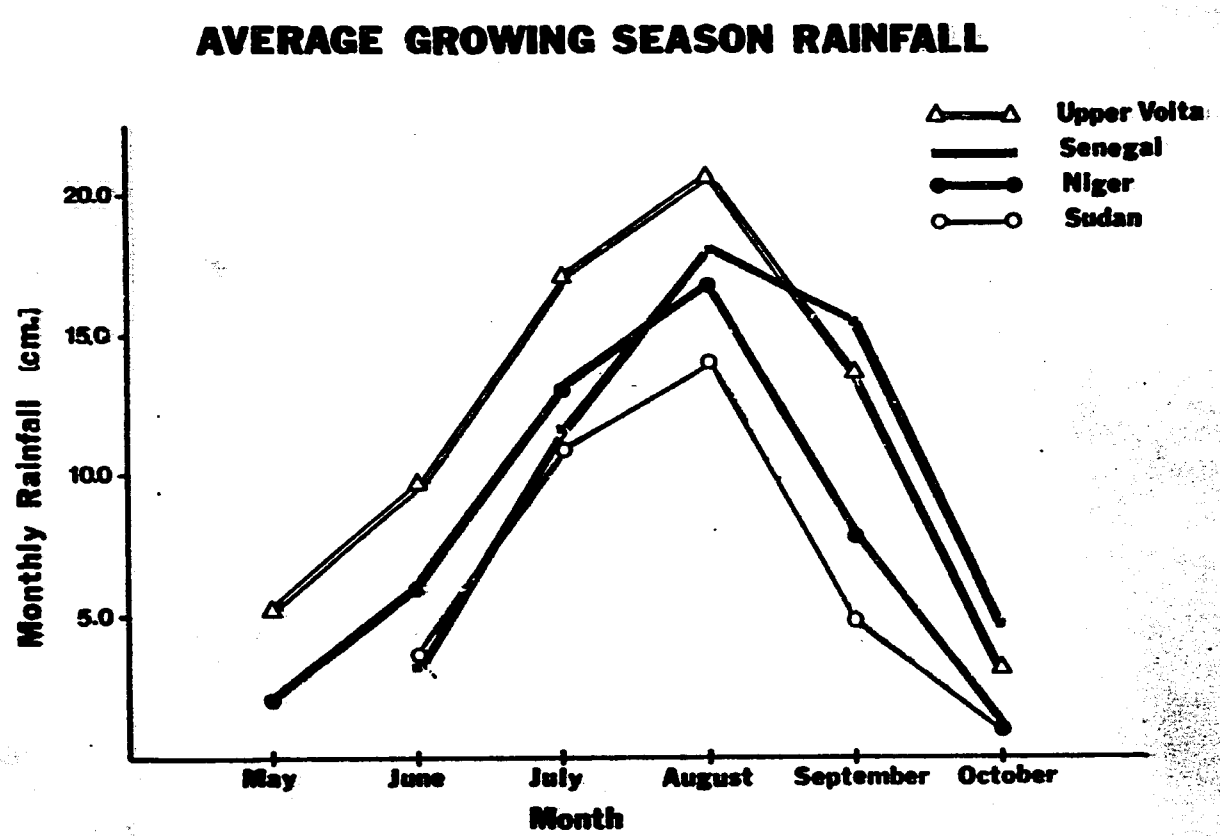


Figure 3.3. Average monthly rainfall patterns for Upper Volta, Senegal, Niger and Sudan.

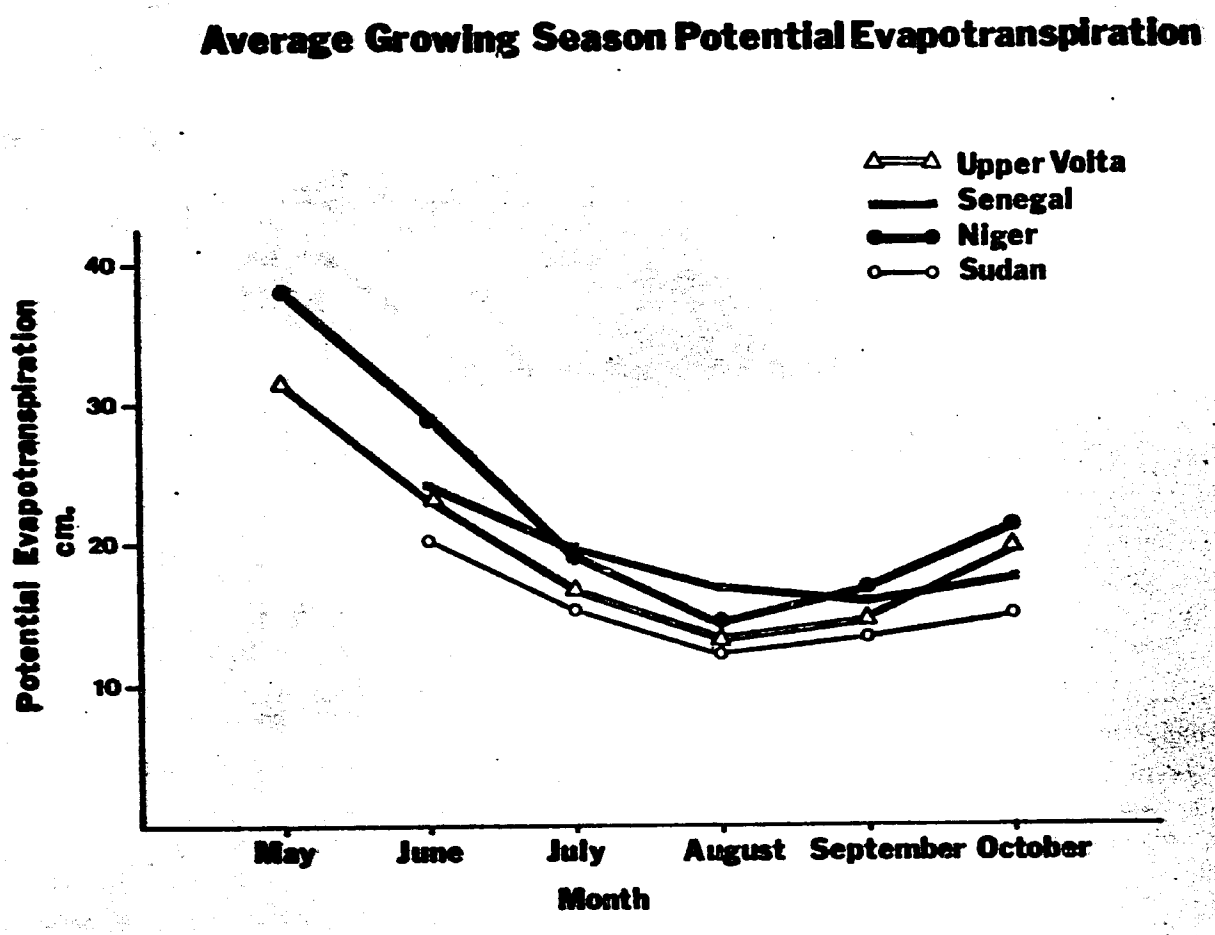


Figure 3.4. Average monthly potential evapotranspiration patterns for Upper Volta, Senegal, Niger and Sudan.

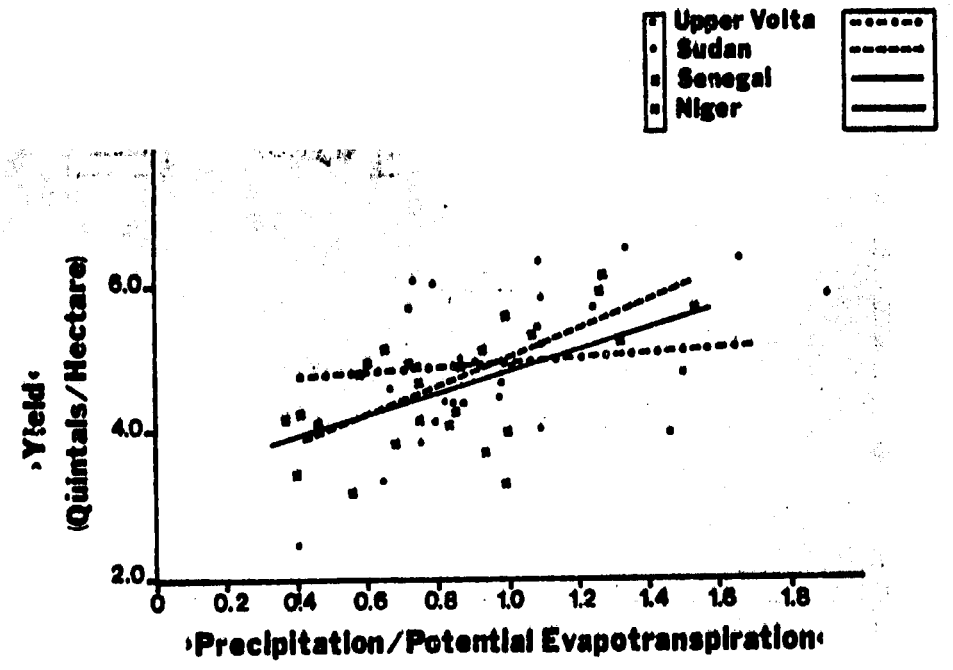


Figure 3.5. Relationships between millet crop yield and crop moisture ratio (CMR) for the vegetative growth stage in Upper Volta, Sudan, Senegal and Niger.

AVAILABLE CROP MOISTURE
(REPRODUCTIVE STAGE)

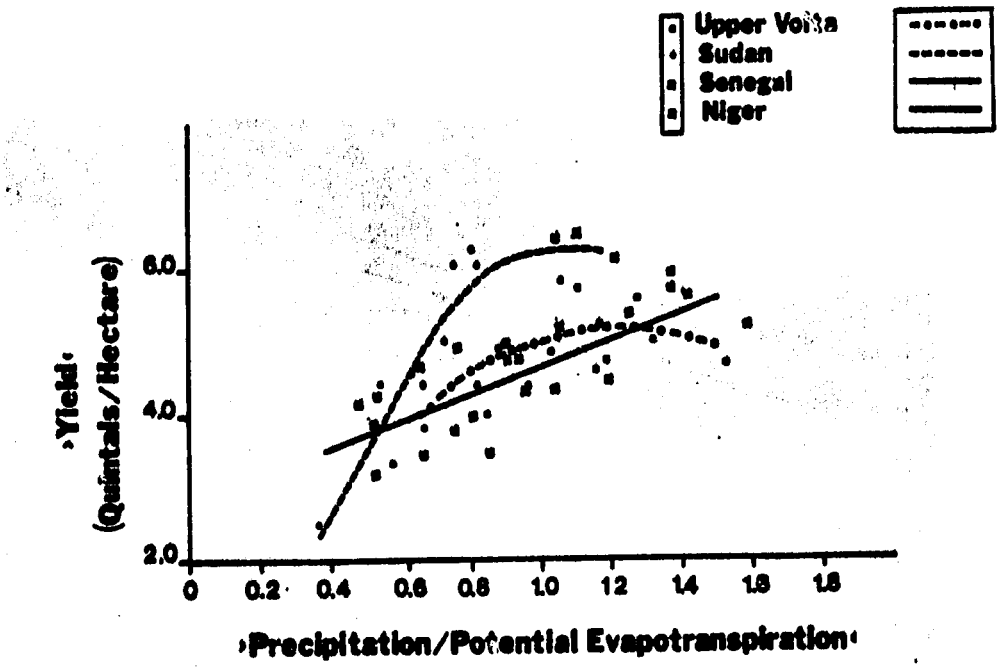


Figure 3.6. Same as Figure 3.5 for the reproductive growth stage.

served in the data for Upper Volta, as expected. Although there is scatter in the actual data, best fit lines do reveal some distinct patterns between countries.

During the vegetative growth stage (Figure 3.5), there is a tendency for a linear increase in yield with an increase in available crop moisture. The increase varies in each country, however, as indicated by the slope of the lines. Upper Volta shows the least response to change in CMR. This would be expected since Upper Volta usually receives greater amounts of rain during the wet season. Thus, yields may not be as dependent upon rainfall as compared with countries which are deeper into the Sahelian Zone. The predominant grain-growing region of Sudan shows the greatest response.

During the reproductive growth stage (Figure 3.6), there are unique patterns. Senegal and Niger were combined (Figures 3.5 and 3.6) since growing season characteristics are similar in these two countries. Both continue to exhibit linear increases in yield with increasing moisture availability. This result suggests that crops adapted to these regions can use all available moisture for grain production. Upper Volta shows only a small increase at first, but reaches a peak beyond which there is a tendency towards decreasing yields with continued increases in moisture. Thus, an optimum condition is reached during the reproductive stage. Sudan shows a wide range with a sharp increase at first, reaching a peak and, as with Upper Volta, shows a tendency for yields to level off with continued increases in moisture availability. This wide range in yields in Sudan would indicate that technology (i.e., fertilizers and cropping practices) is more advanced than in West Africa.

With the right combination of rainfall and technology, yields are high. However, large departures from optimum moisture conditions can seriously affect yield.

This tendency for optimum moisture conditions during the reproductive stage is significant because the period of flowering for cereals is the most critical stage for moisture requirements (Arnon, 1972). As noted earlier, water stress will reduce grain production. Too much rain, however, interferes with fertilization which also reduces grain production.

It should be stressed at this point that these empirical relationships were developed from the available data which, in certain instances, may not be of high quality. However, the results do show meaningful patterns, both statistically and agronomically. As such, they provide qualitative information on the impact of growth-stage precipitation on potential yields.

CHAPTER IV

RESULTS AND DISCUSSION

A. General

This section presents the detailed results of the agroclimatic analysis for the drought-prone countries of Africa. The severity of meteorological drought conditions which prevailed throughout Central Africa during the period 1968-1975 is demonstrated by the analysis of precipitation data from over 800 reporting stations in 11 West and Central African countries. These countries include Senegal, Mauritania, Mali, Upper Volta, Niger, Chad, Nigeria, Togo, Benin, Cameroon and Central African Republic. The results clearly indicate the adverse environmental conditions which prevailed throughout the region for agricultural production activity.

After this background analysis, the results of weather/crop yield model development are presented. A discussion of the results of this agroclimatic analysis is included to highlight important features and significant problems in model development. Another objective of the project is to examine the impact of climate fluctuations on the rangeland areas of the northern Sahel. The results, formulated into a rangeland index for specific regions, are discussed.

Finally, specific crop-season weather analyses are presented for Nigeria, and Kenya and Tanzania. These results are based primarily upon climate analysis and general crop calendar information. The study of Nigeria is designed to examine the climatic pattern not only

in the Sahelian zone but also further south in greater rainfall zones. The objective is to determine if there are any consistent climatic patterns throughout the entire region when the Sahelian zone is experiencing below normal rainfall periods. The study of Kenya and Tanzania is undertaken to provide an initial agroclimatic analysis for countries situated either in the equatorial zone or in Africa south of the equator.

B. Precipitation Analysis (1968-1975)

Since the mid-1960's many parts of Africa have been experiencing severe drought conditions over prolonged periods of time. Winstanley (1976) noted that the isohyet pattern across the breadth of the central African region shifted south by one to two degrees of latitude during the 20-year period, 1952-1972. Bunting et al., (1976) and Katz (1978) observed that from examination of rainfall records in the Sahel region, no trends or periodicities could be found in the long-term data base to indicate that a systematic pattern of below-normal rainfall had been established. Using an expanded data base, Nicholson (1979) did find a tendency toward persistence in the Sahelian rainfall series. Although the recent succession of drought years is not unprecedented, the impact of this prolonged drought on local subsistence economies has been devastating (Glantz, 1976).

Data from a total of 813 precipitation recording stations were gathered from eleven countries in West and Central Africa (Figure 4.1) for the period 1968-1975. (Data sources are given in Chapter VI.) These data were processed, quality-control checked and analyzed to ex-

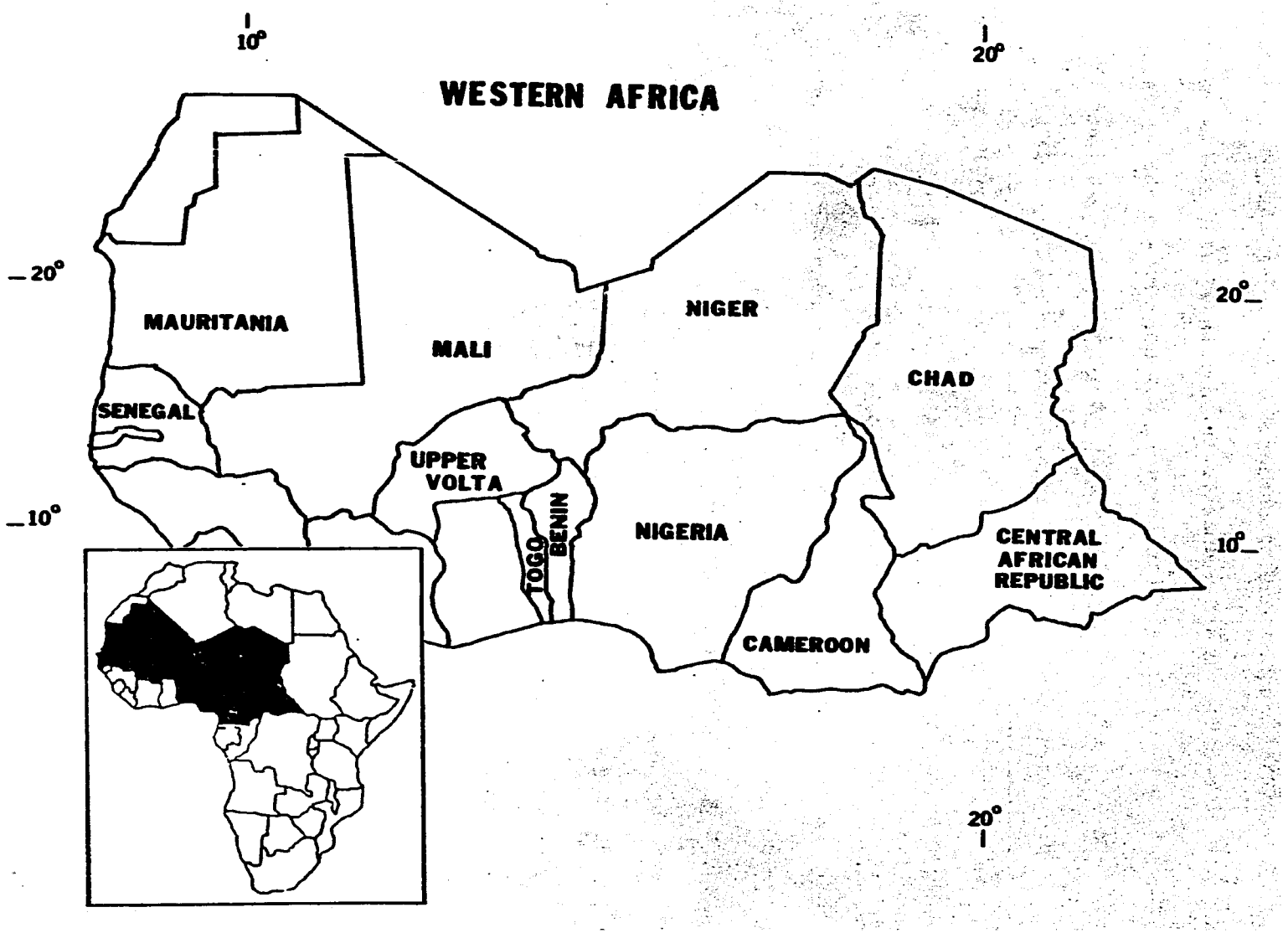


Figure 4.1. Map of Western African countries in which regional precipitation data were obtained and analyzed.

amine the severity and extent of meteorological drought conditions during the past decade. Monthly precipitation data at each station were combined into plant-growth stage as well as seasonal and annual values. These data were further aggregated into regions within each country for the drought analysis. The regional aggregations were based not only upon similar climatic patterns but also upon local influences such as topographical and geographical patterns. The results may provide inputs to scenarios that may occur in the future.

In general, the minimum amount of rainfall required to support a rain-fed crop in semiarid regions is 350 mm (Davy et al., 1976; Hall and Dancette, 1978; Kassam and Kowal, 1975). Using available station data from the WMO reporting network for the period 1951-1977, the 300 to 400 mm zone of annual rainfall was examined to determine the extent of the spatial variability. Figure 4.2 presents the 300-400 mm zones of annual rainfall based upon climatic normals (Wernstedt, 1972) and the WMO precipitation data bases for 1958 and 1973. Above-normal rainfall amounts occurred throughout most of the region in 1958. In contrast, 1973 was considered to be one of the worst years in several decades with respect to lower than normal rainfall.

Figure 4.2 illustrates the potentially serious problem imposed by the harsh environment in those countries bordering the Sahara Desert. For example, the major millet/sorghum region in Senegal is in the so-called "Groundnut Basin." This region is located in western Senegal north of the Gambia. In 1973, the 300-400 mm isohyet range did not penetrate into the Groundnut Basin, suggesting major crop failures in both Senegal and Mauritania. Further inland, the 300-400 mm

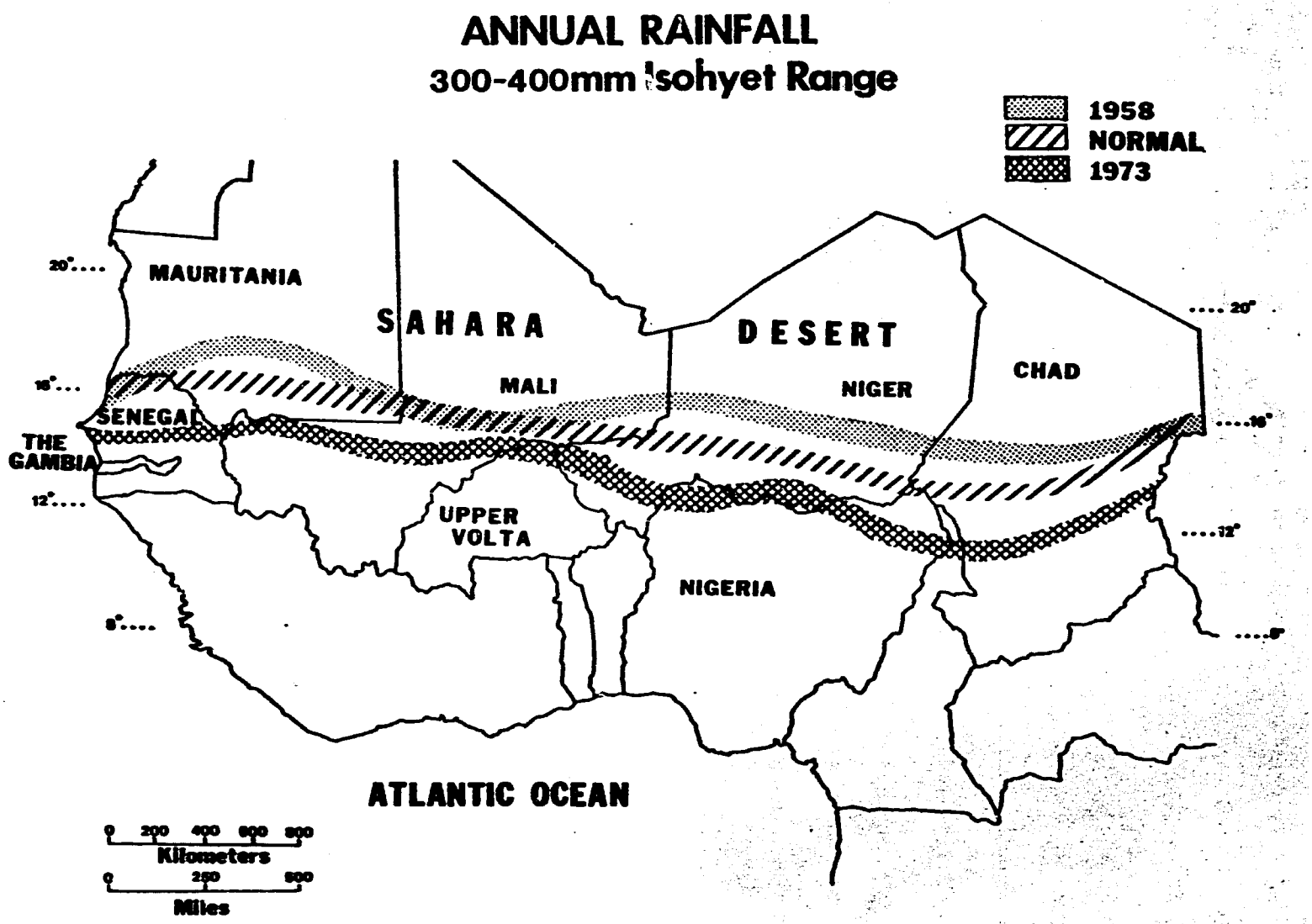


Figure 4.2. Map of West Africa depicting the wide variation in the 300-400 mm isohyet zone between 1958 and 1973.

band barely penetrated the southwestern corner of Niger leaving the major cereal producing region with well-below normal annual rainfall. In most regions of the Sahel, the 300-400 mm zone of annual rainfall was at least 200 km south of its "normal" position. The resulting impact on food production was devastating as will be shown in later sections.

The regional precipitation data were analyzed to provide insight into the magnitude of meteorological drought conditions in Central Africa, south of the Sahara Desert. The annual rainfall patterns, expressed in terms of percentage departures from 30-year normals, are presented in Figures 4.3 through 4.10 for the years 1968 through 1975, respectively. This sequential series of maps illustrates the severity of the recent drought in both spatial and temporal terms. Areas which experienced at least 30 percent below normal annual rainfall (hereafter referred to as severe drought conditions in this analysis) are hatched on these maps. Also, the 30-year normals for 300 mm, 500 mm and 900 mm are represented by dotted lines.

In 1968, pockets of well-below normal rainfall were found along the western edge of the Sahel in Senegal, the Gambia and Mauritania, and in a large portion of eastern Niger and the west-central portion of Chad (Figure 4.3). The below normal rains of 1968 represent the onset of the prolonged drought period.

Annual rainfall in the Sahel during 1969 shows a more normal pattern (Figure 4.4) with some areas receiving slightly below normal rainfall while Senegal received above normal rain. The following year, 1970, again showed areas of severe drought; i.e., Senegal, the Gambia

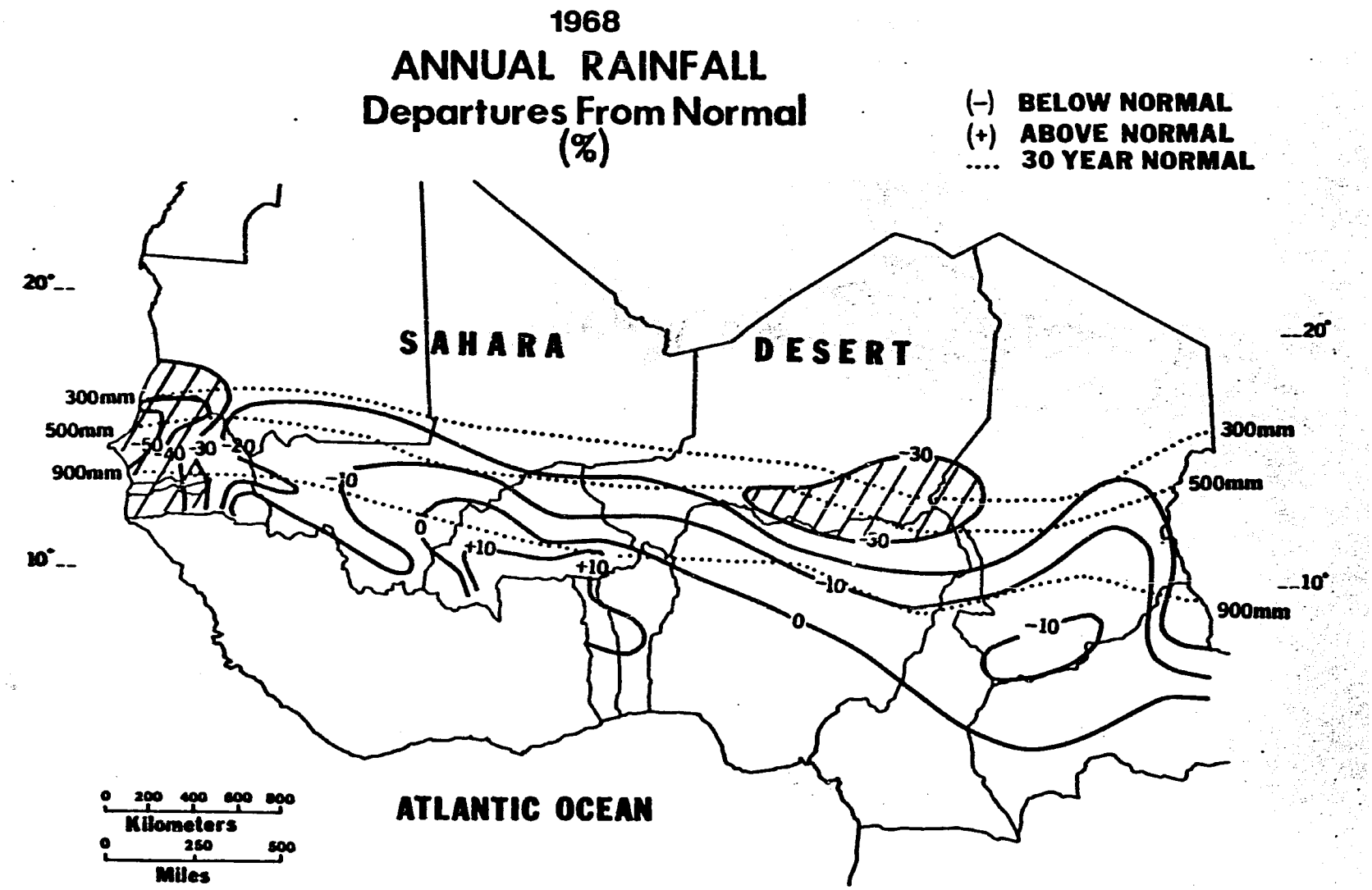


Figure 4.3. Annual rainfall patterns expressed in terms of percentage departures from normal for West Africa in 1968. Hatched areas indicate greater than 30 percent below normal. Normal 300 mm, 500 mm and 900 mm isohyets are included.

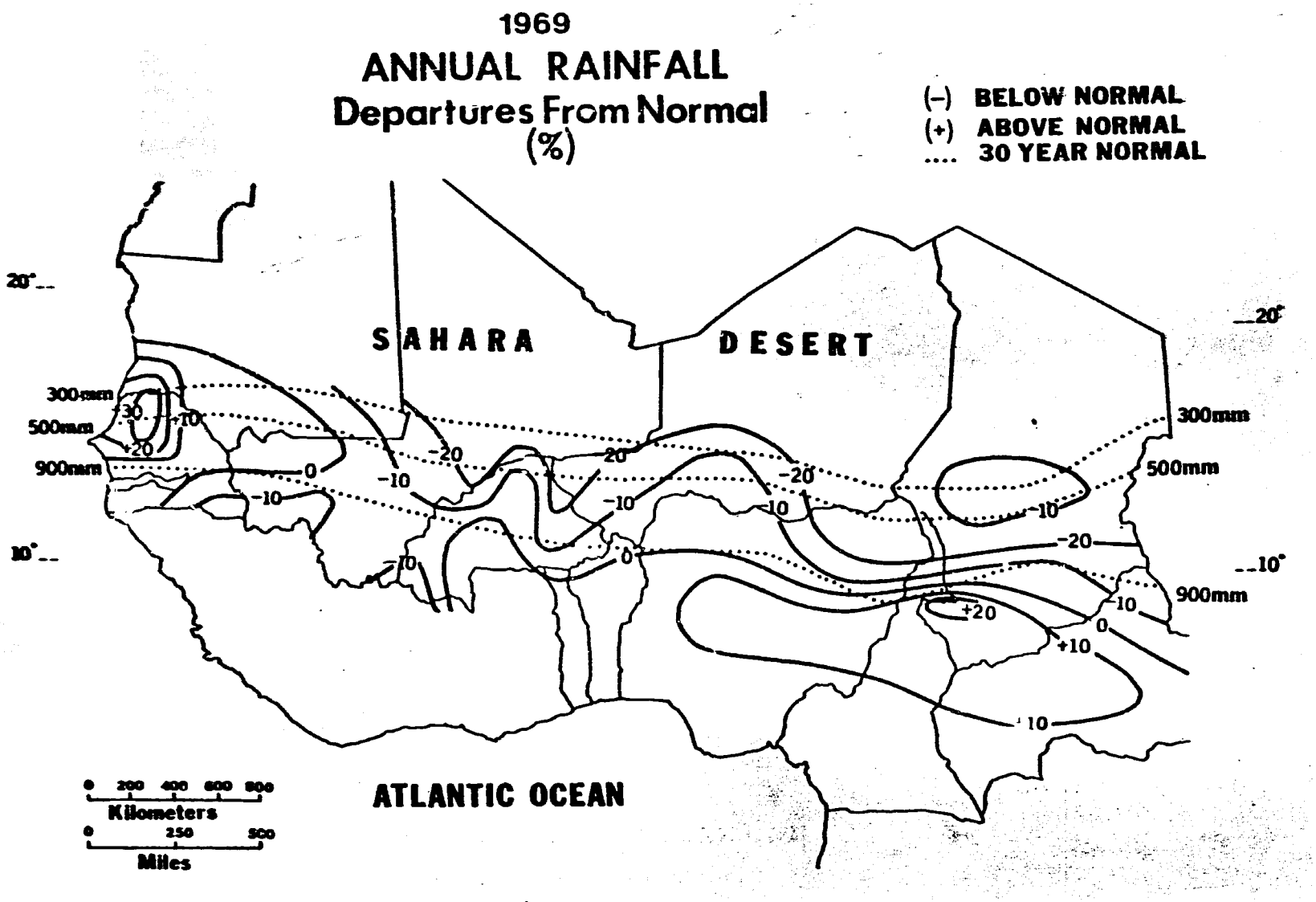


Figure 4.4. Same as Figure 4.3 in 1969.

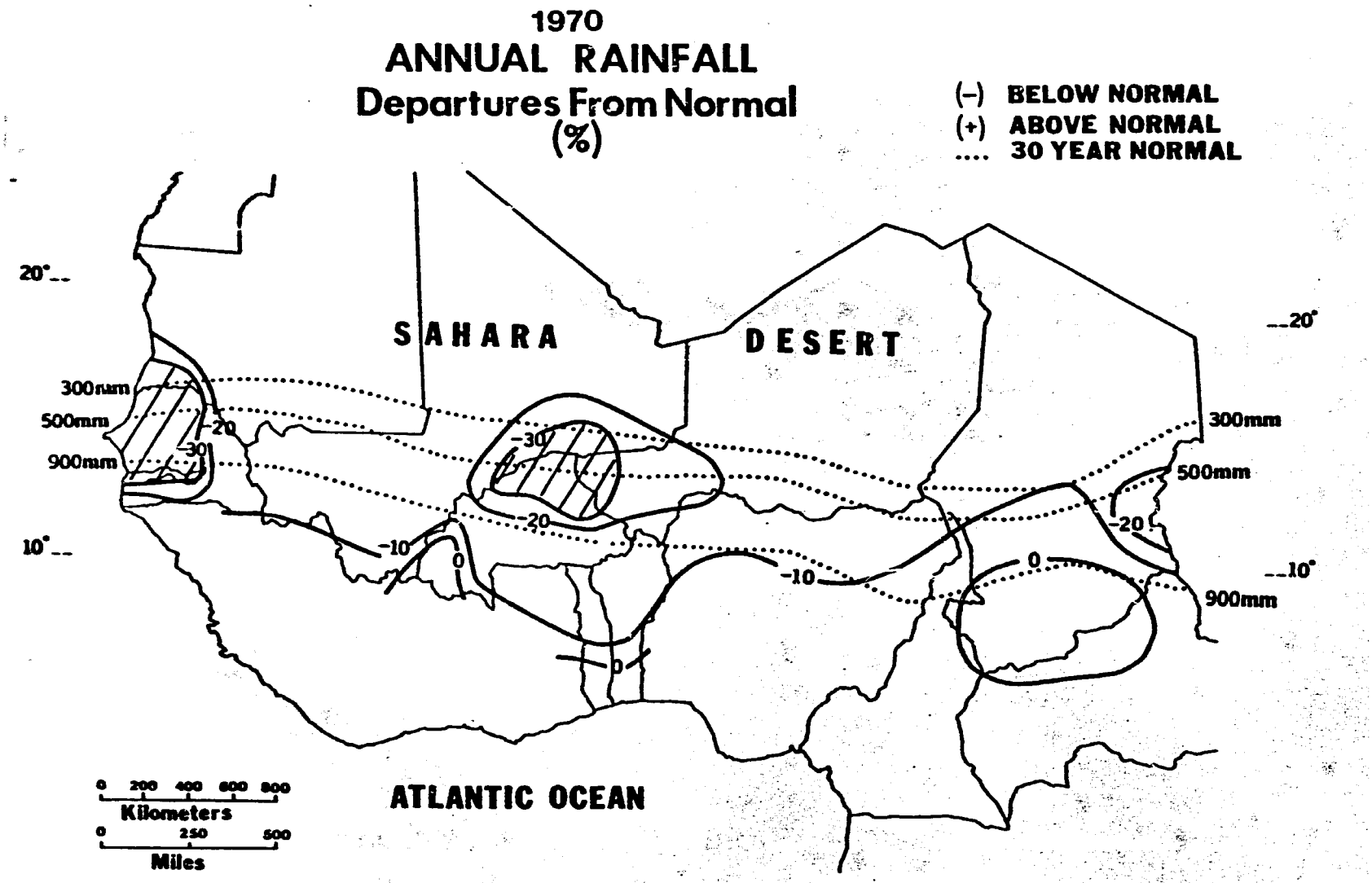


Figure 4.5. Same as Figure 4.3 in 1970.

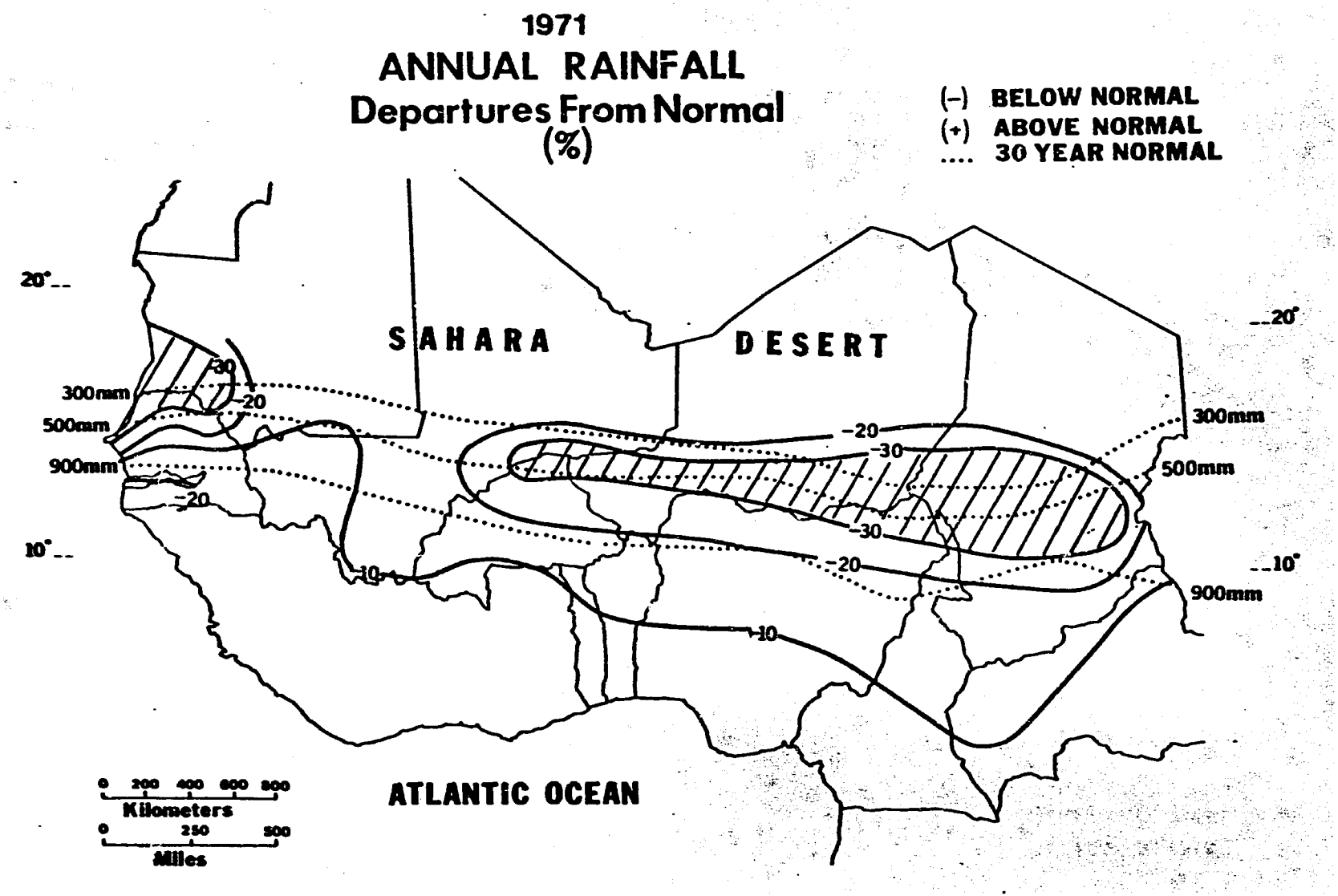


Figure 4.6. Same as Figure 4.3 in 1971.

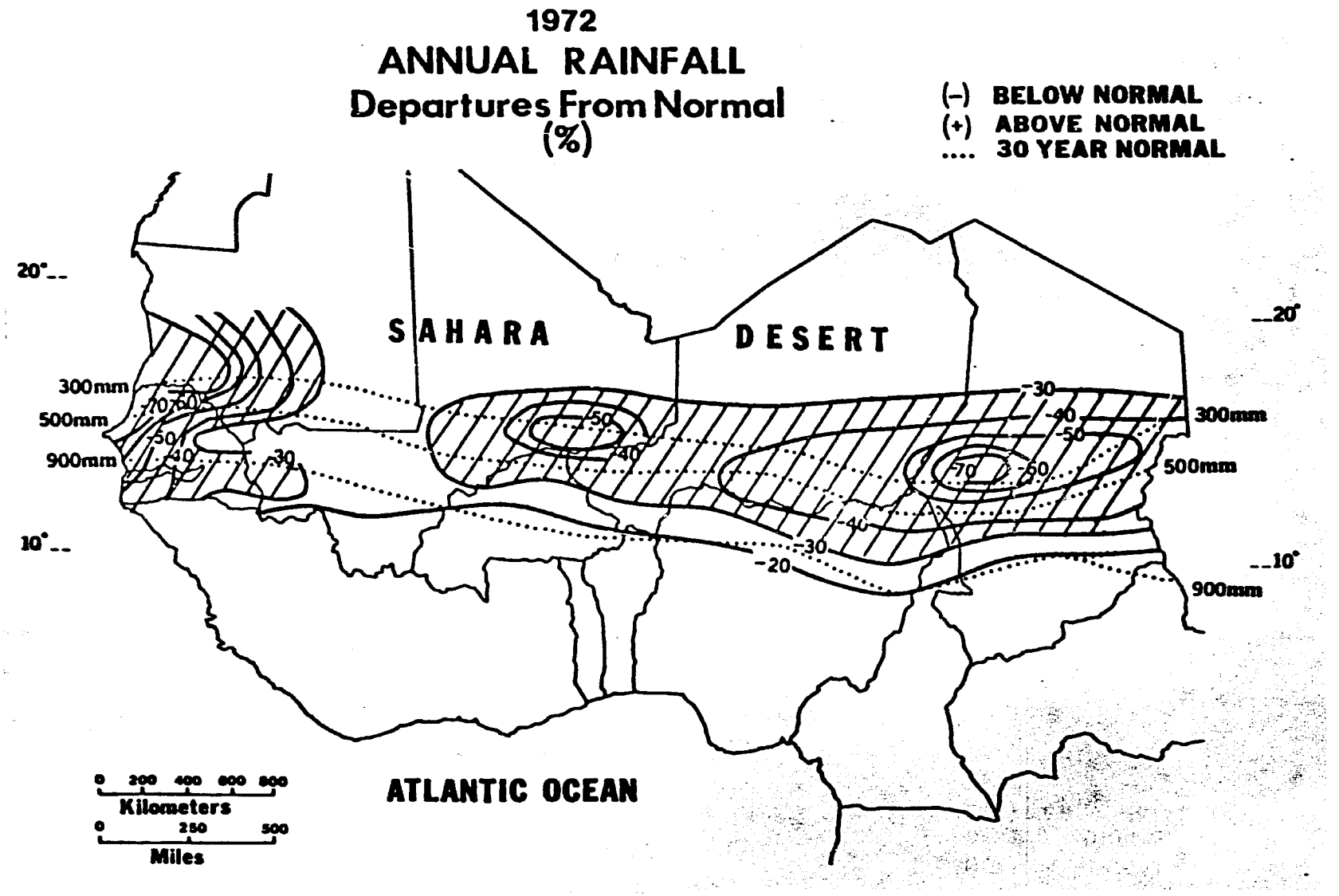


Figure 4.7. Same as Figure 4.3 in 1972.

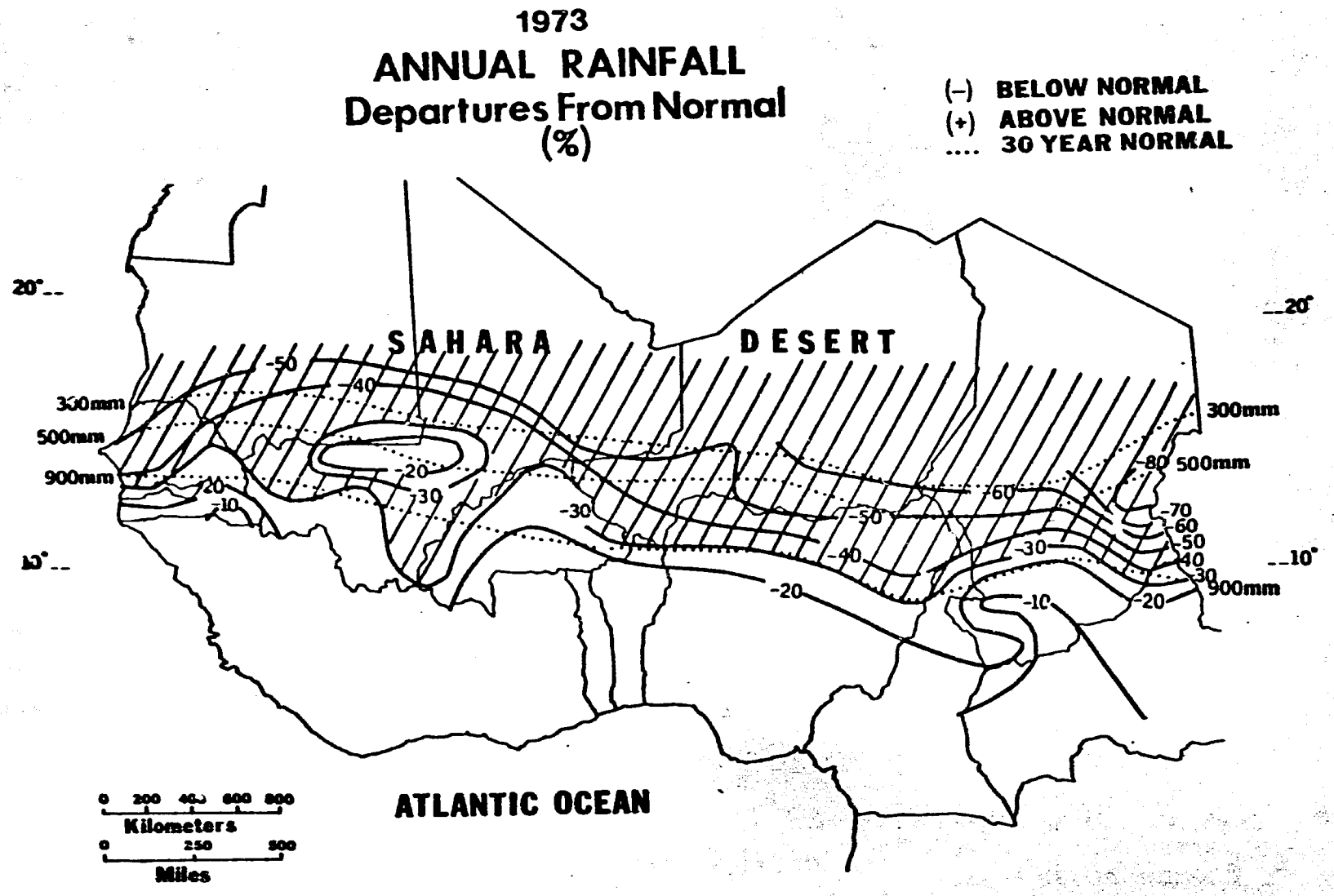


Figure 4.8. Same as Figure 4.3 in 1973.

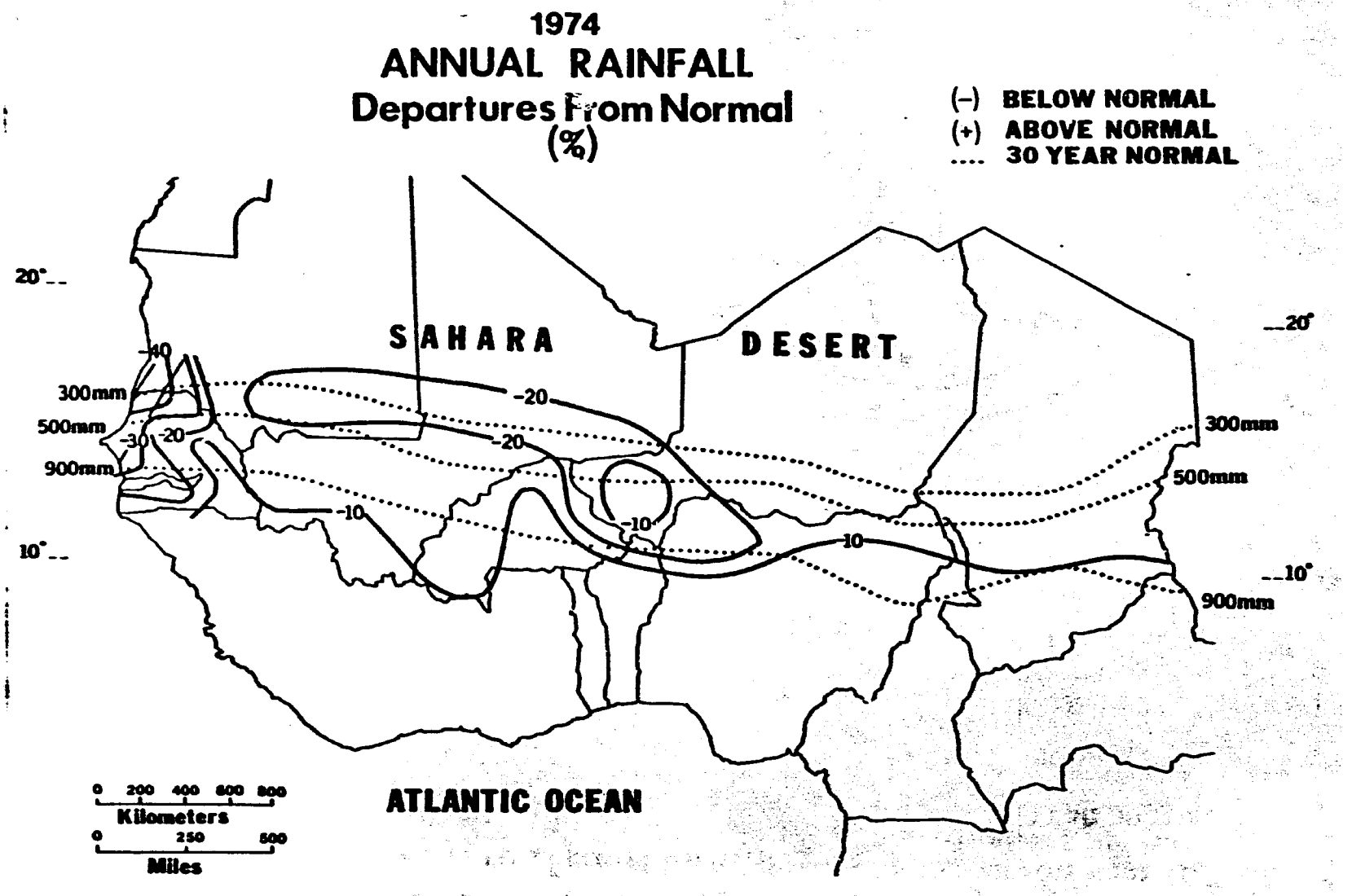


Figure 4.9. Same as Figure 4.3 in 1974.

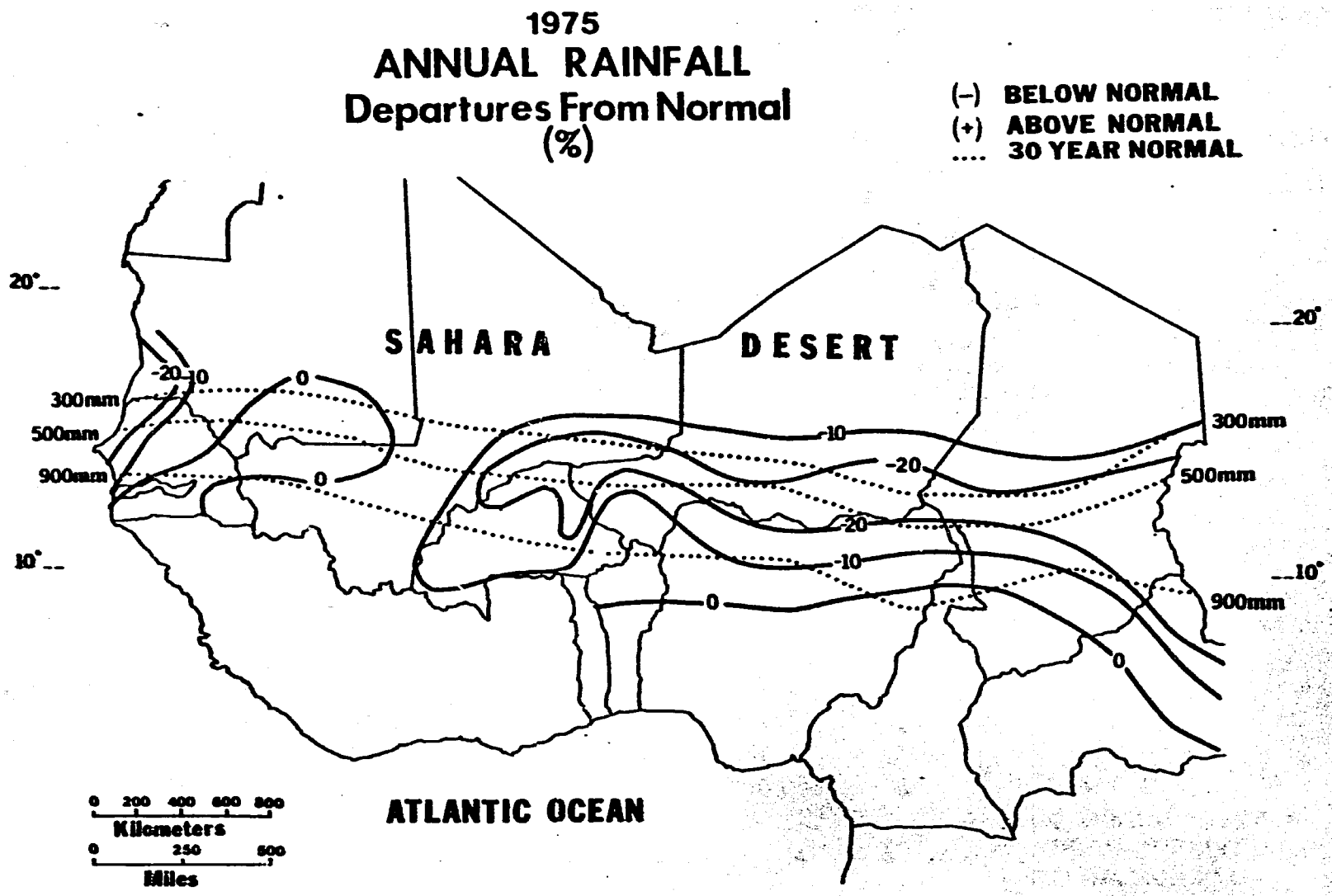


Figure 4.10. Same as Figure 4.3 in 1975.

and Mauritania in the west and parts of Mali, Upper Volta and Niger (Figure 4.5). The below normal rainfall in 1970 marked the beginning of a prolonged period of intensified drought throughout the entire Sahelian region as clearly depicted in Figures 4.5 and 4.10.

In 1971 the area of severe drought conditions in Senegal (Figure 4.6) was not as great as in 1970 but, further east, the area of severe drought expanded considerably from 1970. This area of poor rains now encompassed the entire east-west extent of both southern Niger and central Chad as indicated in Figure 4.6. In 1972 the area and intensity of drought conditions continued to increase (Figure 4.7) with many regions in the Sahel experiencing greater than 50 percent below normal rainfall. Figure 4.8 shows that in 1973 the entire Sahelian area including northern Nigeria and northern Cameroon faced severe drought conditions.

Figures 4.9 and 4.10 show a return to more normal precipitation patterns for 1974 and 1975 with the exception of a small pocket of severe drought conditions in western Senegal and southwestern Mauritania during 1974 (Figure 4.9). However, based upon available meteorological data after 1975, the prolonged period of severe drought conditions throughout the Sahel had not been completely alleviated.

This series of maps (Figures 4.3 to 4.10) presents a clear picture of the magnitude of meteorological drought conditions which have plagued the Sahelian region during the last decade.

The impact of this climatic pattern on local, rural economies throughout the region has been well-documented in the literature as discussed in Chapter II. Subsistence agriculture plays a dominant

role in these local economies which, in turn, have major influences on the entire socioeconomic policies of national governments. Having established the severity of the meteorological drought by analysis of the precipitation data, we can now examine the climatic impact on subsistence agriculture in these developing countries using agroclimatological techniques discussed in Chapter III.

C. Climate-Crop Yield Models

This section presents the results of crop yield model development using the traditional linear regression model approach (see Section III.C.1). Meteorological and agricultural data were deemed adequate for specific crop model development in Senegal, Niger, Sudan and northern Nigeria. A regional model was also developed combining the meteorological data bases for Senegal and the Gambia. Each of these models will be presented and discussed in a format by country beginning with Senegal. A brief discussion on the attempt to develop a sorghum model for Upper Volta will also be presented. Table 4.1 summarizes the statistics for the climate-crop yield models developed for individual countries during this project. Included are the weather-predictor variable, data base, intercept coefficient, slope coefficient, R^2 (coefficient of determination), standard error of estimate (quintal/hectare), standard deviation of yield (quintal/hectare), mean yield (quintal/hectare) and the coefficient of variation. R^2 represents the fraction of the variation in yield explained by the predictor variable(s).

The predictor variable for all models was the crop moisture ratio (CMR, discussed in Section III.D) for the appropriate stage of

TABLE 4.1

WEATHER-CROP YIELD MODELS FOR CENTRAL AFRICA

$$Y = A_0 + A_1 \text{ (CMR)}$$

COUNTRY	CROP	VARIABLE (CMR)	DATA BASE	A_0	A_1	R^2	S.E.E.[1] (Q/HA)	S.D.[2] (Q/HA)	MEAN (Q/HA)	COEFFICIENT OF VARIATION
SENEGAL	RICE	LATE: AUG-OCT	1963-1974	12.73	0.07	0.76	1.33	2.44	12.12	0.20
	MILLET	VEGE: JUL-AUG	1960-1973	5.42	0.02	0.68	0.44	0.74	4.92	0.15
	GROUNDNUTS	FLOW: AUG-SEP	1966-1974	8.14	0.04	0.68	0.82	1.36	7.48	0.18
	COWPEAS	VEGE: JUL-AUG	1963-1974	3.14	0.02	0.62	0.42	0.65	2.77	0.24
	CORN	FLOW: JUL-SEP	1966-1973	7.82	0.03	0.53	0.61	0.83	7.73	0.11
NIGER	MILLET	FLOW: AUG-SEP	1964-1975	4.84	0.02	0.62	0.50	0.77	4.29	0.18
	SORGHUM	FLOW: AUG-SEP	1964-1975	5.31	0.04	0.73	0.68	1.26	4.56	0.28
SUDAN	MILLET	FLOW: AUG-SEP	1961-1975	5.36	0.03	0.60	0.82	1.26	5.01	0.25
	SORGHUM	VEGE: JUL-AUG	1961-1975	8.04	0.03	0.64	0.66	1.06	8.15	0.13
	SESAME	FLOW: AUG-SEP	1961-1975	3.82	0.03	0.71	0.46	0.82	3.51	0.23
NIGERIA	SORGHUM	VEGE: JUL-AUG	1964-1975	6.87	0.02	0.54	0.51	0.72	6.79	0.11

[1] STANDARD ERROR OF ESTIMATE

[2] STANDARD DEVIATION OF YIELD

crop development. The CMR is a measure of available crop moisture with respect to the potential moisture demand of rain-fed agricultural crops. Model results show that this parameter provides an adequate indicator of moisture availability for a crop grown in regions of alternating dry and wet seasons.

The CMR is computed from precipitation data and potential evapotranspiration estimates for successive growth stages; namely, planting, vegetative, reproductive (or flowering) and late (or maturation). Therefore, crop calendar information is essential for the computation of the CMR. The important information includes such agronomic practices as approximate planting dates, length of growth season, types of crop varieties grown in a specific region and phenological information. All of this information may not be available in a given region under study. It was, therefore, necessary to make inferences from available crop calendar information.

With regard to crop growth stages, most crops grown in the semi-arid region south of the Sahara Desert are planted after the first meaningful rains which usually begin in June. Thus, the crop calendar begins at planting. Vegetative growth occurs primarily throughout July and August. Flowering and reproduction follow in early September, and seed grain reaches maturation by October. There are, of course, departures from the described scheme depending upon locality, cultural practices and topography. Moreover, in higher rainfall zones with longer wet seasons such as in Upper Volta, the crop calendar is adjusted to account for longer crop growth cycles.

The analysis of crop-weather relationships in this study revealed that the CMR, using meteorological data, can provide meaningful information in model development for cereal and cash crops (see Table 4.1). An advantage of using the crop moisture ratio in model development is that an assessment of potential yield estimates can be made at successive growth stages based upon the available meteorological data. An example is presented later for millet grown in Mali. These assessments can be updated during each stage of crop development until a final yield estimate is made at the end of the wet season.

The model results vary by country as follows.

1. Senegal

Considerable success was achieved in crop yield model development work for Senegal. Due to the large north-south gradient in rainfall regimes, an important task was to identify the major crop regions within the country. Rainfall varies greatly with average amounts decreasing from more than 1,600 mm in the southwestern portion of Senegal to less than 500 mm in the north; Figure 4.11 shows the major crop regions and the 500 mm and 1600 mm isohyet lines. Approximately 80 percent of the rice production in Senegal is grown in the Casamance region which is located in the southwestern portion of the country (Berg, 1977). The major area of millet, cowpeas and groundnut production is situated in the so-called Groundnut Basin. This agricultural area is to the north of the Gambia in western Senegal. About 75 percent of the millet and 80 percent of the groundnut production is from this region (Berg, 1977).

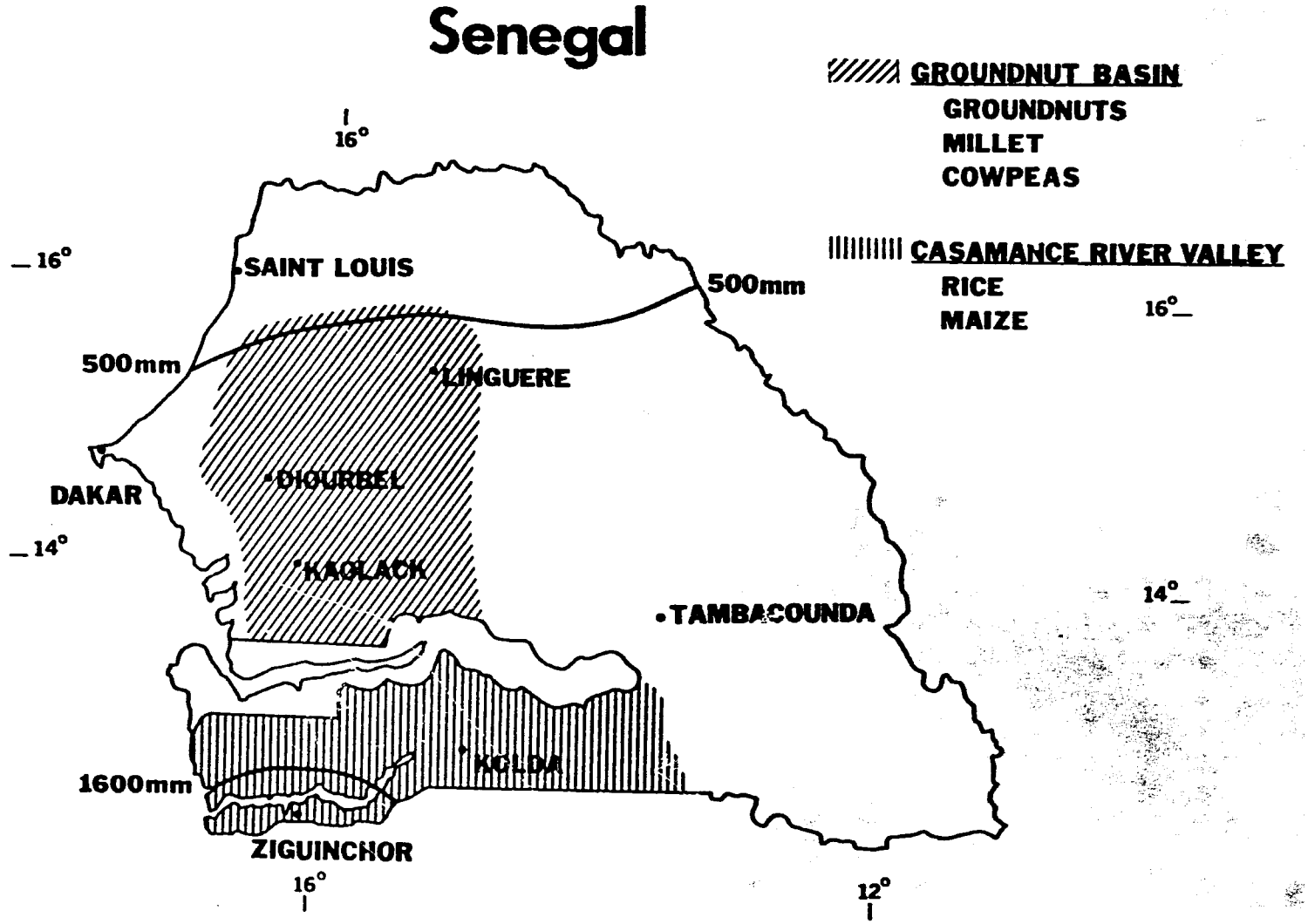


Figure 4.11. Map of Senegal depicting major agricultural regions and 500 mm and 1600 mm isohyets.

The Senegal rice model is presented in Figure 4.12. The data base for the model development covered 1963-1974. The most significant predictor variable for rice grown under non-irrigated conditions was the crop moisture ratio (CMR) for the late stage of crop development (i.e., August-October). R^2 was 0.76 (Table 1). The good response of this predictor variable to variations in actual rice yields reflects the importance of high temperature, ample light and adequate moisture during the seed development and maturation stage.

Two years of independent test data (1975, 1976) for the Senegal rice model compared very well with model estimates. These test data were obtained from the West African Rice Development Association (WARDA), Monrovia, Liberia. Unofficial estimates for 1977 support model estimates of a large drop in rice yields as compared to the previous two years.

One point should be elaborated concerning this particular model and all following models developed for Senegal. A well-documented rise in producer prices for almost all agricultural crops occurred in 1974 (Berg, 1977). Production and acreage statistics for 1974 suggested that these changes in the marketing structure influenced crop yields. To account for this non-weather related event in 1974, an adjustment was made in the Senegal rice model for the 1974 crop year.

A comparison between yield fluctuations and fluctuations in growth-stage precipitation was made to examine the relationship between

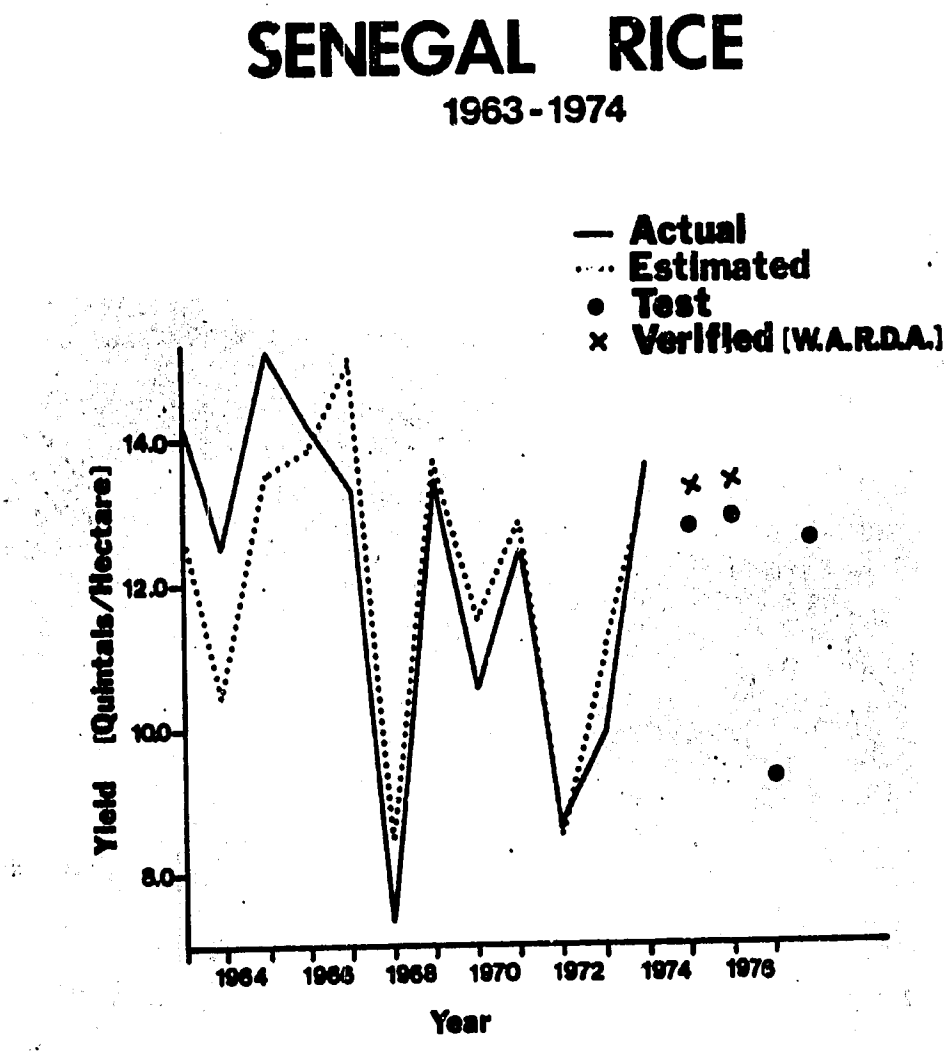


Figure 4.12. Senegal rice model. Independent data for 1975 and 1976 were obtained from the West African Rice Development Association (WARDA), Monrovia, Liberia. Yield estimates for 1977 and 1978 are also included.

yield and rainfall during successive stages of growth. Figure 4.13 presents such a comparison for millet grown in Senegl. The upper portion shows the yield fluctuations while the lower portion shows rainfall fluctuations during both the vegetative (early season) and reproductive (late season) stages. In general, there is a tendency for both stages to show similar precipitation patterns with the notable exception in 1966. Rainfall during the early season was more than 60 percent below normal but was only 10 percent below normal later in the season. The importance of timing of rainfall during crop growth can be seen by the fact that yields dropped by more than 15 percent from the previous year. The impact of poor early season rainfall might have been an important factor in decreased yields. The late rains probably helped prevent even further decreases in yields but were too late for the crop to recover completely.

Figure 4.13 also reveals another important problem in data analysis. Prior to 1965 there is relatively little variation in yield even though rainfall exhibits yearly fluctuations (especially after 1963). This emphasizes a recurring problem, particularly in the historic crop yield data bases (i.e., suspect data in the early years following independence). This problem has been quality controlled very closely, and in many cases the data from the early years have been excluded from regression analysis.

Results of the Senegal millet model, developed from 1960-1973 data, are presented in Figure 4.14. Model estimates are included for 1974-1978. The best predictor variable was the CMR for the vegetative

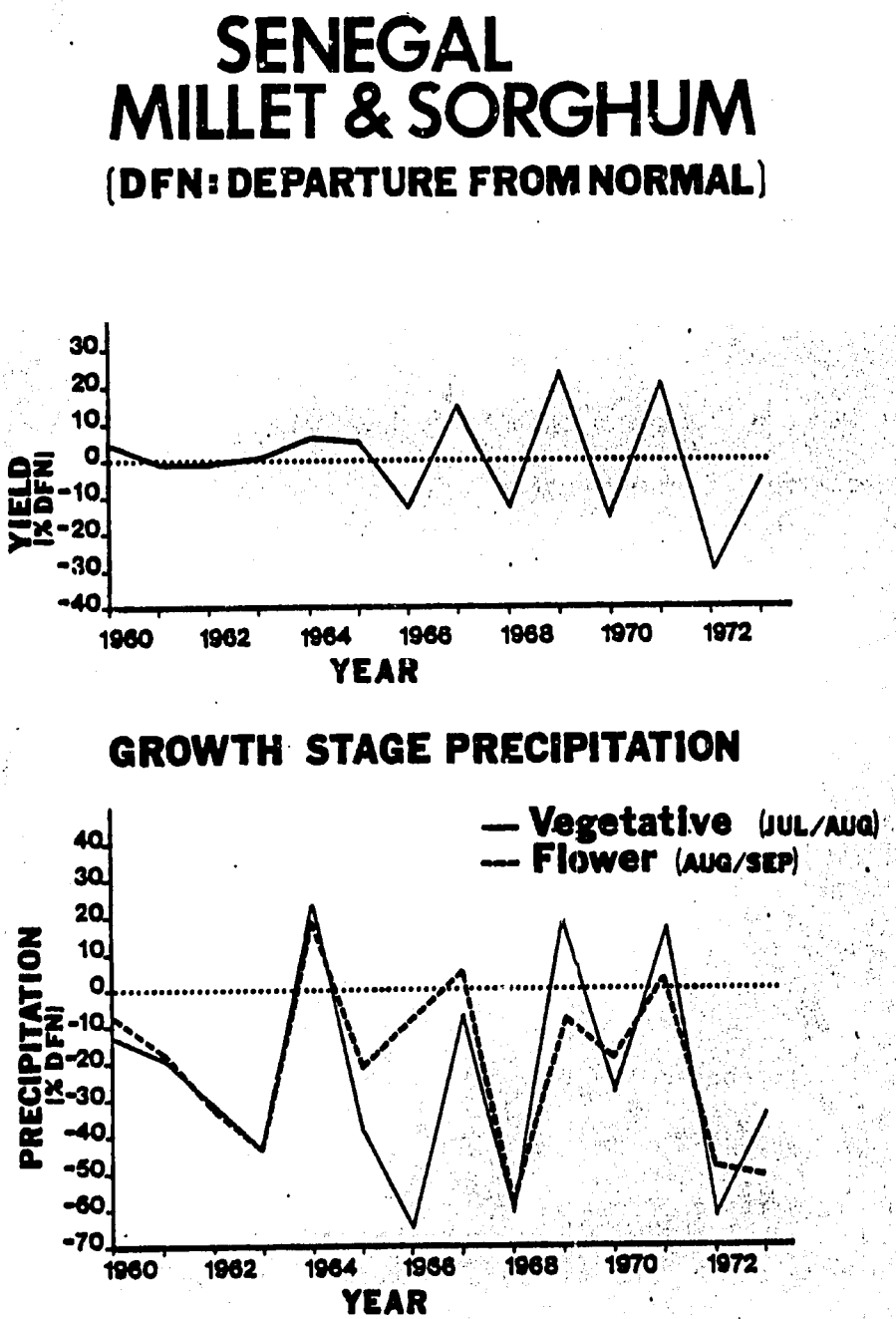


Figure 4.13. Comparison of fluctuations in annual millet yields (top) and growth stage precipitation (bottom) for both the vegetative and reproductive (flower) stages in Senegal.

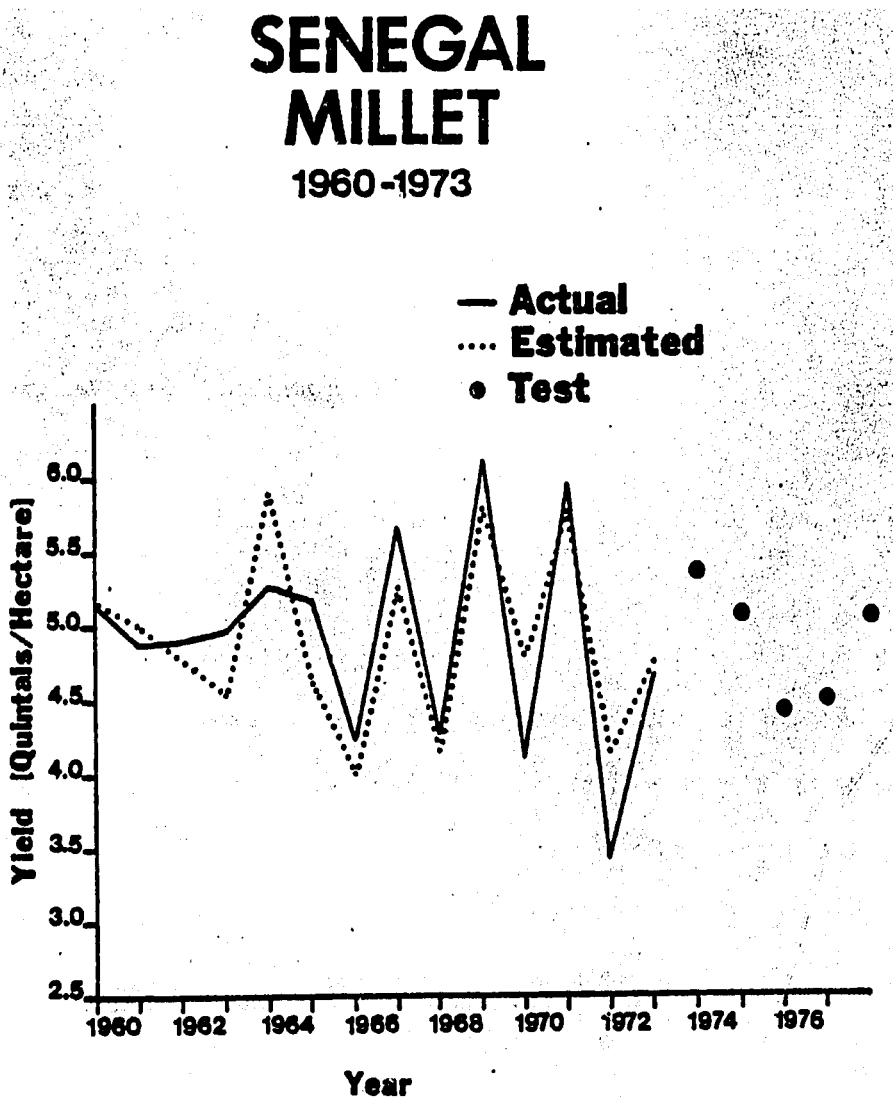


Figure 4.14. Senegal millet model with yield estimates for 1974 through 1978.

stage with an $R^2 = 0.68$ (Table 4.1). The model estimates do reasonably well with actual estimates. Unofficial estimates were obtained through the AID Mission in Dakar, Senegal. As noted in the discussion of the Senegal rice model, 1974 estimates were affected by marketing changes at the producer level.

Figure 4.15 contains the data and estimates from the Senegal groundnut model. During the earlier years (i.e., 1960-1965), there was a poor correlation between groundnut yields and all climatic or agroclimatic variables. After 1965 the model reflected observed yields quite well, using the CMR for the flowering stage as the predictor variable ($R^2 = 0.68$, Table 4.1).

The groundnut crop is a major export commodity for the Senegalese economy. As such this crop has been geared to a nationalized marketing agency since 1960 (Berg, 1977; Nelson, et al., 1974). As noted in Section III.B., there was a period of instability in the cooperative-marketing system established by the government which led to reforms of the system in the early 1970's. The points representing actual groundnut yields in Figure 4.15 exhibit a negative trend. The decline in both groundnut production and yield were likely due to both adverse weather conditions during the growing season as well as peasant unrest and dissatisfaction with the cooperative system.

The Senegal cowpeas model is presented in Figure 4.16. As with millet, the best predictor variable for cowpeas was found to be CMR vegetative stage with $R^2 = 0.62$ (Table 4.1). Cowpeas are usually grown in combination with millet and provide an important pulse crop for regions of low rainfall.

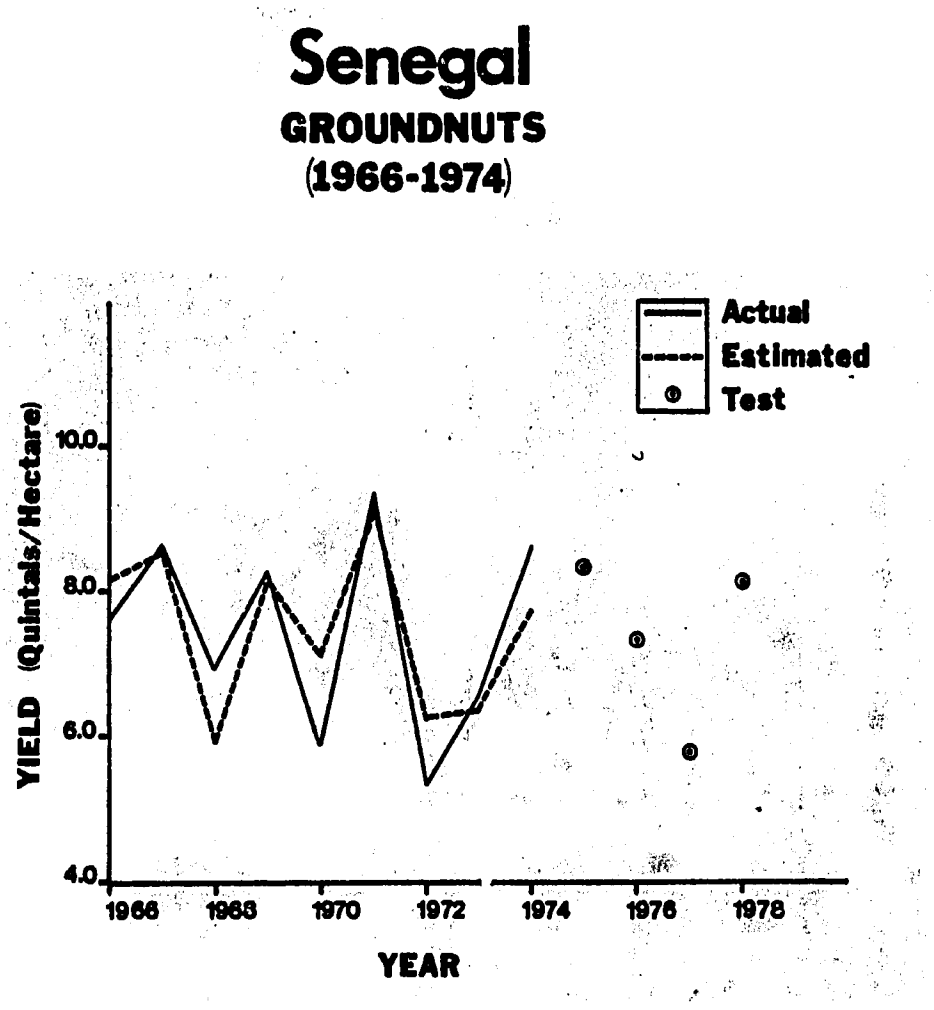


Figure 4.15. Senegal groundnut model with yield estimates for 1975 through 1978.

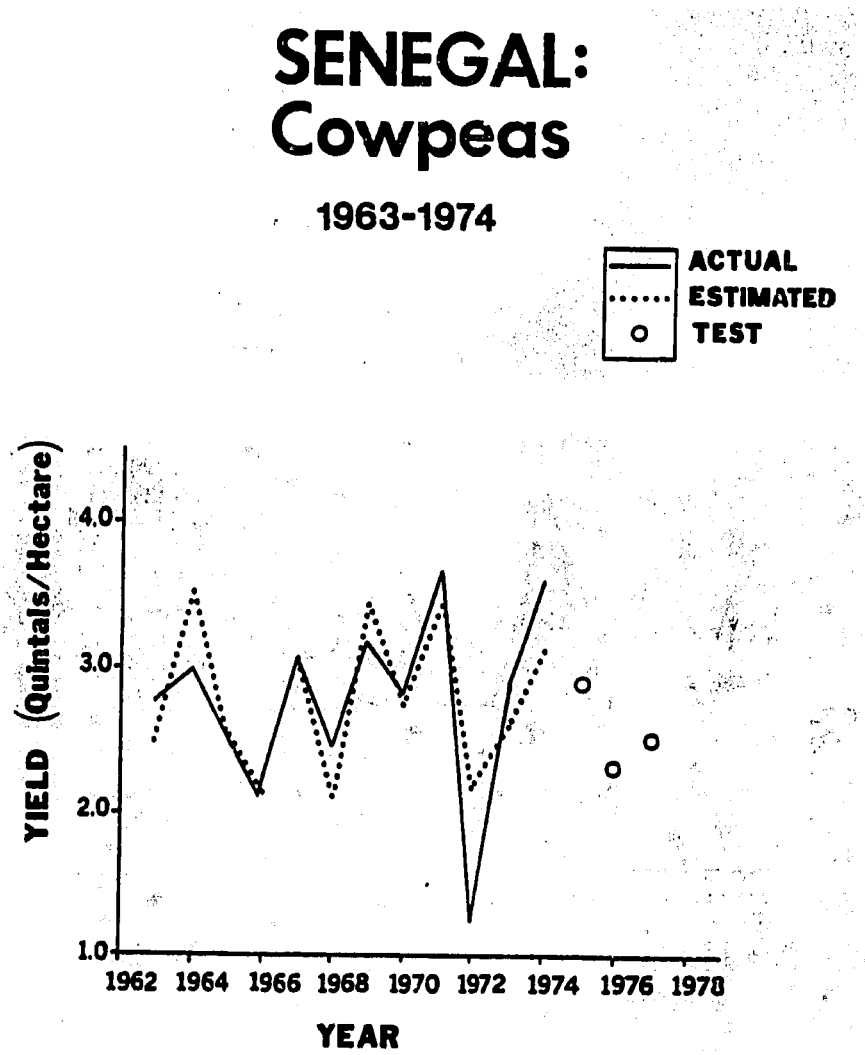


Figure 4.16. Senegal cowpeas model with yield estimates for 1975 through 1977.

Figure 4.17 presents the model fit and test data for corn grown in Senegal. It is important to note the difference in the performance of the corn model developed with early years of data and that developed excluding those early years. Figure 4.17 shows a sharp, but nearly linear, decline in yield from 1960 to 1965 which could not be explained by meteorological variables. With the years 1960 through 1965 omitted from the analysis, the explained variance, R^2, increased from 0.26 to 0.53 (Table 4.1). These results, in conjunction with results of model development for groundnuts (Figure 4.15), suggest that the crop statistics in the early years following Senegal's independence may not be reliable for use in crop yield modeling efforts.

The Gambia is situated between the Groundnut Basin area of Senegal and the Casamance River Valley region of Senegal. It was decided to incorporate meteorological data from the Gambia in the computation of CMR for development of both the Senegal millet and rice models. Crop yield data were available only for Senegal, however. The results of both regional millet and rice models along with test data are presented in Figures 4.18 and 4.19, respectively. R^2 equals 0.56 and 0.71 for the regional millet and rice models, respectively, as compared to 0.56 and 0.76 for the millet and rice models developed from Senegalese data only. These results indicate consistency among data from both Senegal and the Gambia.

2. Niger

Figure 4.20 shows a map of Niger which indicates the strong dependence of subsistence agriculture on adequate rainfall during the

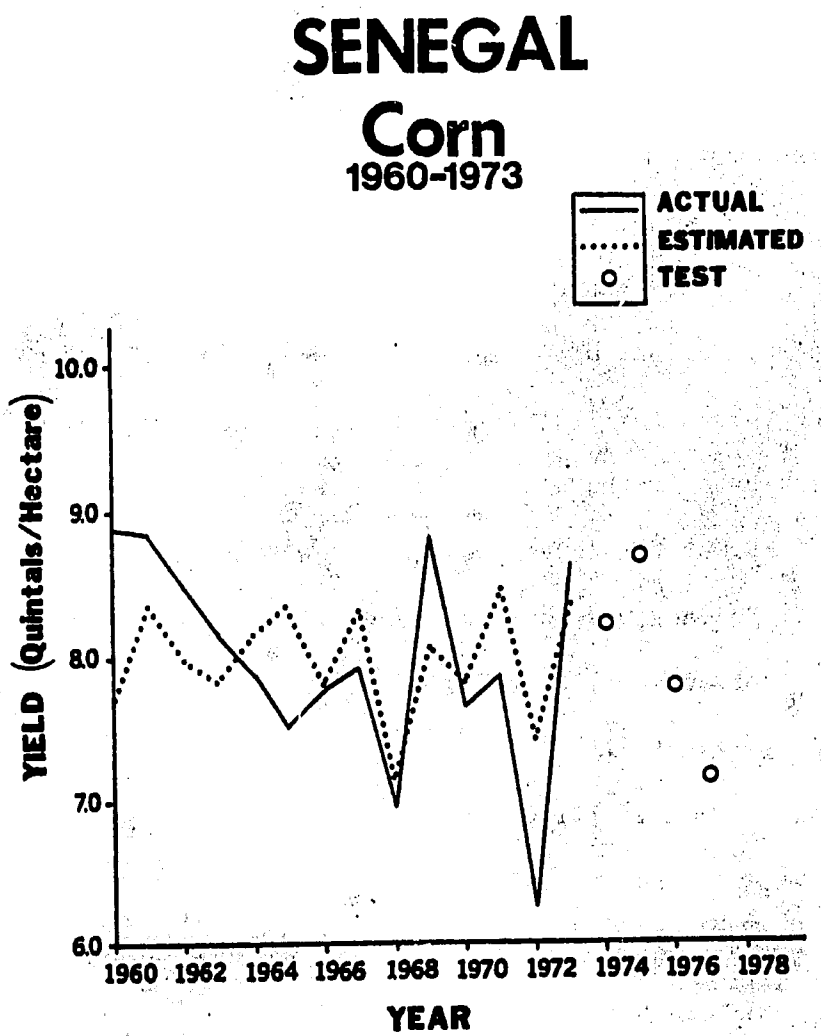


Figure 4.17. Senegal corn model with yield estimates for 1974 through 1977.

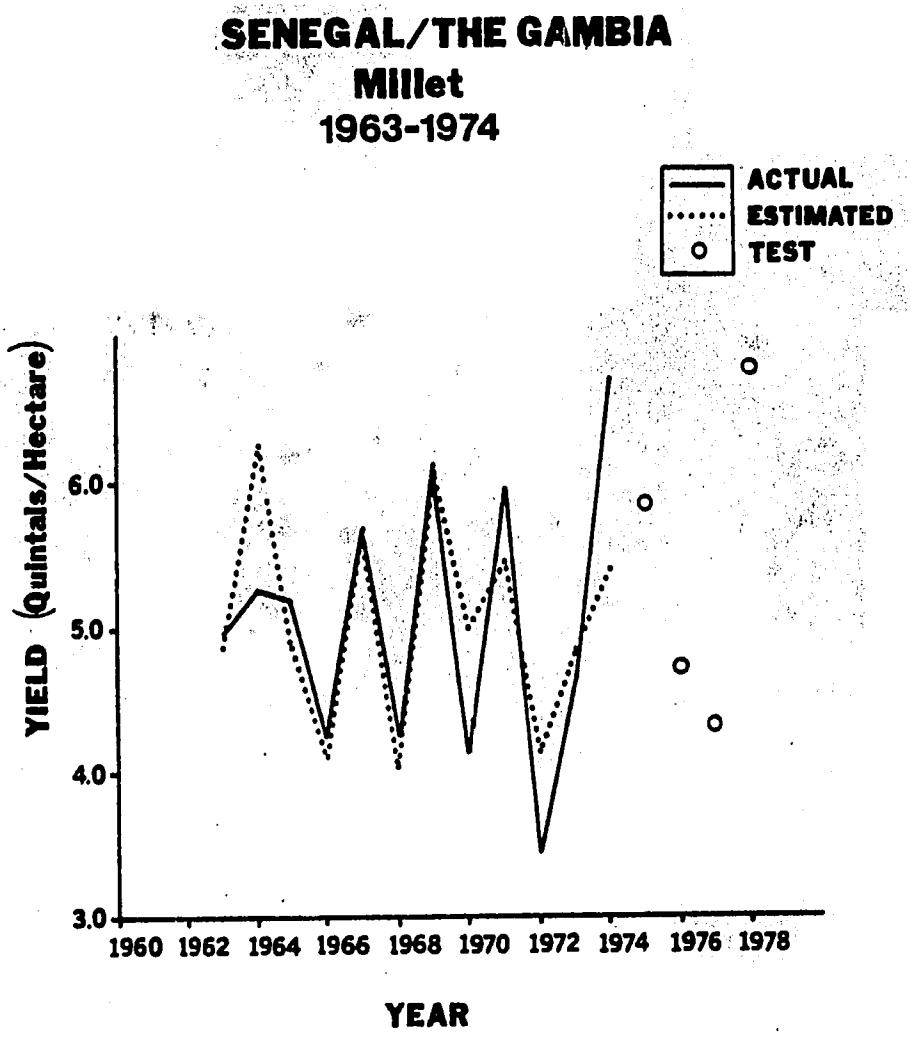


Figure 4.18. Senegal/The Gambia regional millet model with yield estimates for 1975 through 1978.

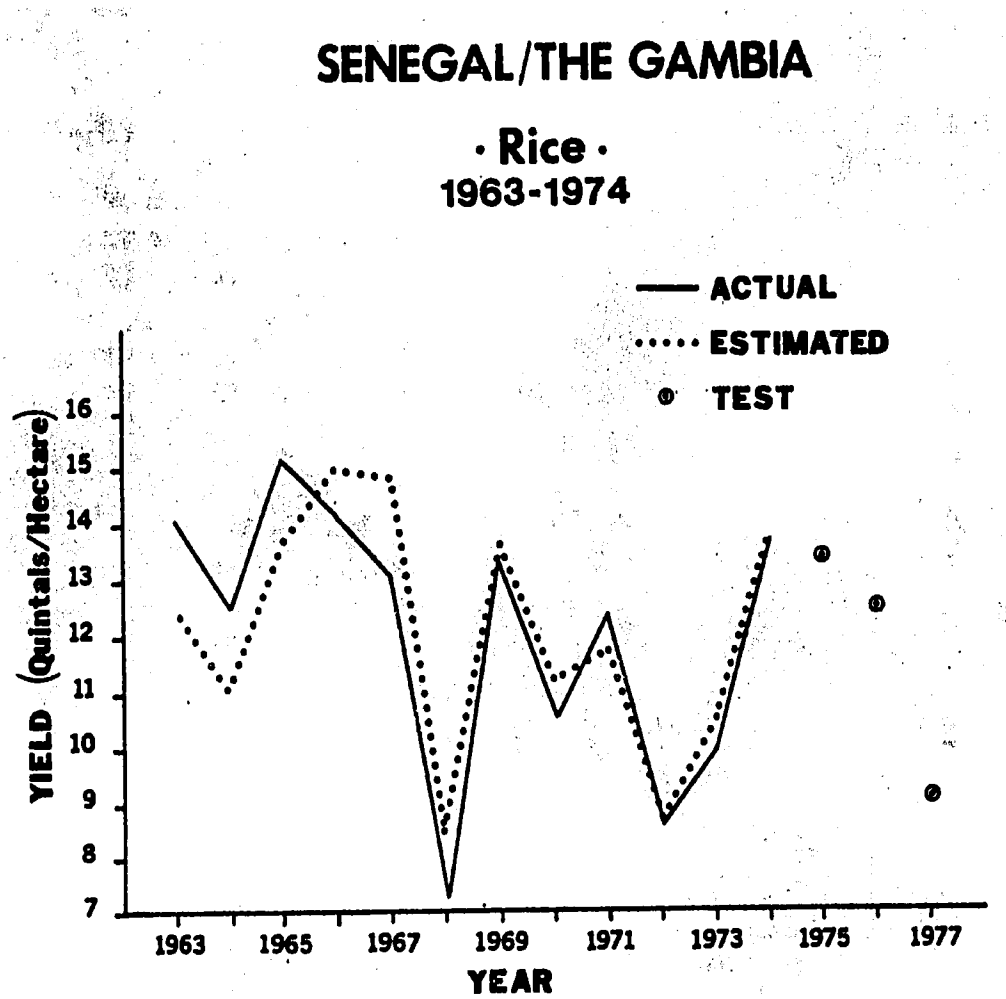


Figure 4.19. Senegal/The Gambia regional rice model with yield estimates for 1975 through 1977.

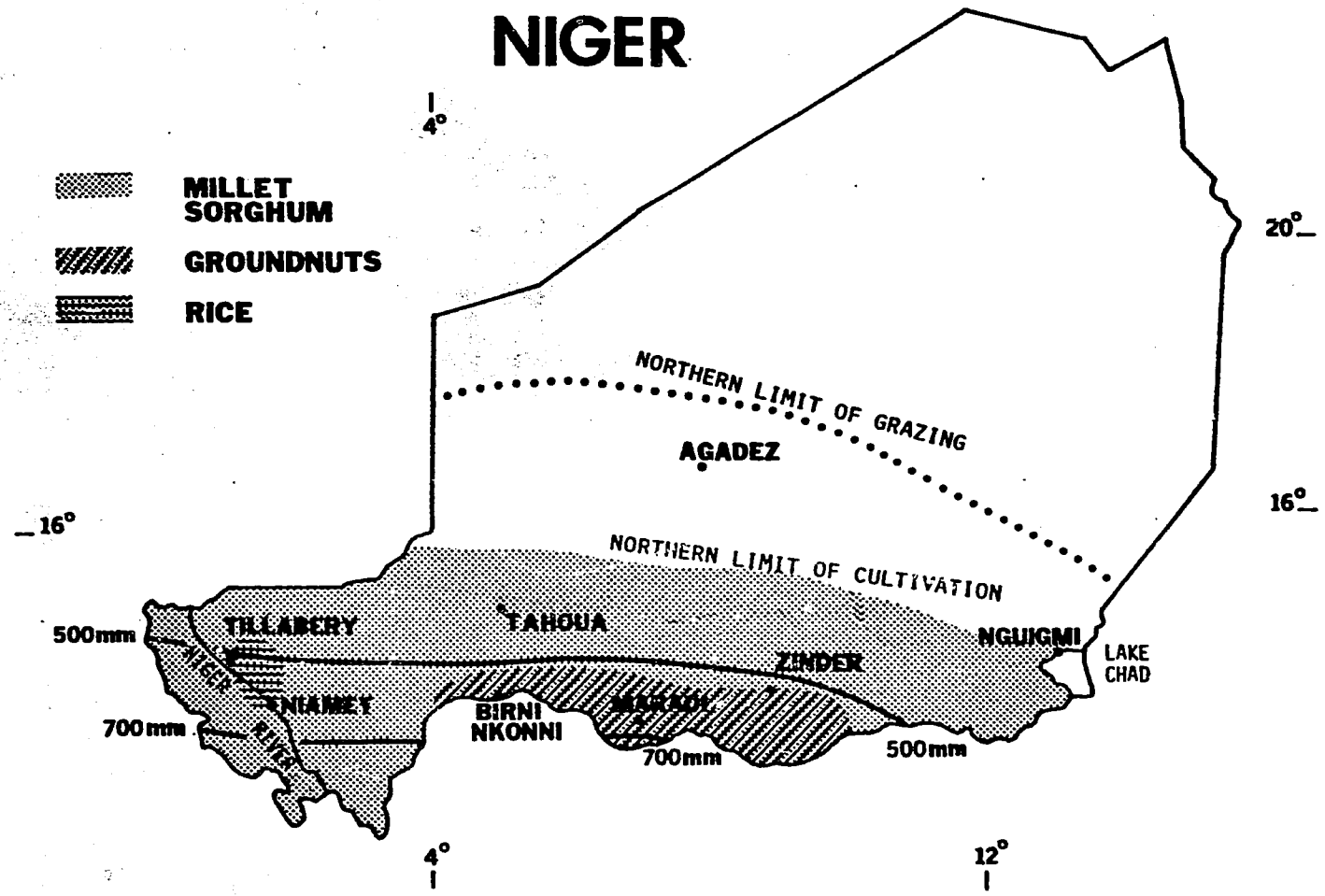


Figure 4.20. Map of Niger depicting major agricultural regions and 500 mm and 700 mm isohyets.

growing season. Agricultural production activities are restricted to the southern-most regions of the country. The yearly percentage departures from normal (DFN) for millet and sorghum grown in Niger and corresponding DFN for growth stage precipitation are presented in Figures 4.21 and 4.22. In summary, both Figures 4.21 and 4.22 show decreasing millet and sorghum yields throughout the entire period (1964-1975). The corresponding precipitation patterns, also shown in these figures, indicate similar tendencies of decreasing annual rainfall with large yearly fluctuations.

Figures 4.23 and 4.24 present the model fit and test data for Niger millet and sorghum, respectively. Model results compare reasonably well with actual estimates. R^2 equals 0.62 for Niger millet and 0.73 for sorghum (Table 4.1). A major problem was highlighted in Niger with regard to the competition between the export crop (groundnuts) and the major subsistence crops (millet and sorghum) for the existing cultivated lands.

A comparison of the acreage devoted to both millet and groundnuts is presented in Figure 4.25. Beginning in 1968 there are some major shifts in the acreage patterns of these two crops. An increase in acreage of one crop usually corresponds to a decrease in acreage of the other. A drastic decline in groundnut acreage began after 1972.

The impact of shifting patterns in crop acreage on yields can be significant. For example, a significant increase in millet acreage in 1969, which came largely at the expense of groundnut acreage (Becker, 1974), was probably caused by a large deficit in cereal

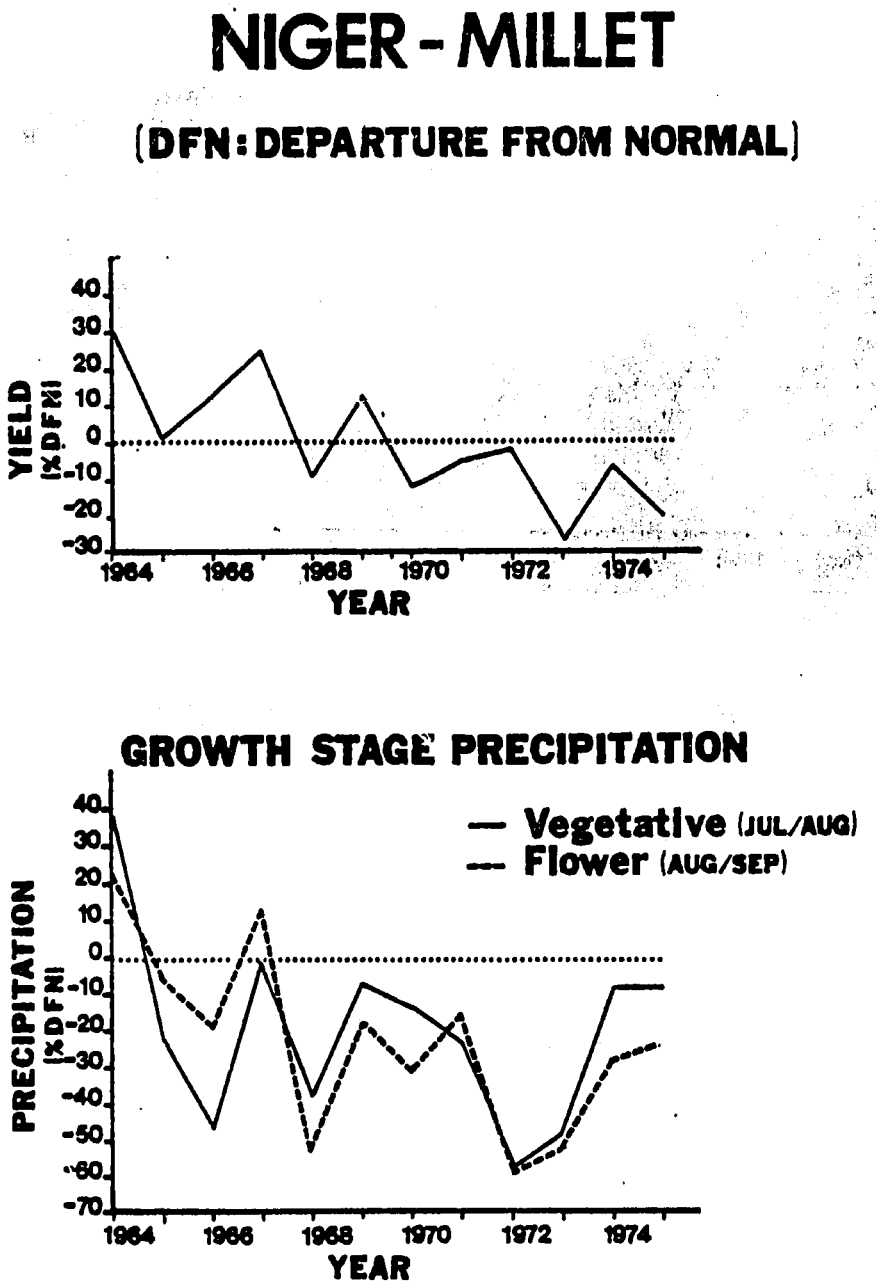


Figure 4.21. Comparison of fluctuations in annual millet yields (top) and growth stage precipitation (bottom) for both the vegetative and reproductive (flower) stages in Niger.

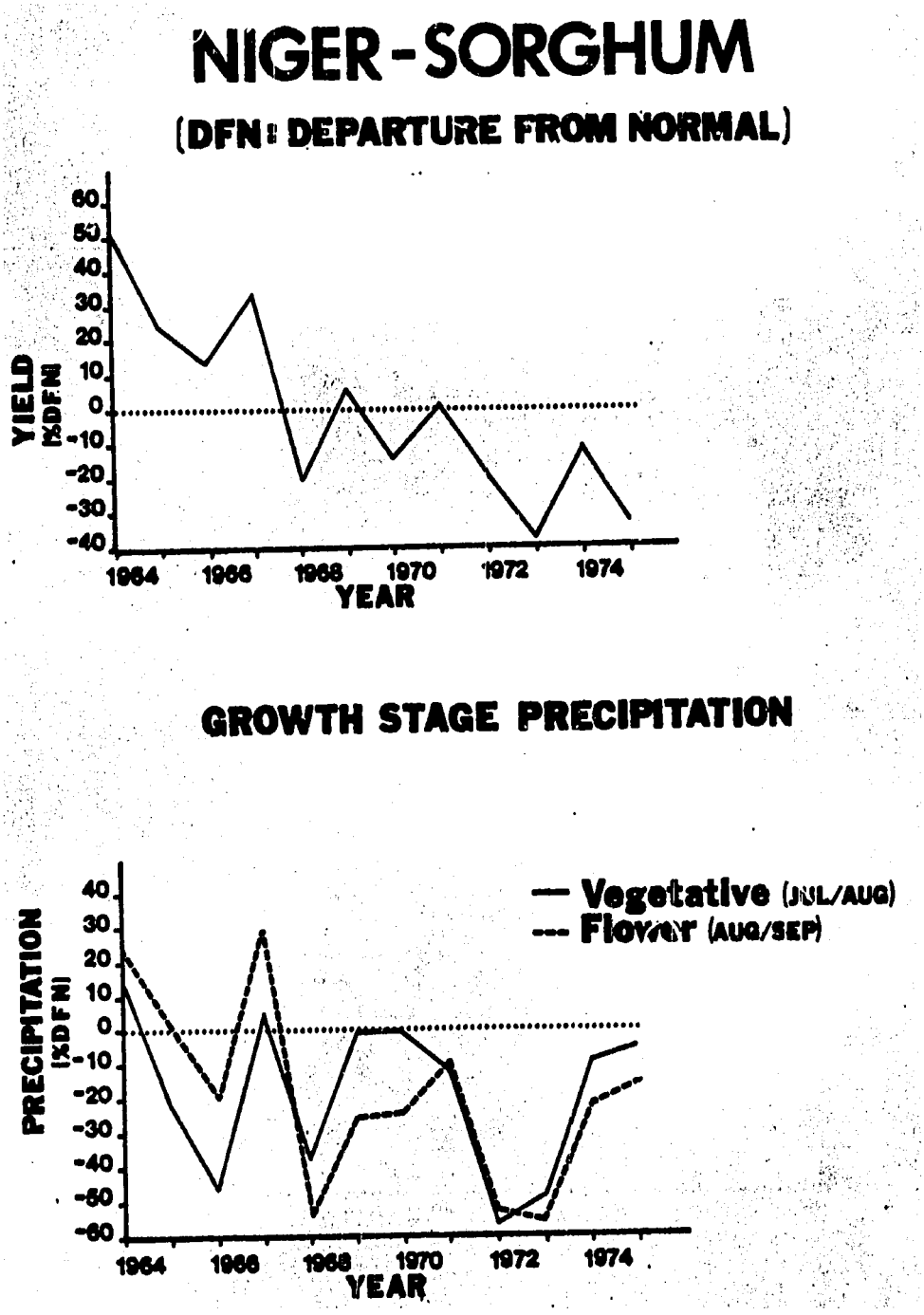


Figure 4.22. Same as Figure 4.21 for sorghum.

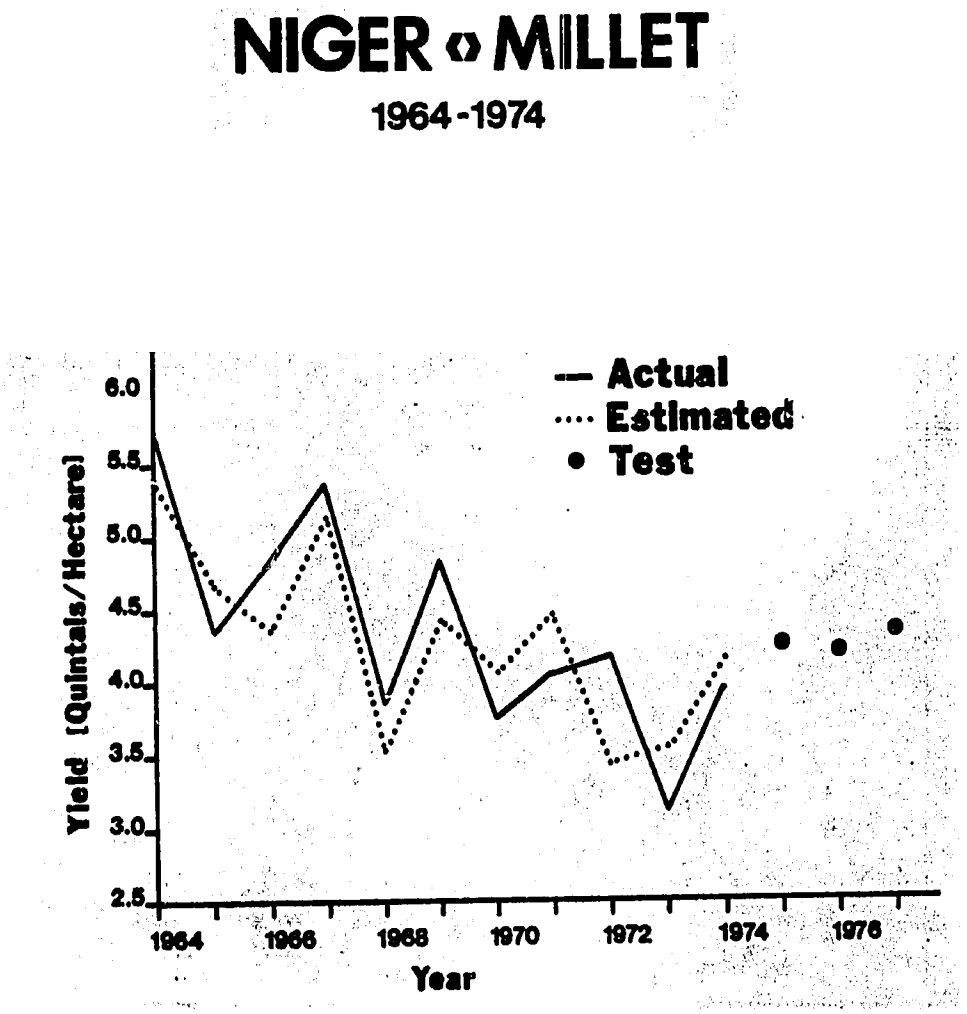


Figure 4.23. Niger millet model with yield estimates for 1975 through 1977.

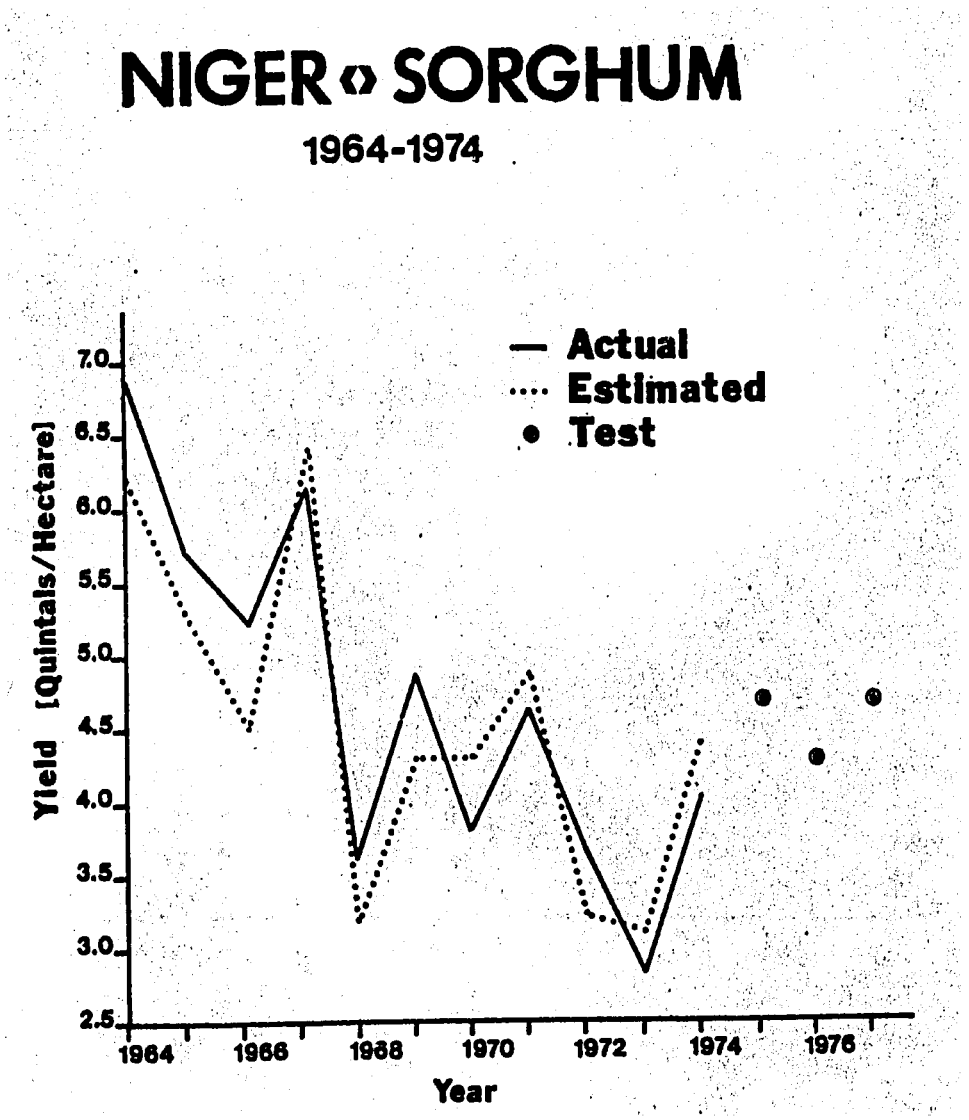


Figure 4.24. Niger sorghum model with yield estimates for 1975 through 1977.

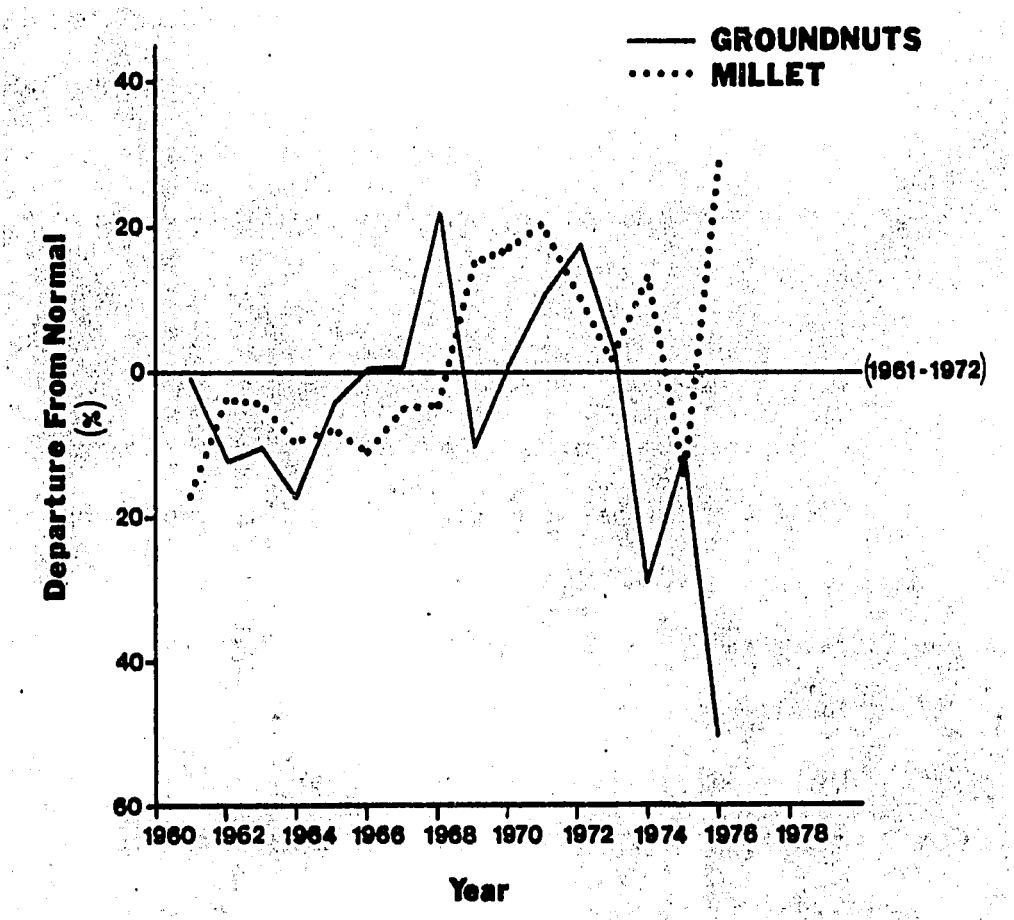


Figure 4.25. Comparison of acreage planted to groundnuts and millet in Niger from 1961 to 1976.

production during the severe drought year of 1968. The emphasis on cereal production in 1969 boosted millet production to an all-time high although rainfall was slightly below average. During the next few years, however, the prolonged period of below normal rainfall caused millet and sorghum yields to decrease even though emphasis was on subsistence food production.

Attempts to model Niger groundnuts were not successful. It is believed that this is, in large part, due to the acreage problem discussed in the last paragraph. There are positive correlations between weather variables and yield statistics for Niger groundnuts, especially during the reproductive stage; however, there is not a high enough level of confidence in these relationships to support reliable model estimates.

3. Sudan

Figure 4.26 presents a comparison between yield fluctuations for Sudan millet and fluctuations in growth stage precipitation during successive growth stages. A pattern similar to that found in Senegal and Niger is observed in these data; i.e., a tendency for decreasing yields and rainfall beginning in the mid-1960's.

Models for millet, sorghum and sesame grown in Sudan are presented in Figures 4.27, 4.28, and 4.29. The explained variances (R^2) for each model were 0.60, 0.64 and 0.71, respectively (see Table 4.1). As with cash crops grown in West Africa, the sesame crop showed a sharp decline in yields throughout the 1960's and early 1970's. The

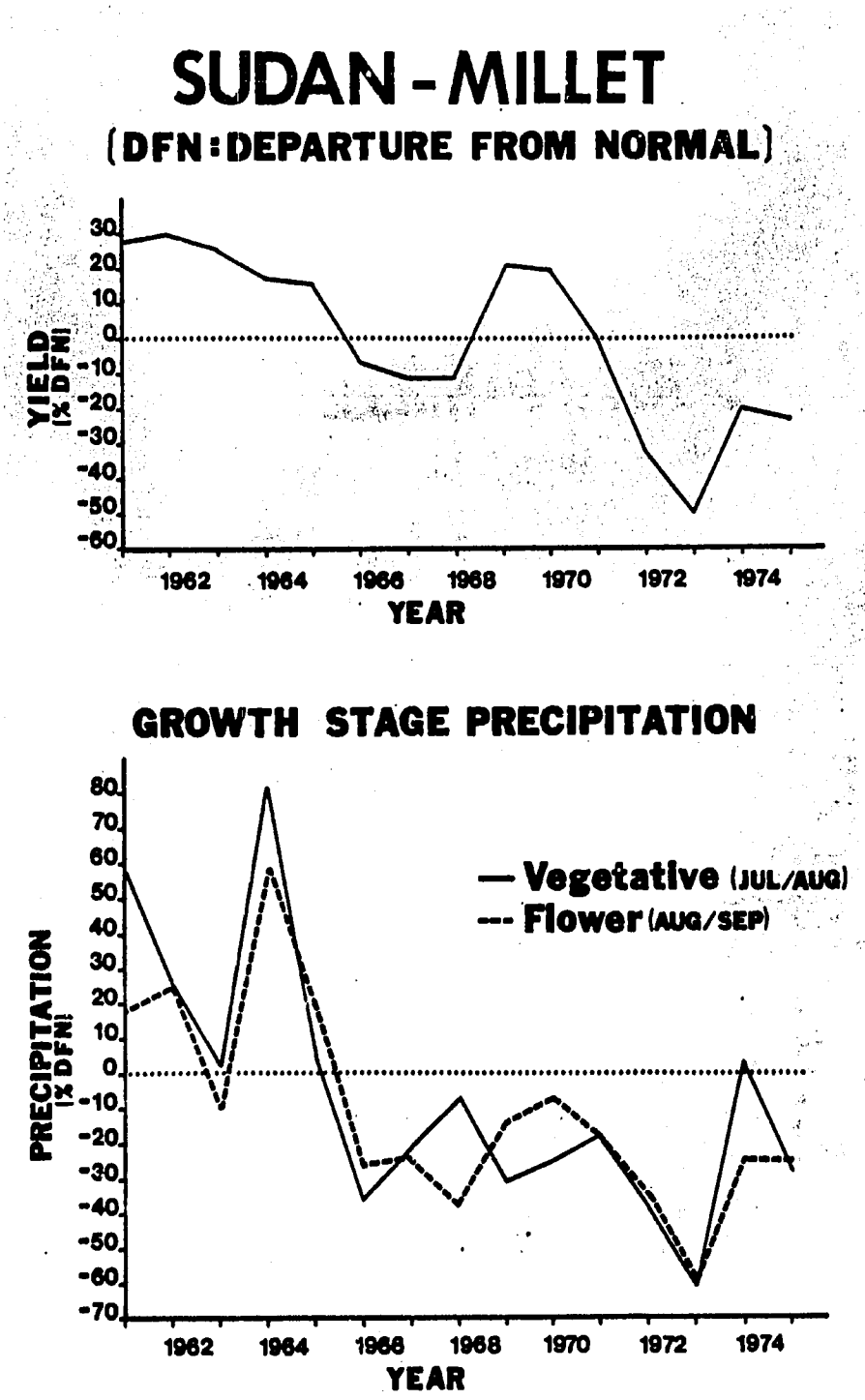


Figure 4.26. Comparison of fluctuations in annual millet yields (top) and growth stage precipitation (bottom) for both the vegetative and reproductive (flower) stages in Sudan.

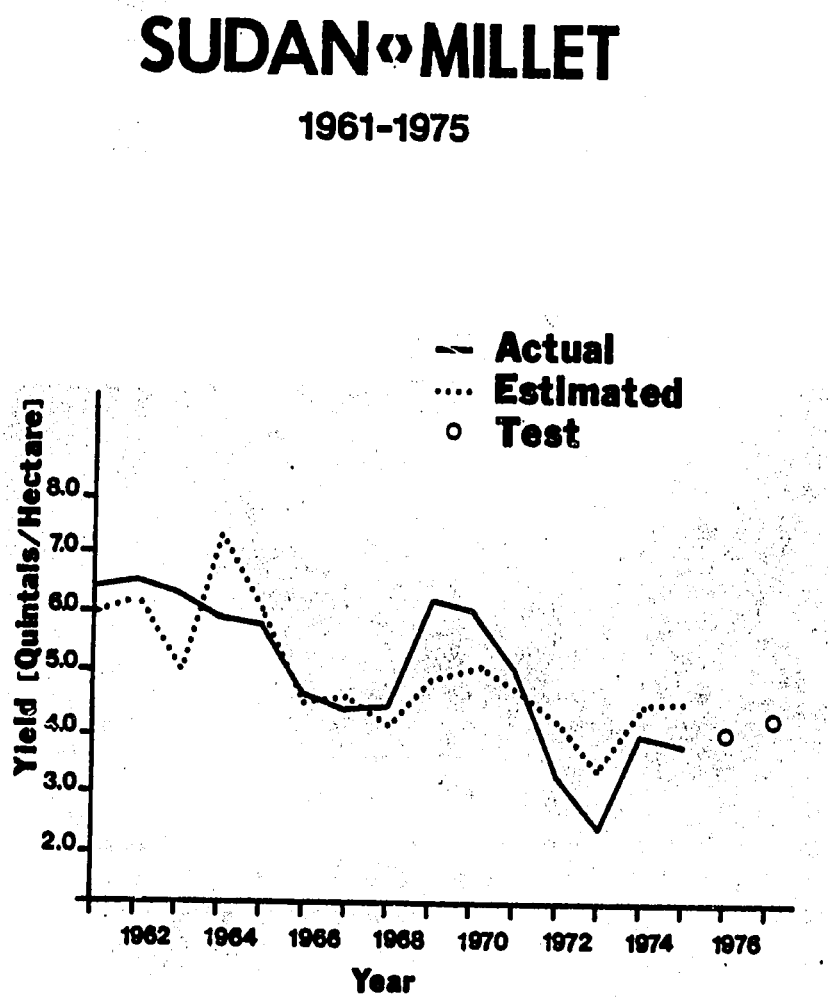


Figure 4.27. Sudan millet model with yield estimate for 1976 and 1977.

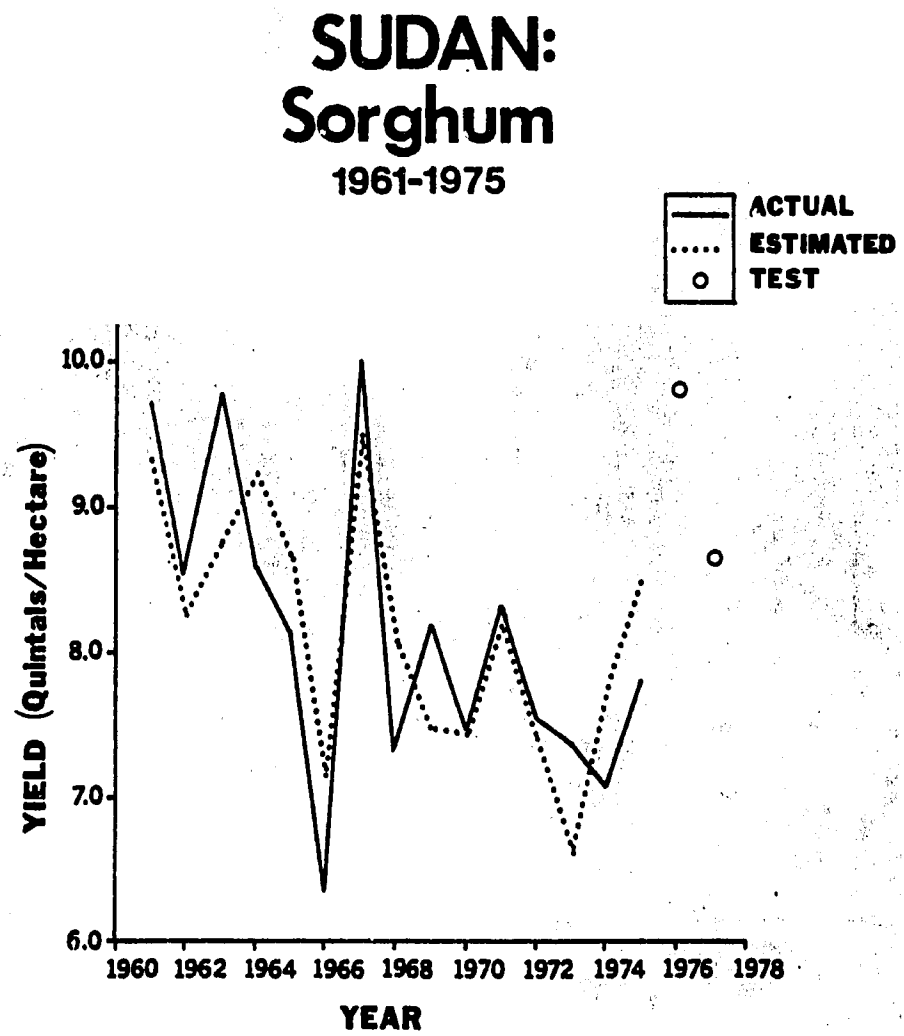


Figure 4.28. Sudan sorghum model with yield estimates for 1976 and 1977.

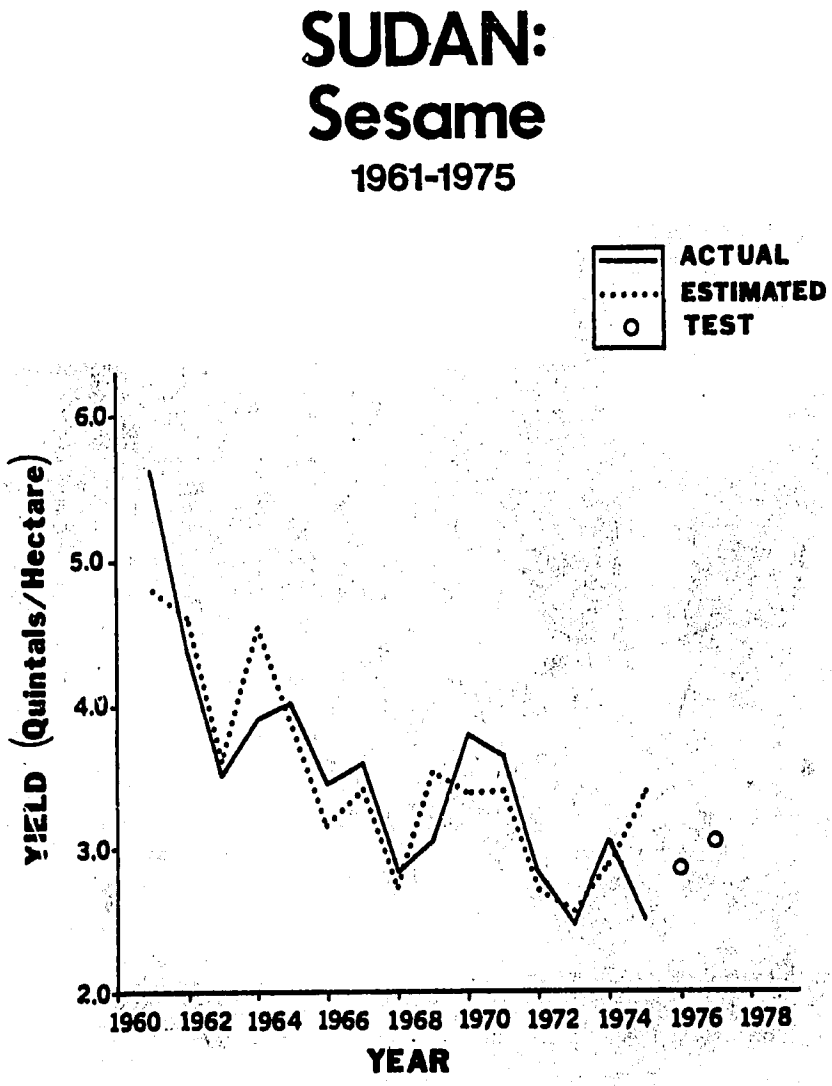


Figure 4.29. Sudan sesame model with yield estimates for 1976 and 1977.

yield reduction reflected the decrease in seasonal rainfall as indicated by Figure 4.26.

4. Nigeria

A model for sorghum grown in northern Nigeria, within the Sahelian Zone, was developed as shown in Figure 4.30. Model estimates compared reasonably well with actual yield data ($R^2 = 0.54$, Table 4.1). The best predictor variable for the sorghum model was the CMR for the vegetative stage. Attempts to develop a millet model failed because millet data showed no consistent response with the climate data.

The usefulness of the Nigerian sorghum model on an operational basis may be restricted by the lack of available meteorological data. Only two stations were available in northern Nigeria which report temperature data as compared to a total of six stations reporting precipitation. The loss of either of the temperature reporting stations during critical periods of the crop season may seriously affect the computation of the crop moisture ratio. These model results may serve to qualitatively support model results in other sorghum producing regions, however.

5. Upper Volta

Efforts to develop a sorghum model for Upper Volta proved unsuccessful due to inherent difficulties in the agricultural data base (see Section III.A.1). A preliminary model was developed which showed a relatively good correlation between observed yields and the CMR for the late stage (i.e., September-October).

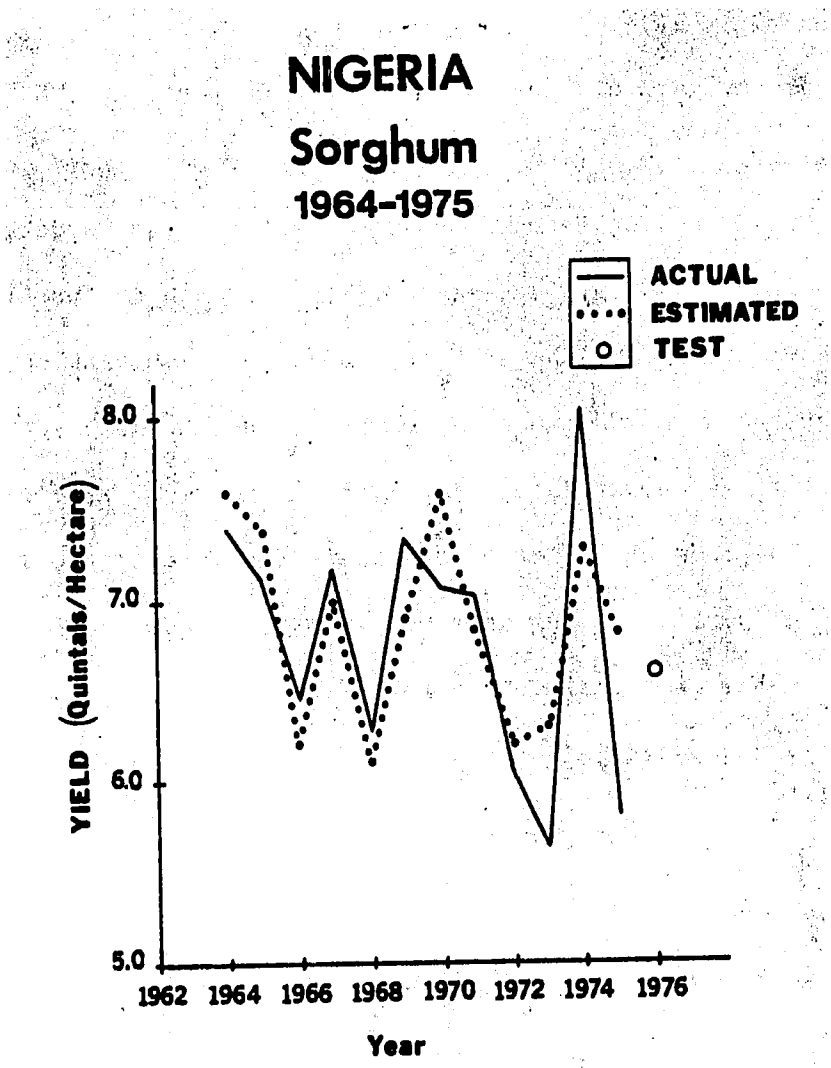


Figure 4.30. Nigeria sorghum model with yield estimates for 1976 and 1977.

A primary reason why the late stage shows the most statistically significant contribution to the final yield estimates, as opposed to the vegetative or reproductive stage as in other models presented, is that Upper Volta receives, on the average, more seasonal rainfall than the other countries in which models have been developed. Thus, with other conditions remaining the same, rain-fed agriculture in Upper Volta can usually rely more consistently on sufficient rainfall than in the more marginal areas to the north. The growing season is also longer in Upper Volta. Whereas the 90 to 95 day maturing variety of millet is predominantly grown in Senegal, Niger and other Sahelian Zone countries, a longer 120-140 day variety may be grown in Upper Volta.

Although positive correlations were found between weather variables and sorghum yields in Upper Volta, there was not the high level of confidence in the relationships which is required for meaningful model development. Another agroclimatic approach will be discussed later which can be used to assess crop conditions in Upper Volta.

D. Analogue Models

In countries where no historical yield data are available but climatic data and crop calendar information are available, the CMR can be used in the analogue approach to crop yield modeling. In this approach, existing models developed for similar climatic and agronomic conditions may be applied to provide indicators of potential yield estimates using meteorological data from the country under study.

123

1. Mali

Figure 4.31 presents the results of the analogue model for millet grown in Mali using two different models - the Senegal vegetative (early season) model and the Niger reproductive (late season) model. These two models were chosen for two reasons. First, agro-climatic conditions in Mali are relatively similar to both Senegal and Niger in the primary cereal growing regions. Second, Mali rainfall during the early season correlated well with rainfall in Senegal ($r = 0.73$, significant at the 1 percent level). However, Mali rainfall correlated better with Niger rainfall during the late season ($r = 0.73$, significant at the 1 percent level). This is probably due to the anomalous rainfall patterns in Senegal during the late season (see Figure 3.3).

Using Mali meteorological data, both models shown in Figure 4.31 indicate relatively high yields during the early 1960's (i.e., 1961, 1964, and 1965). Both models indicate poor yields in 1968, 1972, and 1973 - the three years considered to be the worst drought years in the Sahel. Also, both models indicate relatively "near-normal" yields (based upon the ranking of yield estimates over the entire period, 1960-1977) in 1974, 1976, and 1977. Although quantitative yield estimates have not been obtained for Mali, Berg (1977) reported good agricultural performances in Mali after 1973. Thus, qualitative assessment of yield estimates support results of the analogue models.

The models also indicate that during certain years (e.g., 1966 and 1975) the CMR may be used to assess the condition of the crop during successive growth stages. In 1966 early season data indicated poor

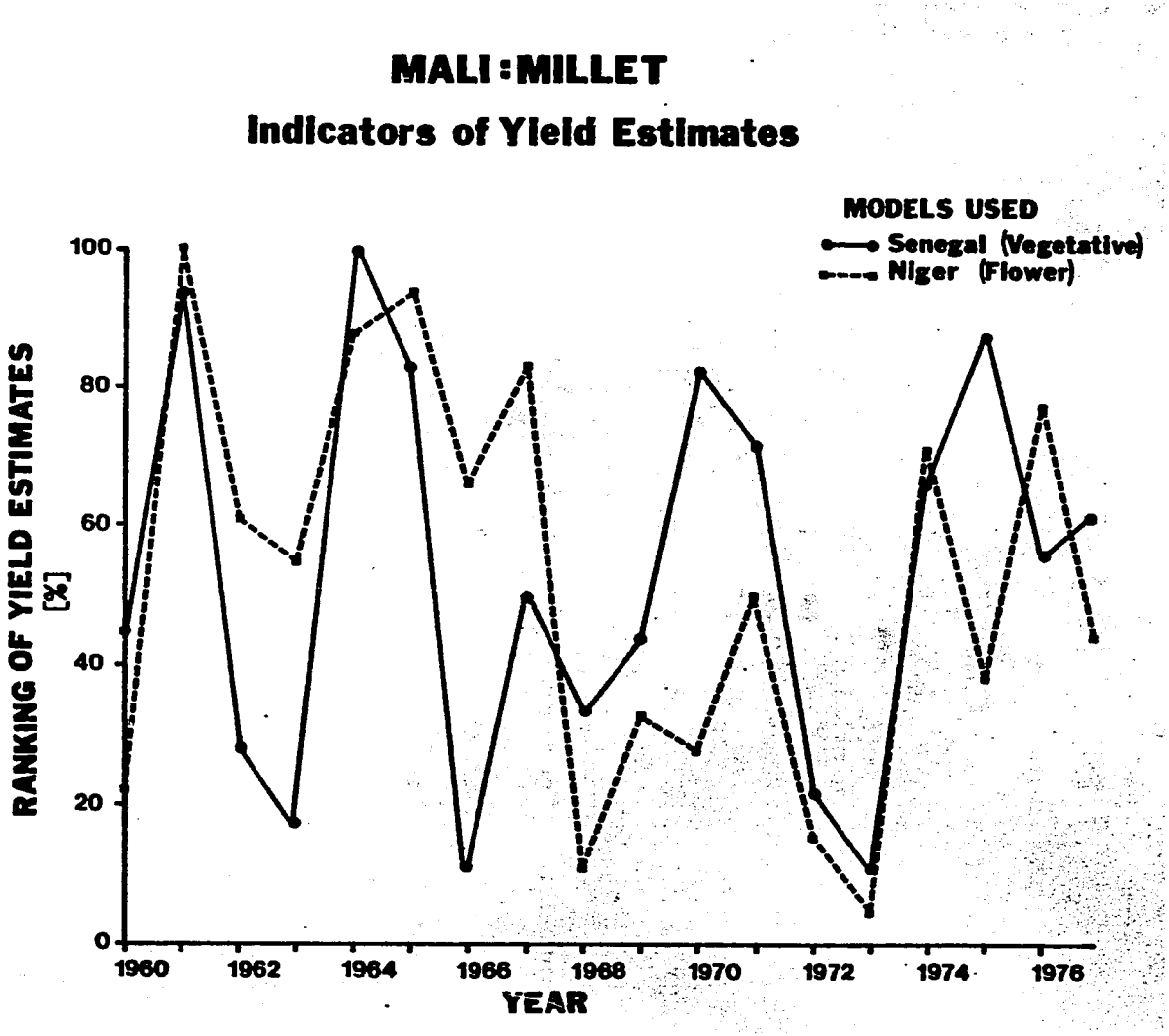


Figure 4.31. Mali analogue model using the Senegal vegetative model and Niger reproductive (flower) model to generate indicators of relative millet yield estimates.

potential yield. However, rainfall during the later stage may have been sufficient, if the timing was right, to indicate adequate crop response to the available moisture. Similarly, in 1975 early season data indicated potentially high yields while late season data suggested that the potential yield estimates should be lowered somewhat.

Recognizing the limitations imposed upon the analogue technique (i.e., no quantitative yield data for verification), this approach may be used as a tool to assess the condition of the crop at various stages of growth and provide qualitative estimates of potential yields based upon the meteorological and crop calendar information.

2. Mauritania

The situation in Mauritania is somewhat different from that in Mali. Mauritania is located to the north of Senegal and its major grain-growing region is on its southern-most border adjacent to Senegal and Mali. Figure 4.32 presents a comparison of actual rainfall data during the months of July and August for Mauritania and Senegal. The direction of both curves is similar. The magnitude of fluctuations is much greater for Mauritania than for Senegal, however. In fact, there is about twice as much variability in precipitation in Mauritania as in Senegal. The coefficient of variation is 35 percent for Senegal and 71 percent for Mauritania. This is also a reflection of the fact that Mauritania receives less monthly rainfall than Senegal. As a result, there is greater climatic variability which, in turn, is likely to increase the variability in agricultural production (assuming, of course, the same level of technology). The comparison of rainfall data strongly

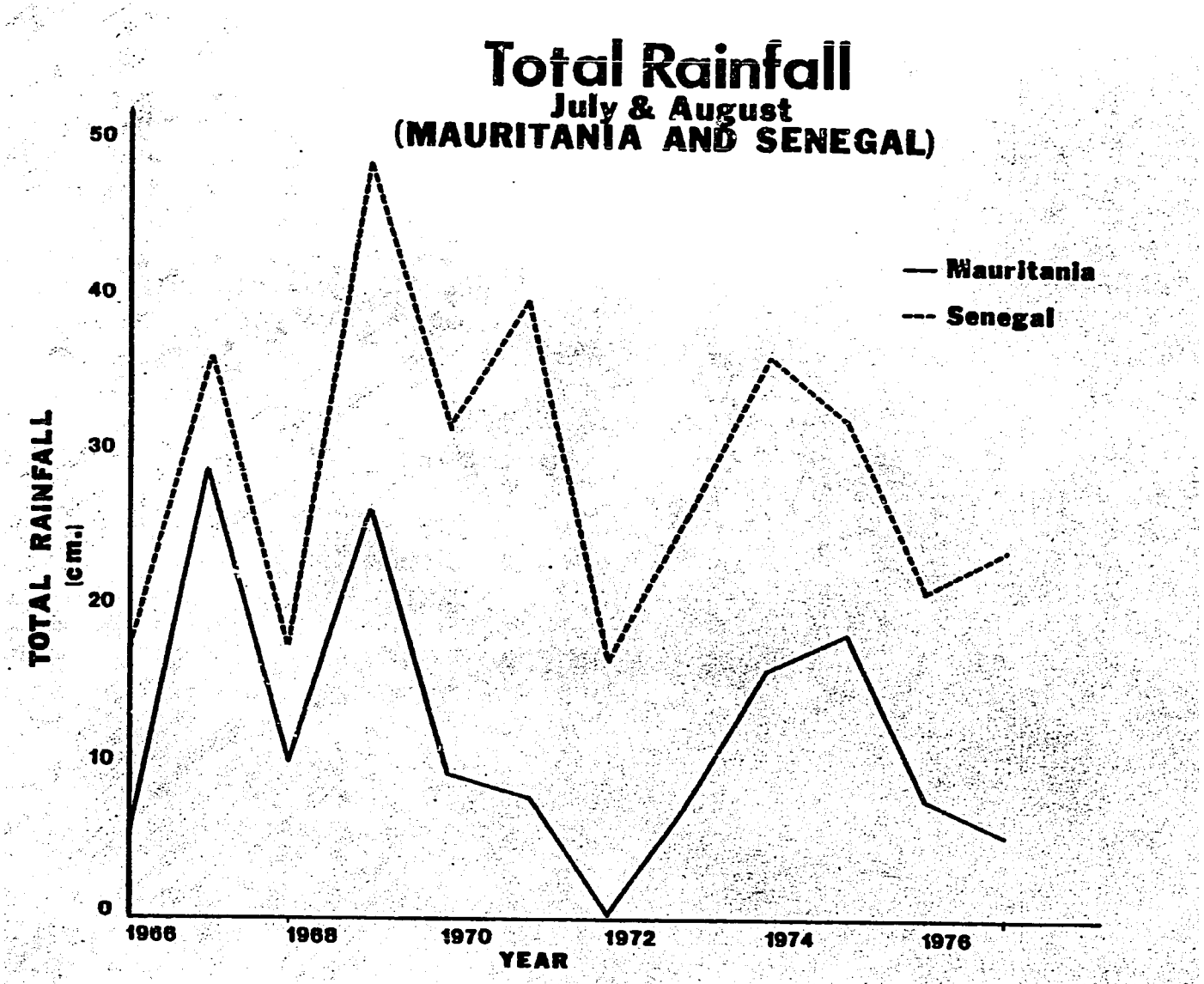


Figure 4.32. Comparison of total rainfall (cm) for July and August between Senegal and southern Mauritania.

suggests that the Senegal millet model (using northern stations) may be used as a tool to assess potential yield estimates in Mauritania as well.

The similarity in climatic conditions between northern Senegal and southern Mauritania was demonstrated during the 1978 growing season. Although crop conditions were good in most of Senegal during 1978, weekly assessments based on cumulative precipitation provided by the Center for Environmental Assessment Services/Climatic Impact Assessment Division (CEAS/CIAD), Assessment Branch and assessments of food shortages by FAO during the 1978 growing season both indicate insufficient rains and below average cereal production in northern Senegal and southwestern Mauritania.

E. Historical Yield Indices

In regions where the analogue modeling technique is not deemed appropriate a third approach is used to provide a qualitative assessment of the condition of the crop at successive growth stages. An historical index for crop yield can be provided by analyzing long-term records of meteorological data associated with the crop growing season. Crop calendar information is essential in this analysis to provide agronomic meaning to the results.

The yield indices developed from this analysis of long-term data are ranked over the entire period to determine conditions of the crop relative to conditions associated with near-normal meteorological conditions. The yield indices are expressed in terms of percentile rankings of the crop moisture ratio. This procedure provides the

basis for objective analysis of crop conditions at successive growth stages based upon meteorological data and crop calendar information only.

Results are presented for Senegal, Niger, Sudan, Mali, Upper Volta and Chad in Figures 4.33 to 4.38. The yield index analysis was performed not only for those countries with no reliable yield data (i.e., Mali, Chad and Upper Volta), but also for countries in which models were developed (i.e., Senegal, Niger and Sudan). Results of the development of agroclimatic yield indices could then be compared with model results.

Figures 4.33 to 4.35 present the yield indices developed for millet/sorghum grown in Senegal, Niger and Sudan, respectively, for both vegetative and reproductive stages. A comparison of these relative yield indices with model results for millet/sorghum yields in Senegal, Niger and Sudan (Figures 4.14, 4.23, 4.24, 4.27, and 4.28, respectively) shows relatively good general agreement. These figures all indicate poor moisture availability during the prolonged drought period beginning in the mid-1960's during either or both growth stages (i.e., vegetative, reproductive). Figure 4.36 shows that the yield indices for millet grown in Mali compare well with analogue model results for Mali using the Senegal and Niger millet models.

Having established methods of providing assessment of crop conditions based upon meteorological data and crop calendar information, percentile rankings of the crop moisture ratio were generated for Chad and Upper Volta. The results are presented in Figures 4.37 and 4.38, respectively. Figure 4.37 shows the same overall pattern of moisture

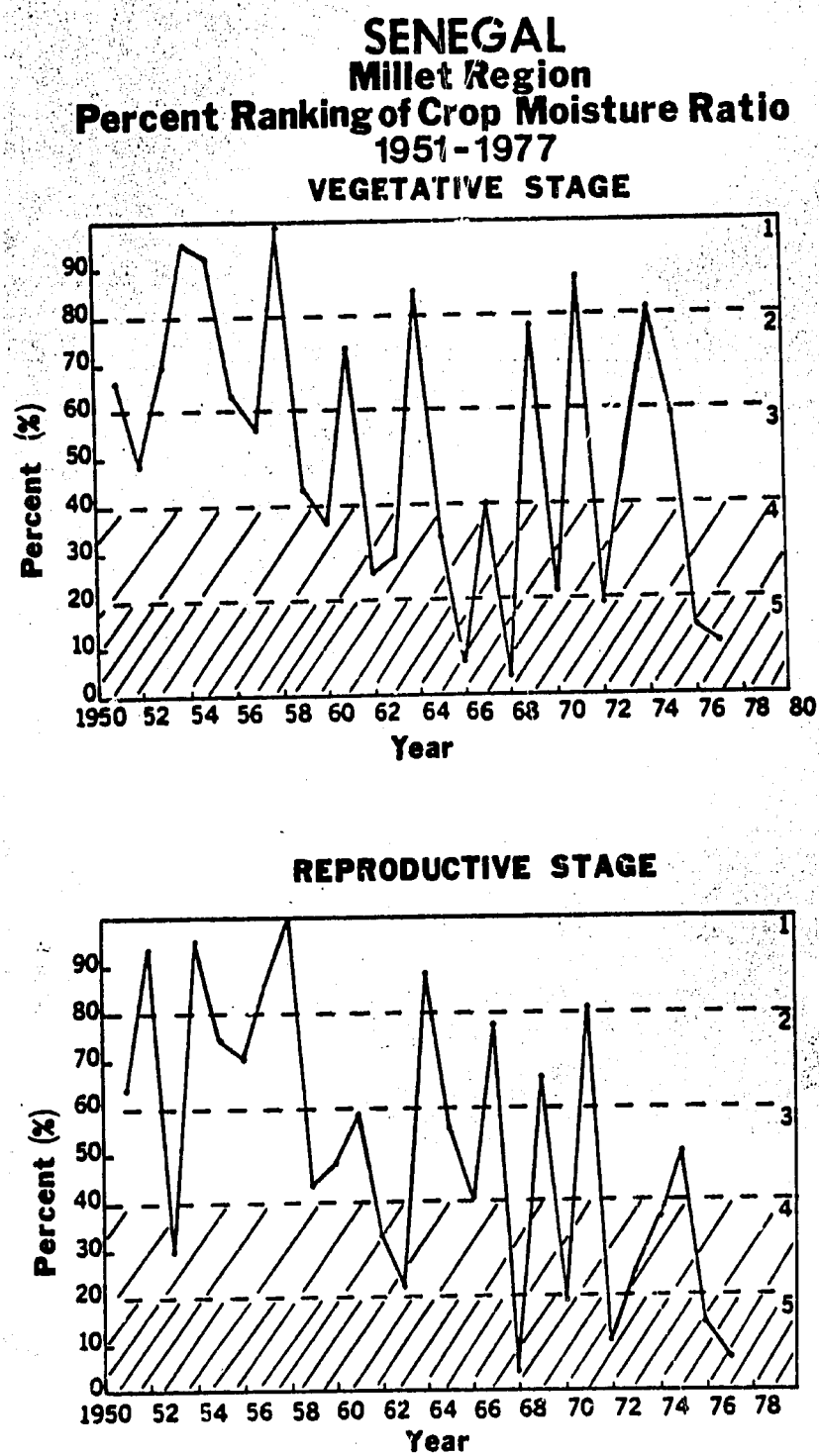


Figure 4.33. Historical yield indices, expressed in terms of percentile rankings of the crop moisture ratio (CMR), for both the vegetative stage (top) and the reproductive stage (bottom) of millet grown in Senegal. The numbers on the right-hand side represent the following: 1, well-above normal; 2, above normal; 3, near-normal; 4, below normal; and 5, well-below normal.

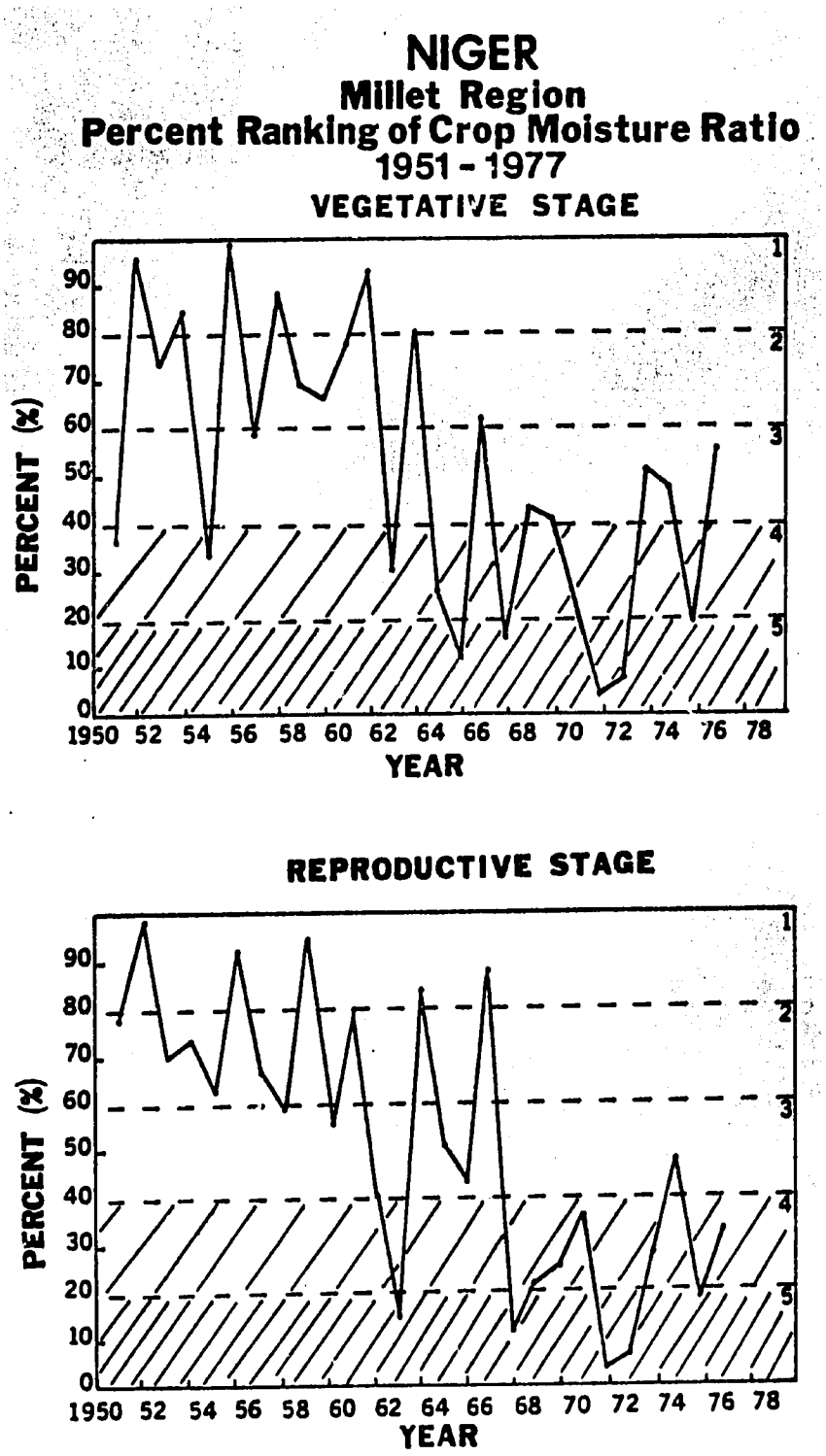


Figure 4.34. Same as Figure 4.33 for millet grown in Niger.

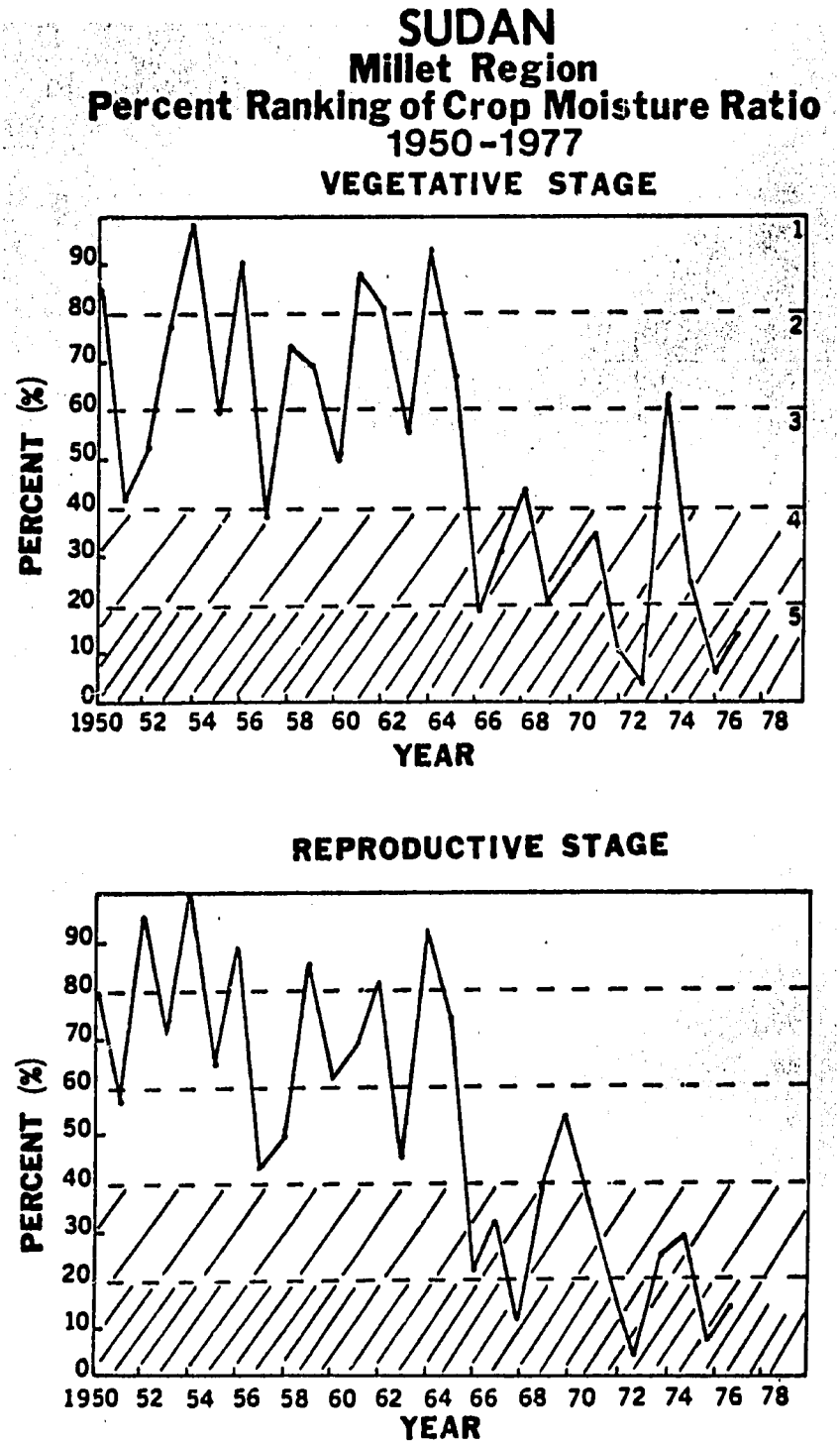


Figure 4.35. Same as Figure 4.33 for millet grown in Sudan.

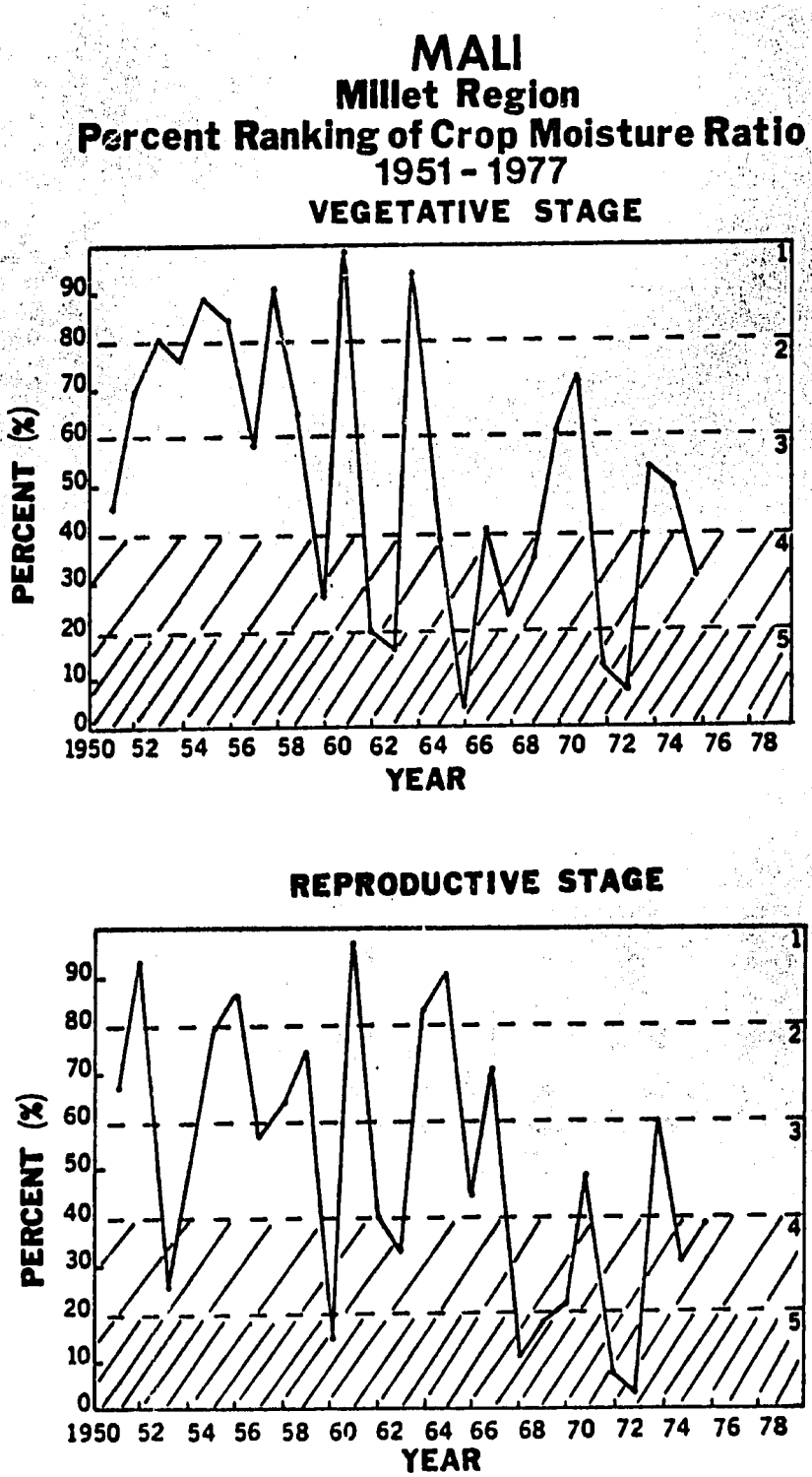


Figure 4.36. Same as Figure 4.33 for millet grown in Mali.

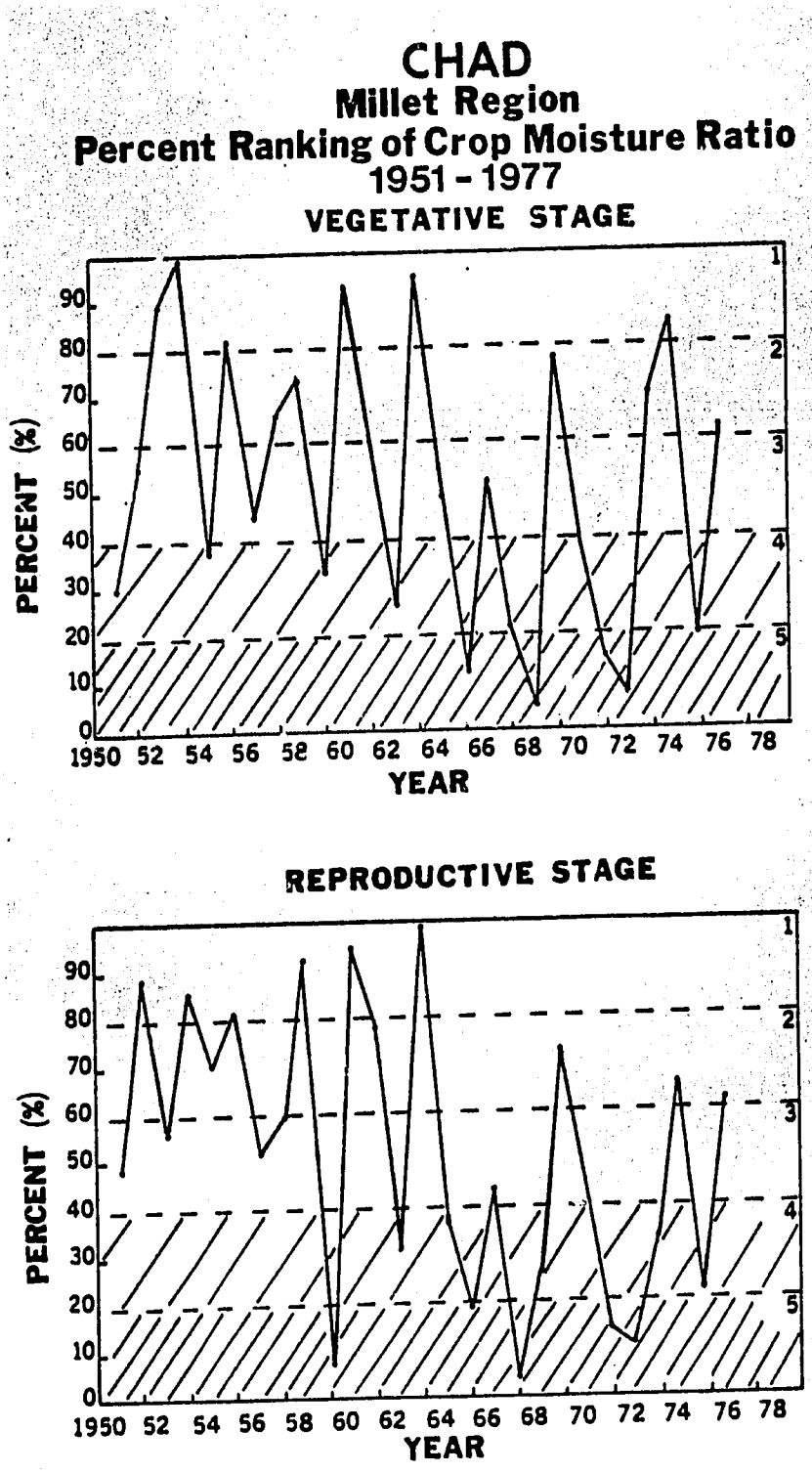


Figure 4.37. Same as Figure 4.33 for millet grown in Chad.

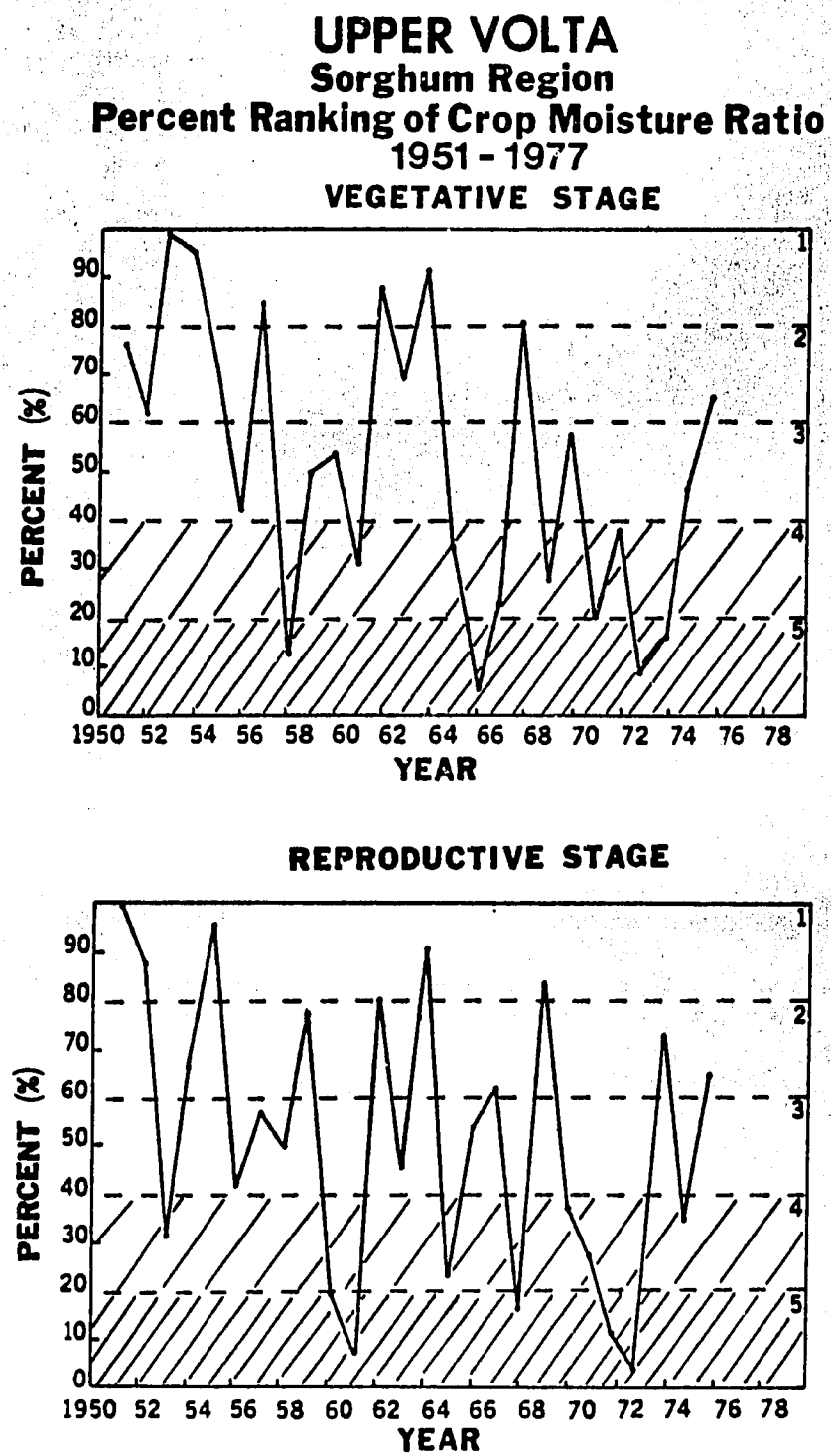


Figure 4.38. Same as Figure 4.33 for sorghum grown in Upper Volta.

availability for the millet/sorghum region of Chad as compared with the other countries already discussed. Specifically, the yield indices show a relative decrease beginning in the mid-1960's with below-normal conditions prevailing throughout recent years during either or both vegetative and reproductive growth stages.

Due to the longer rainy season in Upper Volta, specific crop calendars are suited to longer cycle varieties. Thus, crop growth stages must be adapted to these crop calendars. The vegetative stage for millet includes the period June through August, while the reproductive stage includes the period August through October. Figure 4.38 presents the percentile rankings for both growth stages for the millet/sorghum region of Upper Volta. Again, there is an overall tendency for below normal conditions beginning in the mid-1960's and continuing through the early 1970's.

The use of agroclimatic indices presented in Figures 4.33 to 4.38 provides a useful tool for qualitatively assessing the crop moisture conditions during successive growth stages of the crop. As such, the historical yield index can be used to complement model estimates which are based upon key growth-stage variables and/or provide information concerning potential moisture stress conditions during crop development.

F. Rangeland Indices

Temperature and moisture are the most important factors affecting rangeland growth. Temperature regulates the rate of photosynthesis, respiration and transpiration. The available moisture determines not only the rate of growth but also the type of plant species grown in a particular region (Arnon, 1972).

In a personal communication with Leslie Brown, a rangeland specialist of Kenya, it was stated that temperature was not a limiting factor in rangeland production whereas precipitation had a direct linear correlation. Stoddard et al. (1975) agree with Brown stating that in tropical areas temperature usually does not limit plant growth, and range productivity is controlled by the availability of moisture. Precipitation can be regarded as the most important single factor influencing forage production.

WMO (World Meteorological Organization) data from 54 stations within Senegal, Mauritania, Mali, Upper Volta, Niger, and Chad were collected and analyzed. Long-term records of mean monthly temperature and cumulative monthly precipitation extending from 1941 to 1977 were used to examine the climatic conditions in the Sahel.

For large homogeneous areas, regional divisions were desired. Careful screening and correlative analysis of the climatic data resulted in the four aggregated regions shown in Figure 4.39. The aggregation was determined from correlations among the 54 stations on the basis of annual precipitation and cumulative precipitation through August and September. Geographical locations were also considered.

In the process of aggregating stations into regions, several stations were eliminated. Stations in the extreme northern portion of the Sahel exhibit erratic rainfall patterns due to the insignificant amounts of rainfall during the very short wet season. These stations were excluded from the analysis. In addition, Thies, Senegal, and Bol, Chad, were discarded because of incomplete data sets.

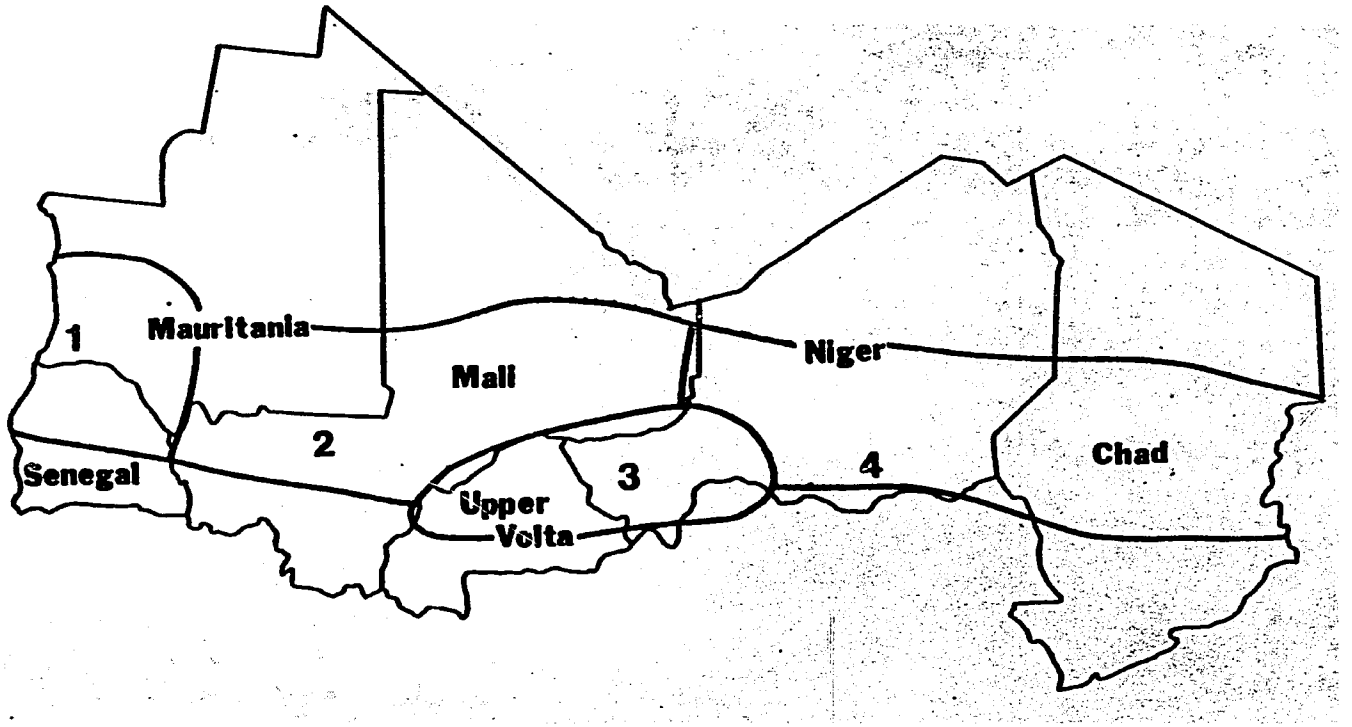


Figure 4.39. Regional divisions of the Sahelian rangelands

During the analysis of the regional data for 1941 through 1950, it was found that some of the data exhibited an inconsistent behavior in two of the four regions. This may be due to the fact that some of the stations making up these regions were missing which could result in a bias or misrepresentation of the regional data. These early years were excluded from the data sets of all four regions.

The procedure for development of the rangeland index for these regions was based upon various rankings of long-term monthly data throughout the growing season. This procedure is similar to that used in the development of historical yield indices (Section IV.E). The climatic variables were ranked to provide indicators of rangeland conditions in the four regions. Because of the relatively low amount of precipitation characteristic of the northern Sahel, the CMR was not considered to be an adequate indicator of rangeland conditions. Therefore, the key parameter in the analysis was cumulative precipitation over the growing season.

It was then important to determine the earliest meaningful indicator of rangeland conditions based upon moisture conditions. The normal monthly precipitation for the years 1951 to 1977 was calculated and plotted in the histograms shown in Figures 4.40 and 4.41. Region One differs from the other regions in that September shows an anomalously high rainfall pattern as noted in Section III.D.

The earliest moisture indicators for Region One are cumulative precipitation for January through September and January through October as well as total precipitation for August, September, and October. The percentile rankings of these indicator variables are plotted in Figure 4.42 together with rankings of the yearly precipitation.

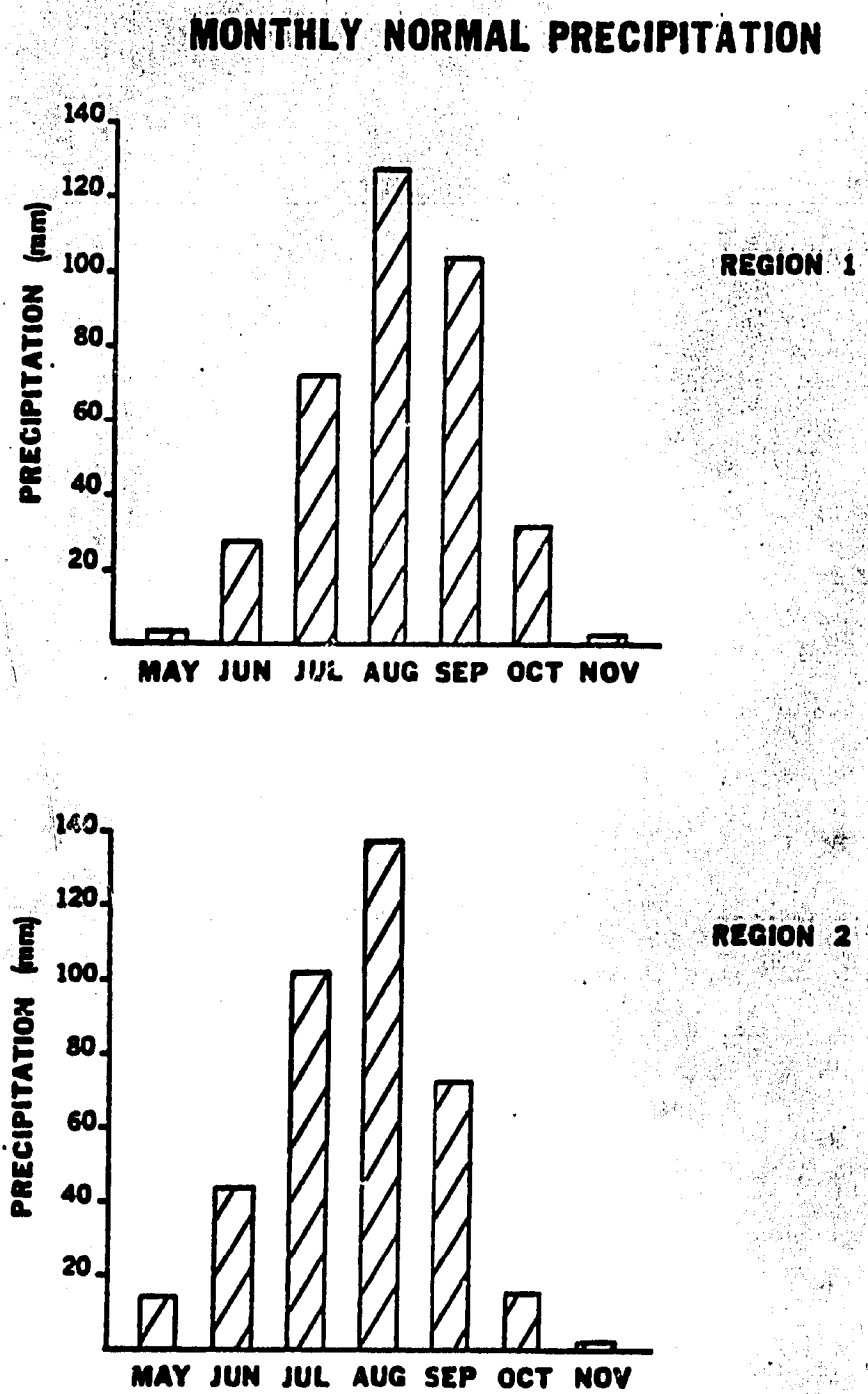


Figure 4.40. Precipitation normals for Region One and Two for 1951-1977.

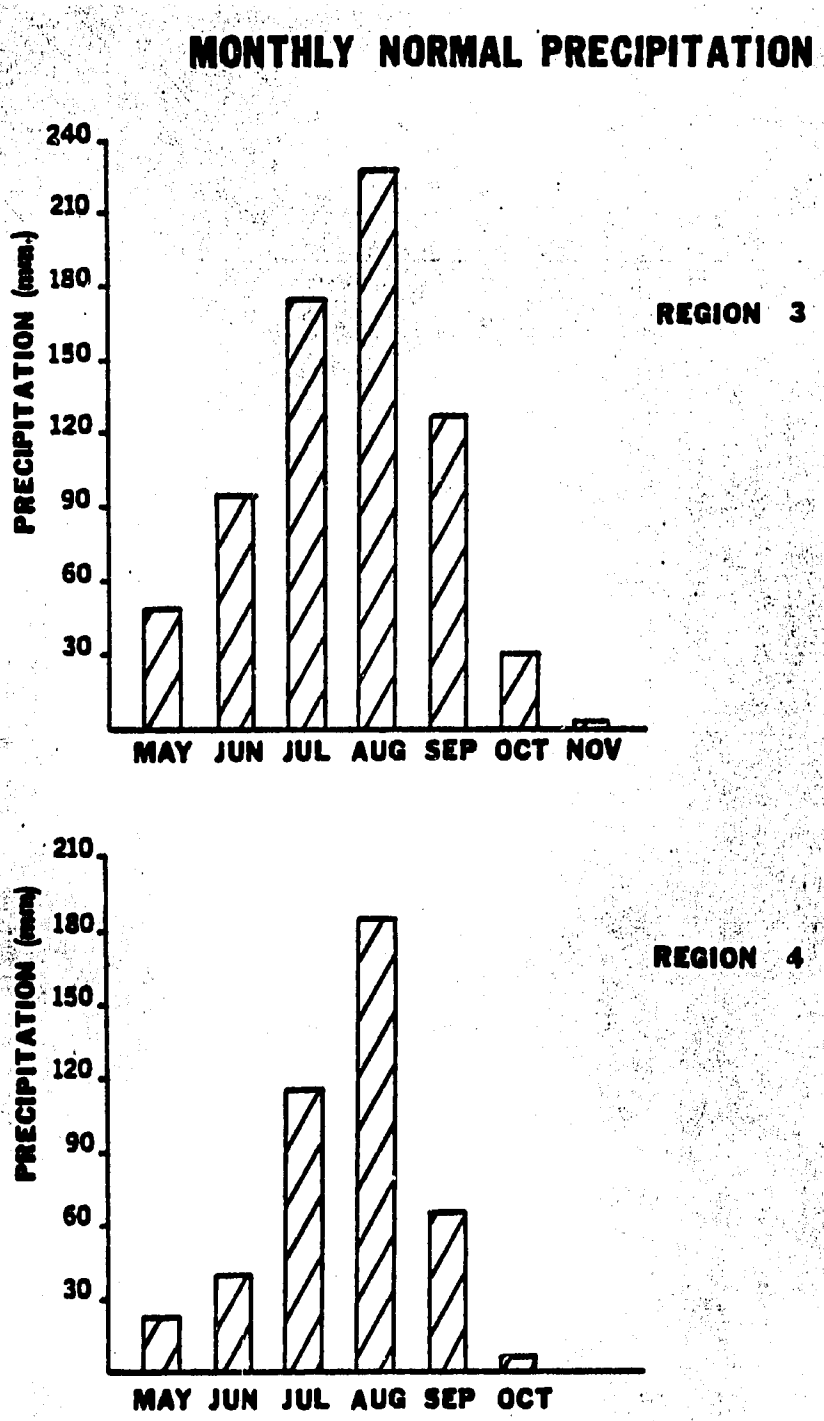


Figure 4.41. Precipitation normals for Region Three and Four for 1951-1977.

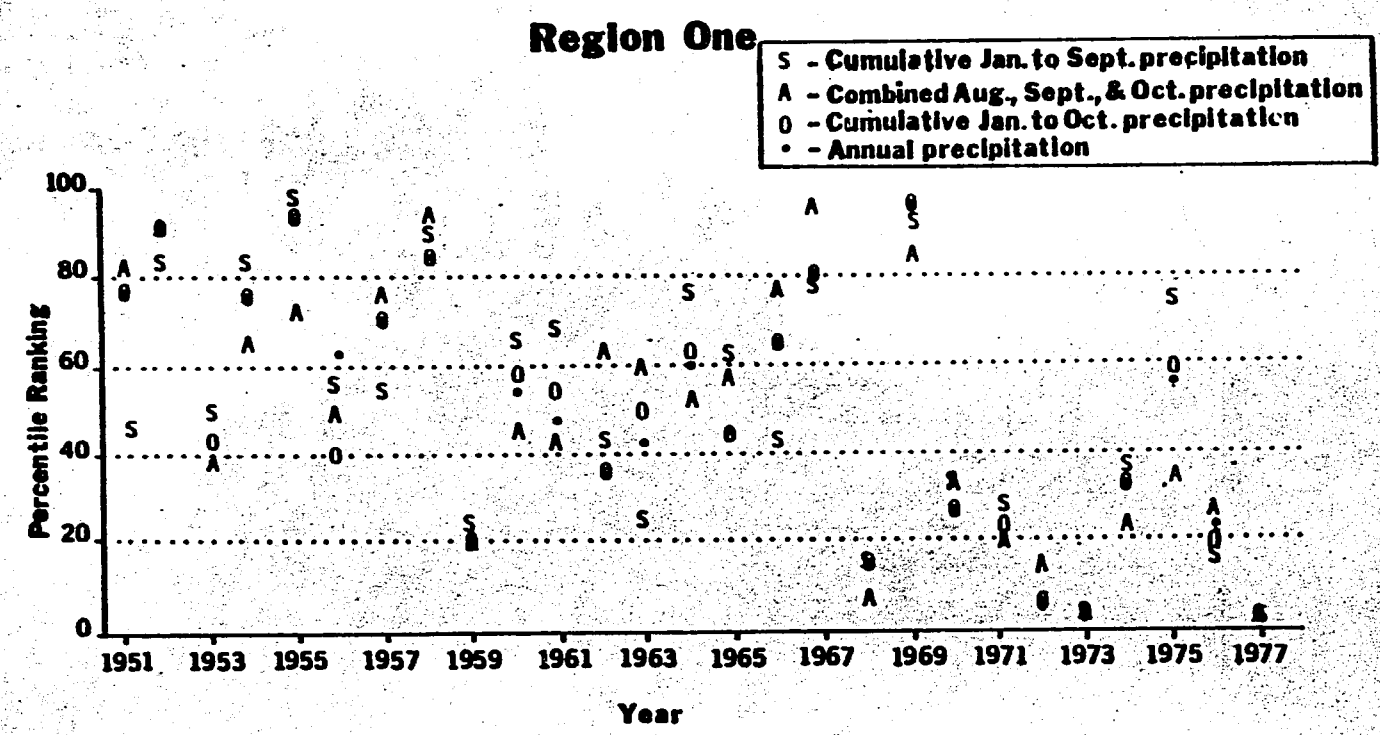


Figure 4.42. Historical rangeland indices expressed in terms of percentile rankings of the following variables: 1) cumulative January through September precipitation, 2) combined August through October precipitation, 3) cumulative January through October precipitation, and 4) annual precipitation for Region One.

Region Two's normal precipitation distribution is shown in Figure 4.40. July and August are the months of greatest precipitation in this region as well as in Regions Three and Four (Figure 4.41). The indicator variables found to be most reliable are cumulative precipitation, January through August and January through September. These two variables and the total annual precipitation are ranked in Figure 4.43.

Region Three receives, on the average, more annual rainfall than the other regions since it extends further south. The two variables, cumulative precipitation through August and combined July and August precipitation, were found to provide the best indication of potential rangeland conditions. Figure 4.44 and 4.45 present the percentile rankings of these variables and the yearly precipitation for Region Three and Region Four, respectively. Region Four has minimal rains in October compared to other regions. The variables for Region Four are the same as for Region Three (Figure 4.45).

The four rankings of regional data (Figures 4.42 to 4.45) show that beginning in the mid-1960's there was a significant decrease in moisture availability in rangelands. The severe moisture deficiency continued through 1973, with 1974-1977 also receiving less than normal rainfall. Based on the "time constant" scheme reported by Picardi (1974) and discussed in Section II.C.2., these years of deficient rainfall would have resulted in severe deterioration of the vegetation in the Sahel.

At this point, climatic indicators of the Sahelian rangelands have been developed. Work is continuing on the significance of the

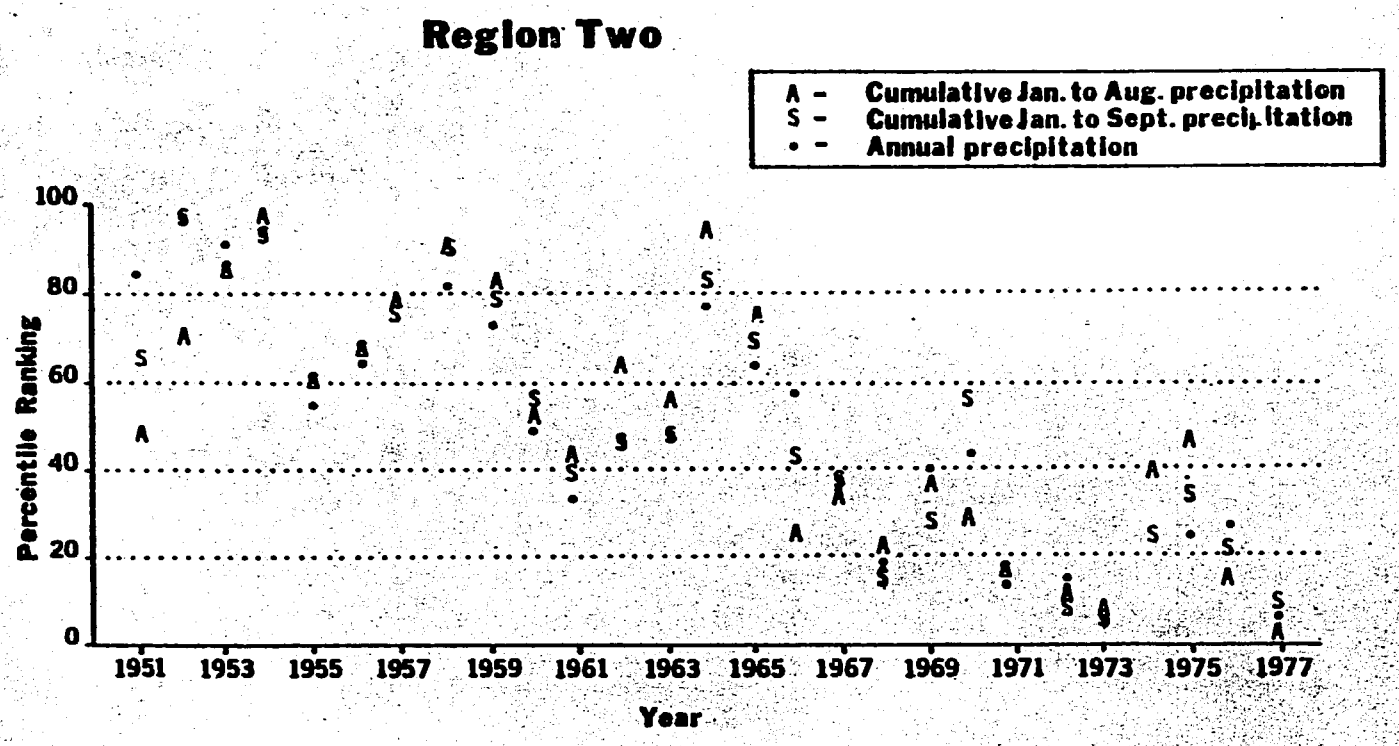


Figure 4.43. Same as Figure 4.42 for the variables: 1) cumulative January through August precipitation, 2) cumulative January through September precipitation, and 3) annual precipitation for Region Two.

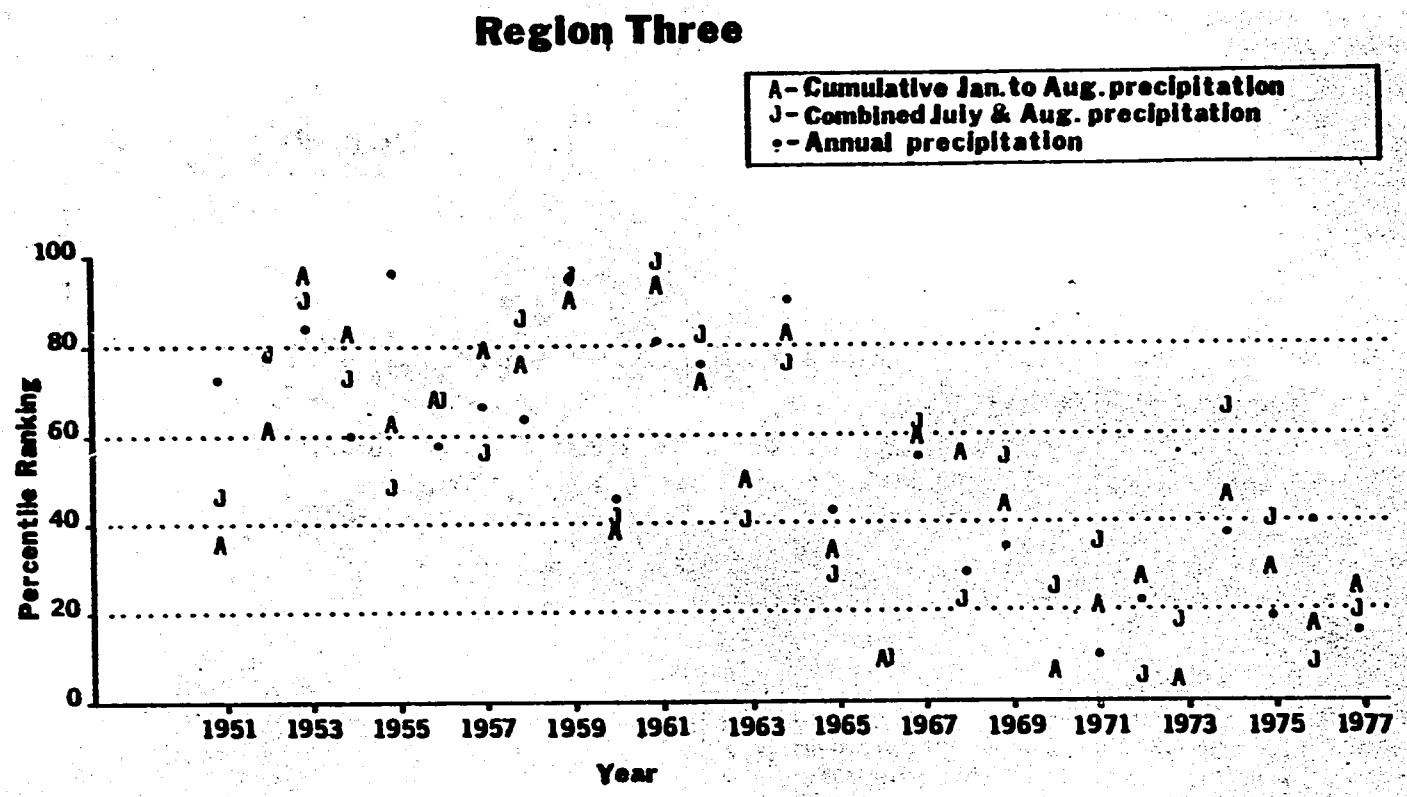


Figure 4.44. Same as Figure 4.42 for the variables: 1) cumulative January through August precipitation, 2) combined July and August precipitation, and 3) annual precipitation for Region Three.

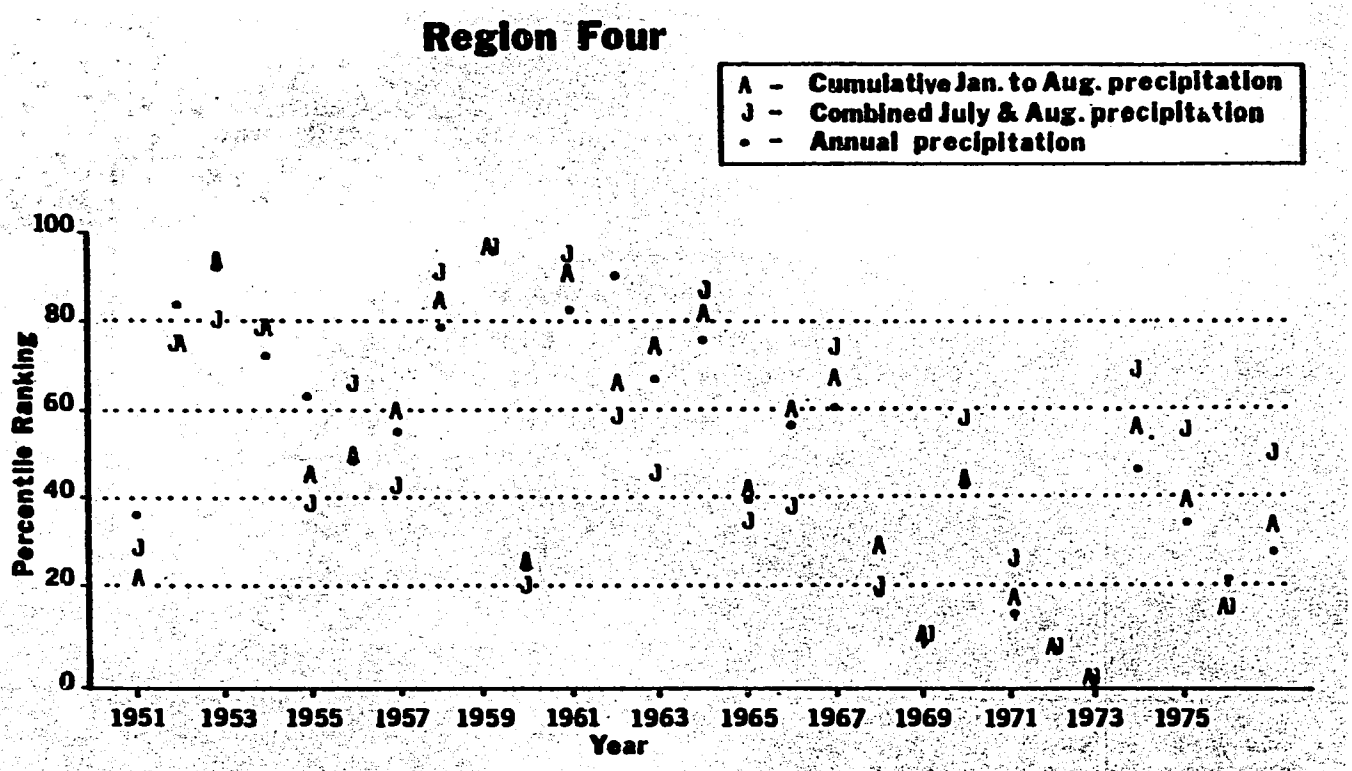


Figure 4.45. Same as Figure 4.44 for Region Four.

precipitation index in relation to vegetative conditions when and if appropriate data become available. However, research on the vegetative aspects of the Sahel rangelands is very limited. An alternative may be to adapt U. S. studies on biomass production in rangelands to the unique problems which exist in the Sahel.

G. Special Studies

This section presents the results of climatic analyses for Kenya/Tanzania and Nigeria. The preliminary results of the agroclimatic survey of the Kenya/Tanzania region are designed to provide the framework for future investigations of climate-agriculture relationships in drought-prone countries of Africa south of the equator. Due to the time constraint, only an introductory examination is presented here. General agricultural regions were identified and certain crop calendar information was gathered. Based upon these guidelines the crop moisture ratio (CMR) was generated for early-period and late-period stages of crop development in various regions. The emphasis was placed upon a qualitative analysis of historical yield indices to provide insight into recent agroclimatic conditions in Kenya and Tanzania.

The second subsection presents the analysis of long-term rainfall series for a relatively comprehensive set of recording stations (28) throughout Nigeria. The objective is to examine the rainfall patterns in the northern region which is characteristic of the Sahelian rainfall zone and compare this long-term series with rainfall patterns in more humid tropical regions to the south. These comparisons may

serve to provide a better understanding of possible mechanisms of rainfall variation in the semiarid regions of West Africa.

1. Kenya/Tanzania Agroclimatic Survey

The area of tropical East Africa in which the countries of Kenya and Tanzania are located is very complex both in topography and climate. Within this zone almost all types of equatorial climatic regimes are found ranging from the hot, humid coast through arid scrub land to the dense equatorial rain forests and the highland climes (Griffiths, 1972). Figure 4.46 shows a map of this area which indicates the complex patterns of climatic and topographical features. Although much of tropical East Africa is situated in the equatorial zone, the region does not necessarily receive large amounts of rainfall.

The ITCZ becomes very diffuse in this area due to the topography. The high mountains break up the more classical frontal patterns and superimpose localized climatic features. The influence of several large lakes also introduces climatic modifications. Generally speaking, however, areas close to the equator have two seasons of maximum rainfall, around April-May and November. Usually, the April-May maximum brings more rainfall and is referred to as the season of "the long rains" as opposed to the season of "the short rains" in October-November. This type of seasonal distribution prevails in East Africa between 5°N and 4°S. Further south of the equator (below 4°S), one wet season prevails from November through April.

Examination of the normal seasonal rainfall distributions by region in Figure 4.46 reveals that a large area of northern and eastern Kenya is not well-suited for significant agricultural production

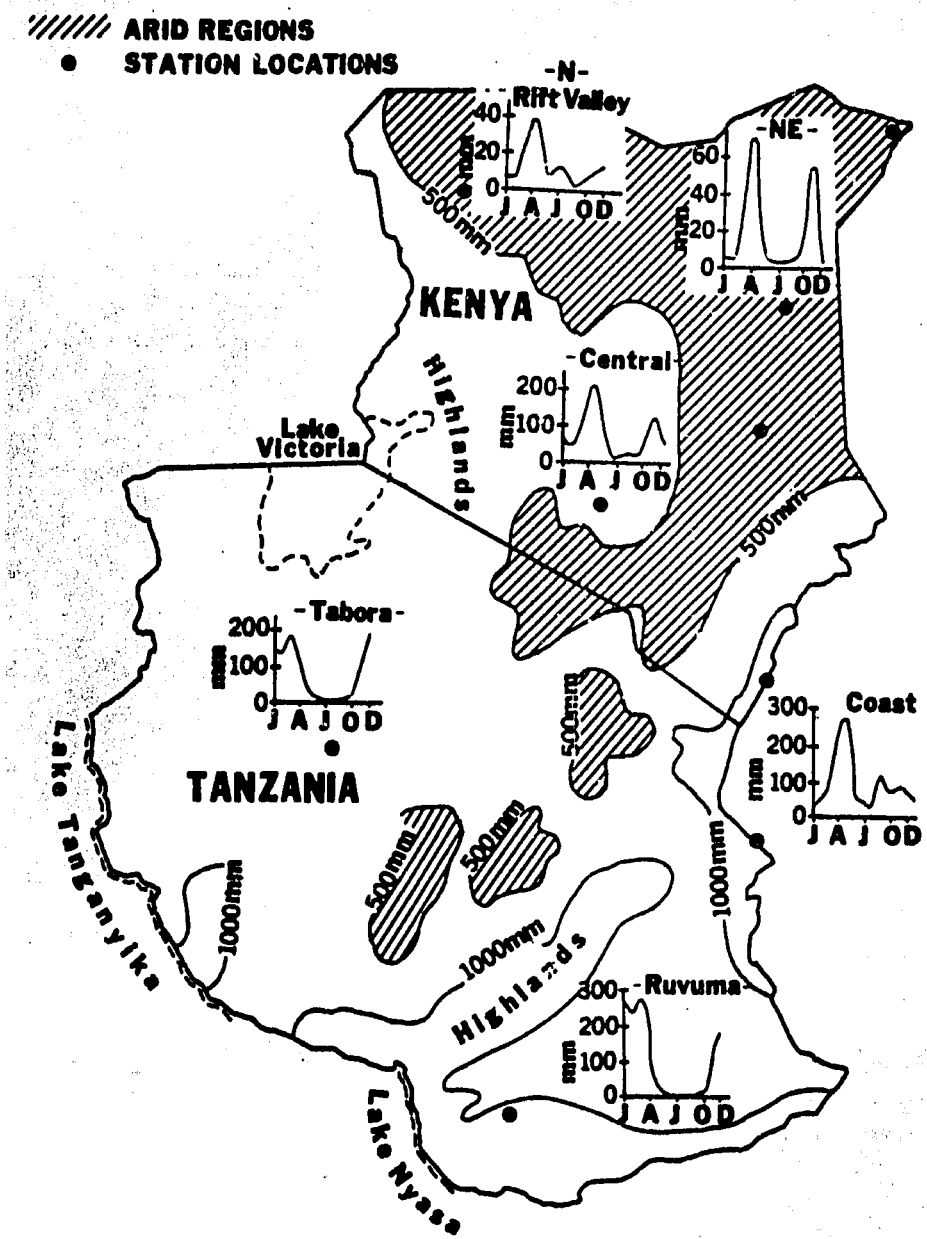


Figure 4.46. Map of Kenya/Tanzania showing the complex topographical and agroclimatic features of the area. Normal seasonal rainfall distributions are shown for various regions as well as the 500 mm and 1000 mm isohyets.

activities. In fact, the major crop regions are restricted to the western highlands, around Lake Victoria and along the southeastern coastal region. Except for some pockets of relatively arid regions and some areas of mountainous terrain, agricultural activities prevail throughout most of Tanzania. The primary subsistence crops throughout this region are millet, sorghum, and corn. Corn is an especially important staple food in Kenya. The major climatic problem imposed upon farmers in Kenya and Tanzania is the large year-to-year variation in rainfall amounts in addition to the wide variation in the time of year at which the rain falls. Griffiths (1972) states that Kenya receives a reliable 750 mm/year in only a seventh of its territory as compared to about half of Tanzania.

With this brief summary of normal agroclimatic conditions in this region, yield indices were developed from available long-term meteorological data. The procedure was the same as that described in Sections III.C.3 and IV.E. Only 9 WMO stations were available from these two countries (6 in Kenya; 3 in Tanzania). Four of the six stations in Kenya are located in the arid northern and eastern areas. Except for the coastal region of Kenya/Tanzania where two stations were averaged together, the results are representative of the specific stations located within a particular region. The results are, therefore, susceptible to the variability of individual stations which represent the region. Results will be presented for those regions which are considered agriculturally productive. Reference to the map of Figure 4.46 shows the normal seasonal rainfall distributions, and includes the following regions: Central, Coastal, Tobora, and Ruvuma.

150

Because of the potential for two crop seasons under rainfed conditions for both the Central and Coastal Regions, percentile rankings of the crop moisture ratio (CMR) were generated for a primary growing season which corresponded to the season of "long rains", i.e., April-May maximum, and a secondary growing season which corresponded to the season of "short rains", i.e., November maximum. For the Tobora and Ruvuma Regions, however, only one growing season is considered which is associated with the single wet season. Each growing season is divided into an early period and late period. The early period represents the planting and vegetative stages of growth while the late period represents the reproductive through maturation stages.

The percentile rankings of the CMR for these regions are presented in Figures 4.47 through 4.52. These results indicate that beginning in the late 1960's there was a general decrease in moisture availability for crops grown especially during the secondary growing season for both the Central and Coastal Regions. (Figures 4.48 and 4.50, respectively). Crops grown during the primary season were also affected by poor moisture conditions during several recent years as demonstrated in Figures 4.47 and 4.49. The historical yield indices for Tabora and Ruvuma Regions, Figures 4.51 and 4.52, respectively, show that poor crop moisture conditions prevailed during several years in the 1950's, and again in the late 1960's through 1970's. During the recent decade the late crop growth period seemed to be affected more than the early period. Finally, Figures 4.51 through 4.52 indicate that poor crop moisture conditions prevailed during the early period of 1976 in Tabora and Ruvuma regions.

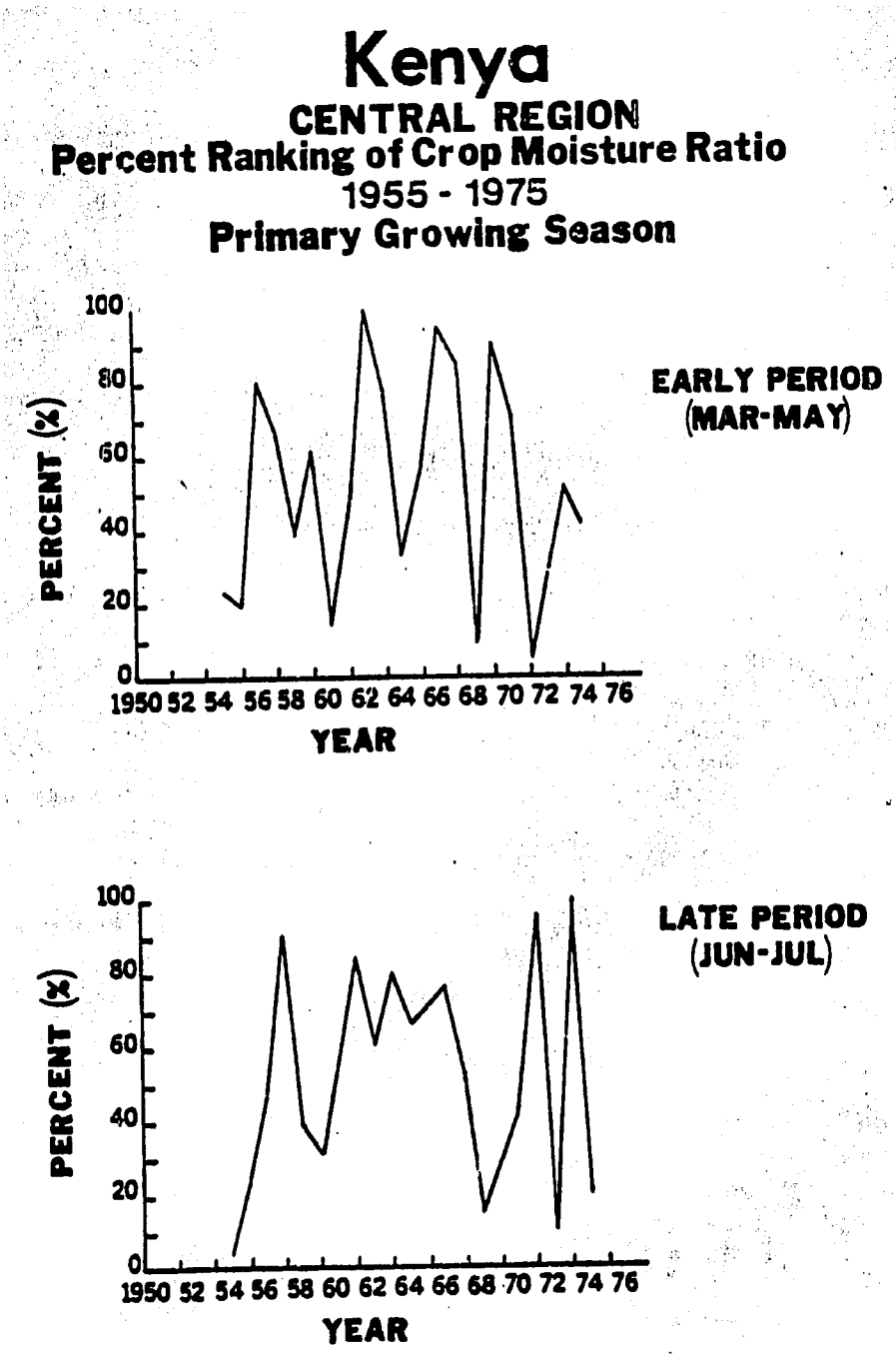


Figure 4.47. Historical yield indices expressed in terms of percentile rankings of the crop moisture ratio (CMR) for both the early period (top) and the late period (bottom) for cereals grown during the primary growing season in the Central Region of Kenya.

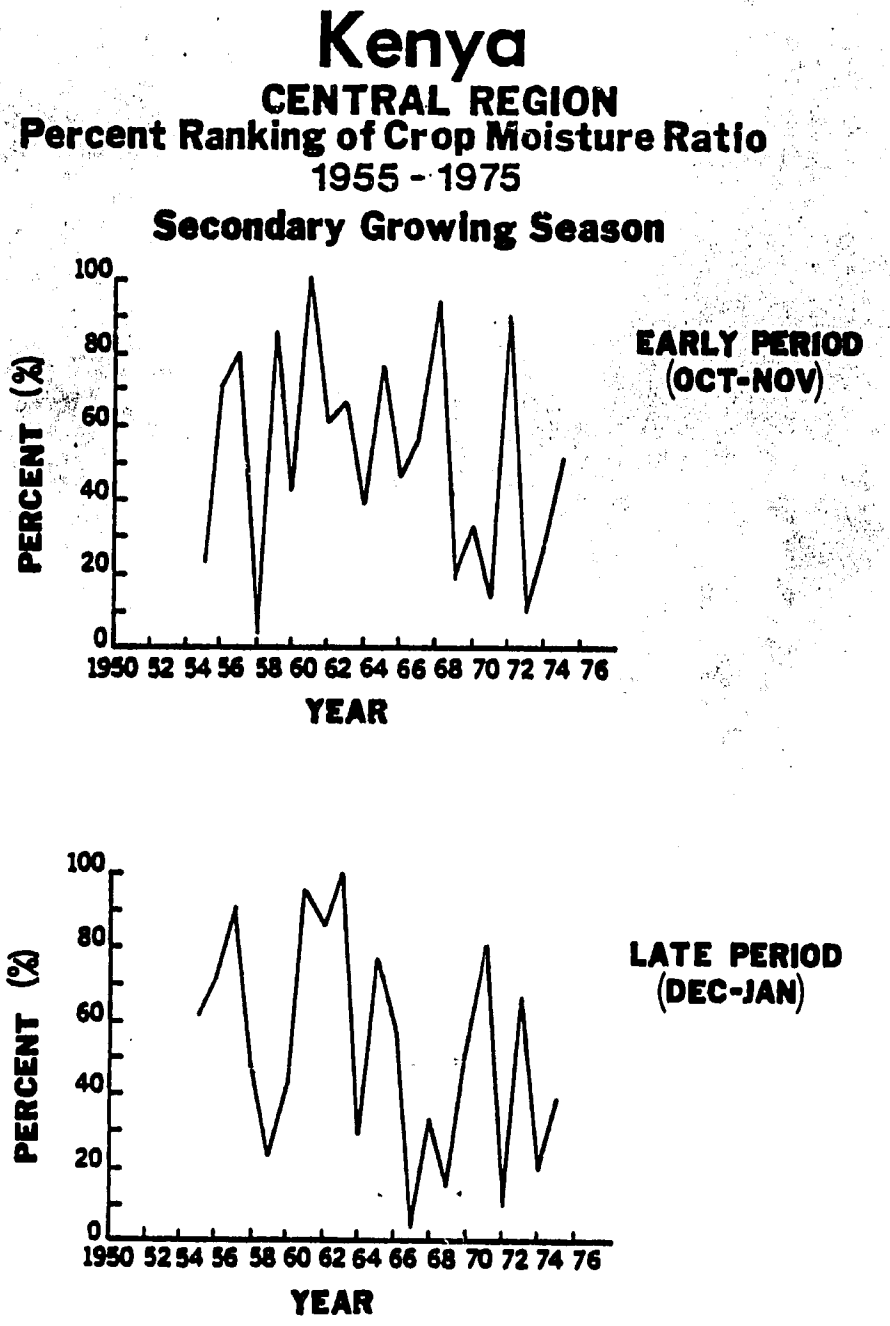


Figure 4.48. Same as Figure 4.47 for cereals grown during the secondary growing season in the Central Region of Kenya.

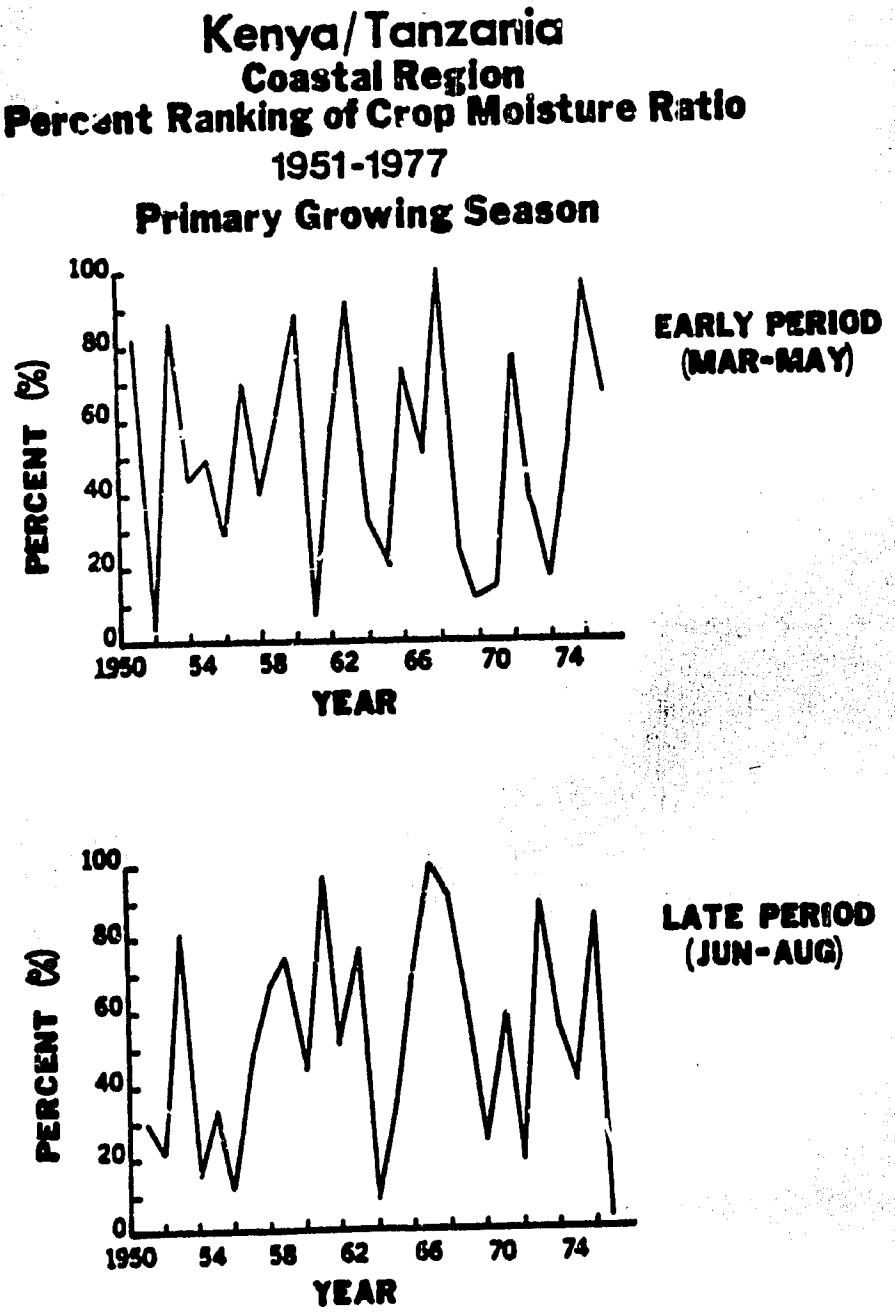


Figure 4.49. Same as Figure 4.47 for cereals grown during the primary growing season in the Coastal Region of Kenya/Tanzania.

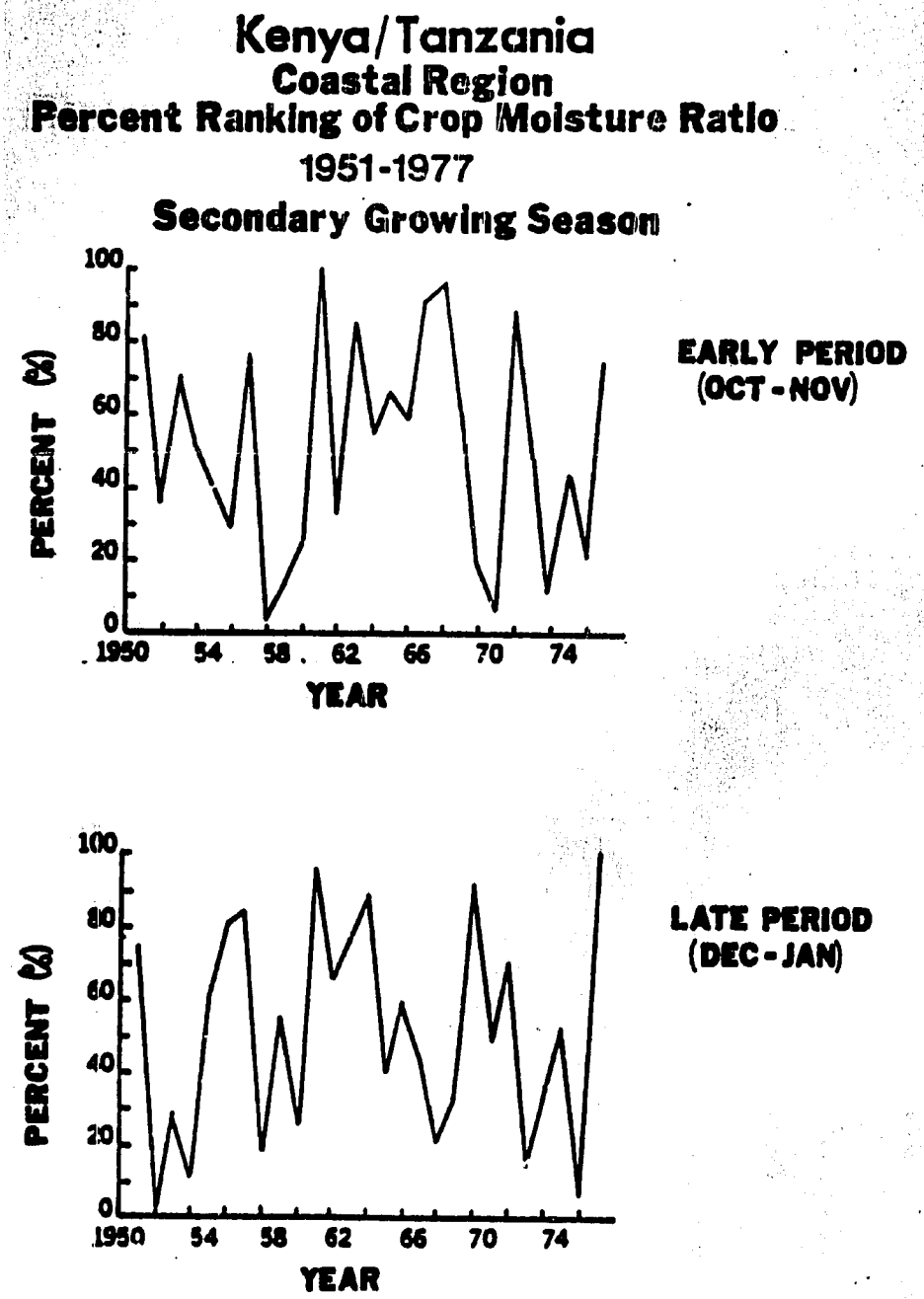


Figure 4.50. Same as Figure 4.47 for cereals grown during the secondary growing season in the Coastal Region of Kenya/Tanzania.

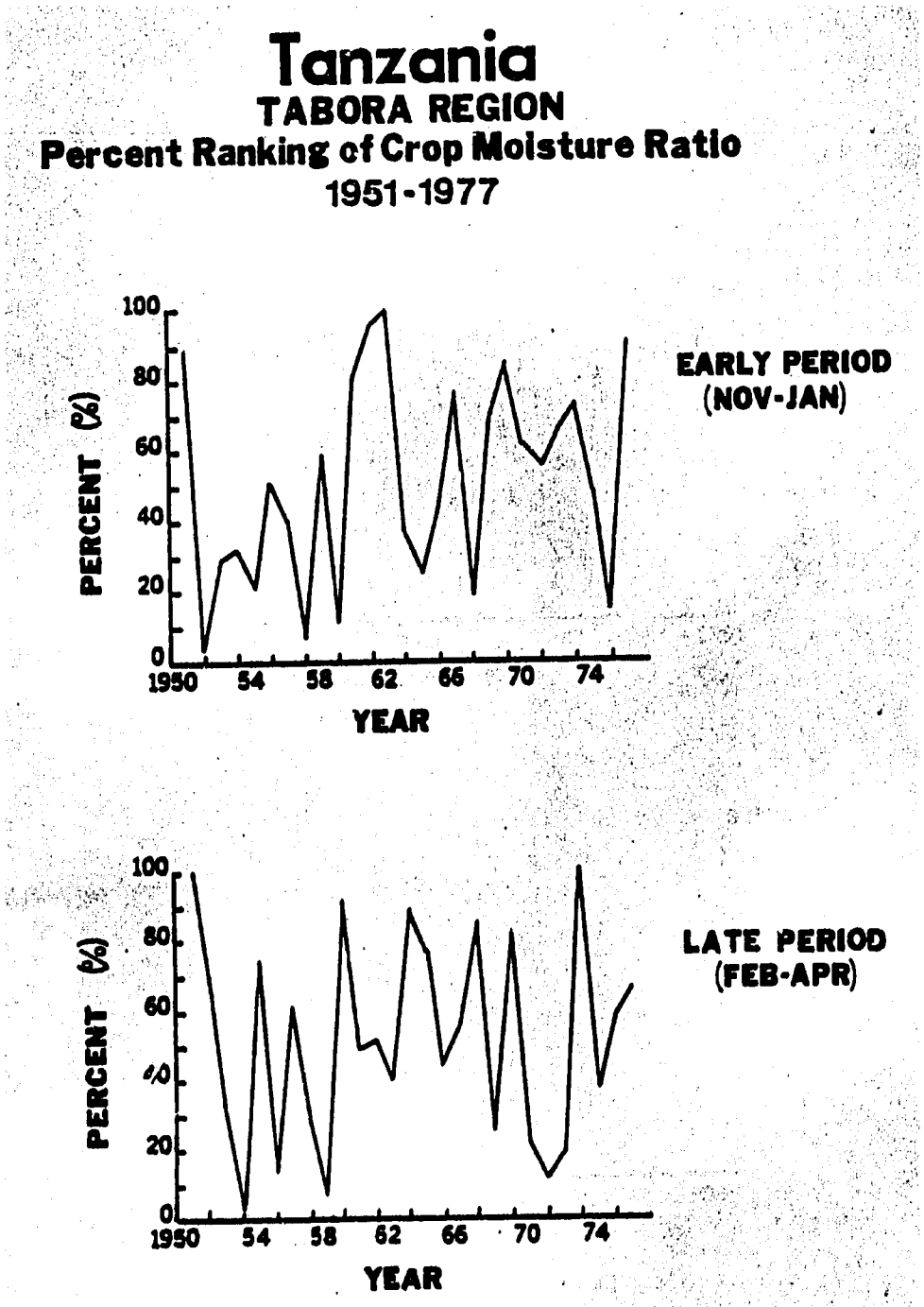
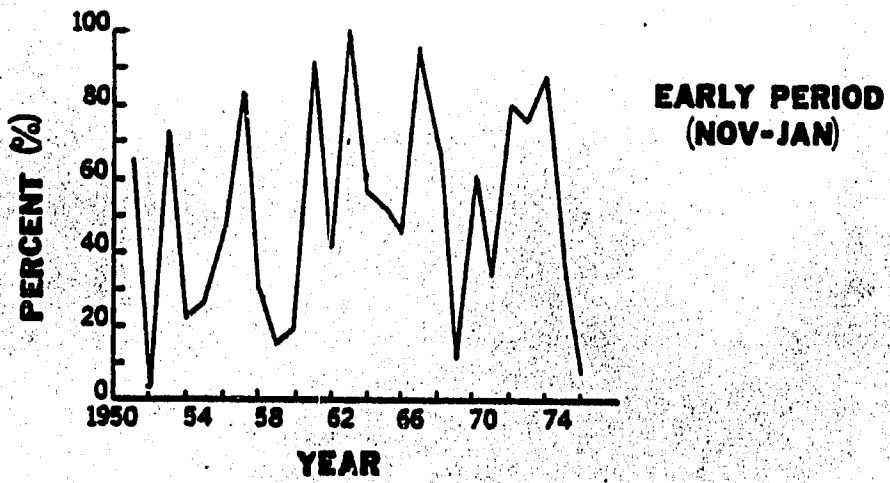


Figure 4.51. Same as Figure 4.47 for cereals grown in the Tabora Region of Tanzania.

Tanzania

Ruvuma Region
Percent Ranking of Crop Moisture Ratio
1951-1976



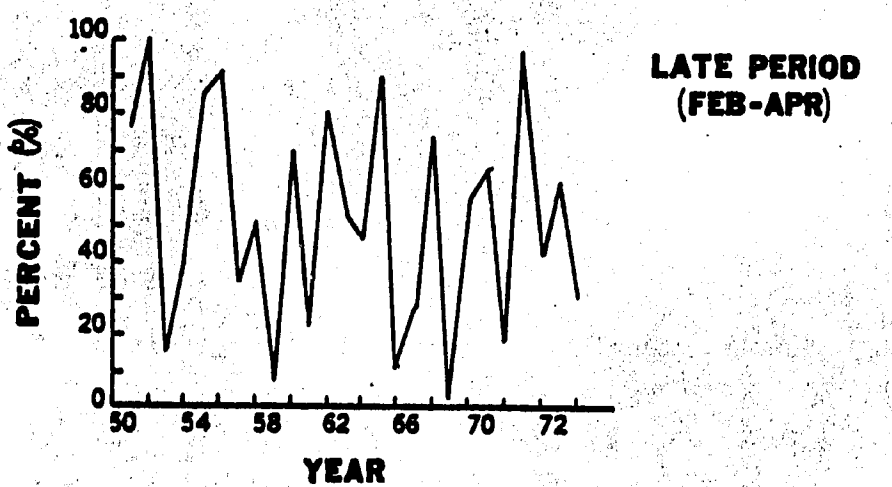


Figure 4.52. Same as Figure 4.47 for cereals grown in the Ruvuma Region of Tanzania.

2. Nigeria: Long-Term Rainfall Analysis

Before discussing the results of this analysis, a brief background of some pertinent literature is reviewed. The regional rainfall analysis which follows is intended to show the relationship between rainfall patterns in the northern Sahelian region and the other more humid regions of Nigeria. The annual rainfall time series will be compared and percentage departures from 50-year normals will be examined.

Recent studies (e.g., Aspliden and Adefolalu, 1976; Bunting et al., 1976; Nicholson, 1979) have examined the climatic pattern of the West African subtropics. Aspliden et al. (1976) presented the results of mean monthly radiosonde soundings up to the 100 mb level for an 11-year period (1960-1970) from eight West African upper air stations. These stations were grouped into southern and northern zones; four stations were located along the latitude of 5°N and the others around 13° - 14°N. The southern zone represents the general monsoon belt within the sub-humid tropical zone, and the northern zone is typical of the semiarid climatic regime of the Sahel. The pronounced latitudinal displacement of large-scale atmospheric systems necessitated the division of the total region into two separate zones. In each zone, however, the spatial characteristics were similar over their longitudinal extent.

Bunting et al. (1976) examined long-term rainfall records from selected stations in West Africa. They concluded that no trends or periodicities could be found in the data bases extending over 50 years or more. Bunting et al. also found that the Sahelian rainfall patterns were not clearly linked to the westerly circulation features

158

over the British Isles. Nicholson (1979) expanded the long-term rainfall series for the semiarid region of sub-Sahara Africa (between 12° and 20°N) and found evidence to support a tendency toward persistence in the subtropical rainfall series. Nicholson also noted periods of drought (1910-1920, 1940's, 1968-1973) in the 75-year rainfall series for the entire region where average annual rainfall varies between 50 and 1200 mm.

With the acquisition of long-term rainfall data from 28 stations in Nigeria a regional analysis was made to examine the wide variation in rainfall patterns over the 50-year period (1927-1976). The data sets are available in a separately published Part 2 of the final report. The country was divided into four regions (North, Central, Southwest, and Southeast) which are characterized by distinct rainfall regimes (Figure 4.53). The stations are grouped by region in Table 4.2. The Northern Region consists of five stations which are representative of the Sahelian zone. The Central Region, which includes six stations, separates the semiarid zone of northern Nigeria from the subhumid tropical zone of the south. The climate of the Central Region is complicated by the topographical features of the highlands.

The southern portion of Nigeria is divided into a Southwest Region and a Southeast Region. Six stations are grouped into the Southwest Region which experiences a double-rainfall maxima in May/June and September/October with a "little dry season" in July/August. The little dry season is associated with a temperature inversion above the surface layer which inhibits convective activity and rainfall. The rainfall minimum in July/August in the Southwest Region coincides with

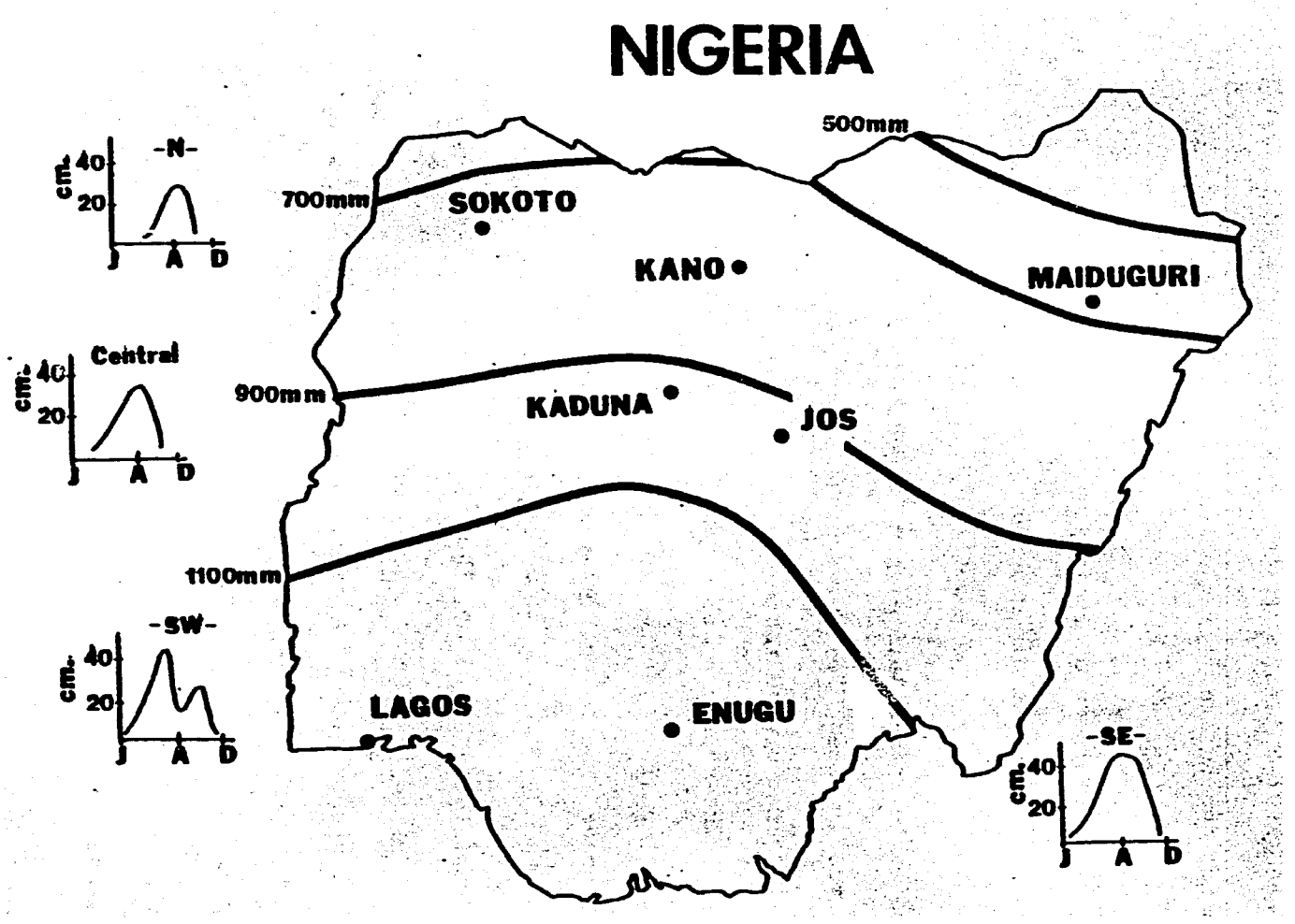


Figure 4.53. Map of Nigeria showing the normal seasonal rainfall distributions for the North, Central, Southwest and Southeast regions as well as the normal 500 mm, 700 mm, 900 mm, and 1100 mm isohyets.

TABLE 4.2

NIGERIA

RAINFALL STATIONS GROUPED BY REGION

Region	Station	Data Base
North	Maiduguri	1915-1976
	Sokoto	1915-1976
	Kano	1905-1976
	Katsina	1922-1976, except 1966-1968
	Potiskum	1936-1976, except 1966-1968
Central	Kaduna	1939-1976
	Zaria	1944-1976, except 1966
	Bida	1928-1976
	Minna	1916-1976
	Lokoja	1917-1976
	Makurdi	1927-1976
Southwest	Lagos	1892-1976
	Ibadan	1905-1976
	Ondo	1906-1976
	Benin	1906-1976
	Warri	1907-1976
	Ilorin	1916-1976
Southeast	Port Harcourt	1948-1976, except 1967-1968
	Enugu	1917-1976, except 1966-1968
	Calabar	1919-1976, except 1967-1968

the most northward progression of the ITCZ. The Southeast Region, which contains three rainfall stations, is typically characterized by a single rainfall maximum as is found in the North and Central Region The high rainfall amounts within the Southeastern Region are a common feature of the more humid equatorial rainfall zone, however.

Figure 4.54 presents the annual rainfall time series for 1927-1976 for the four regions in Nigeria. Actual amounts of rainfall are used to demonstrate the differences in magnitude between regions. Before continuing, a cautionary note is required. The station data were screened for quality and consistency. Some stations were excluded due to incomplete data. Furthermore, examination of the time series in Figure 4.54 reveals different patterns (i.e. trends, variabilities) before and after 1951. Although it may be coincidental, these shifts in patterns may be associated with the organization change in 1951 from the non-governmental International Meteorological Organization to the governmental World Meteorological Organization. However, the data are considered adequate to illustrate the comparisons of the rainfall regimes in the Northern Region with those of the other regions.

The Northern Region receives the least amount of seasonal rainfall and is, therefore, the most drought-prone. Figure 4.54 shows a relatively long period of below normal rainfall in the 1940's, which was interrupted only by two years of good rain (i.e., 1945, 1946), and another low rainfall period beginning in 1968 and lasting through 1976. These two below normal rainfall periods will hereafter be referred to as the drought periods. These rainfall series are similar to those of Bunting et al. (1976) and Nicholson (1979).

162

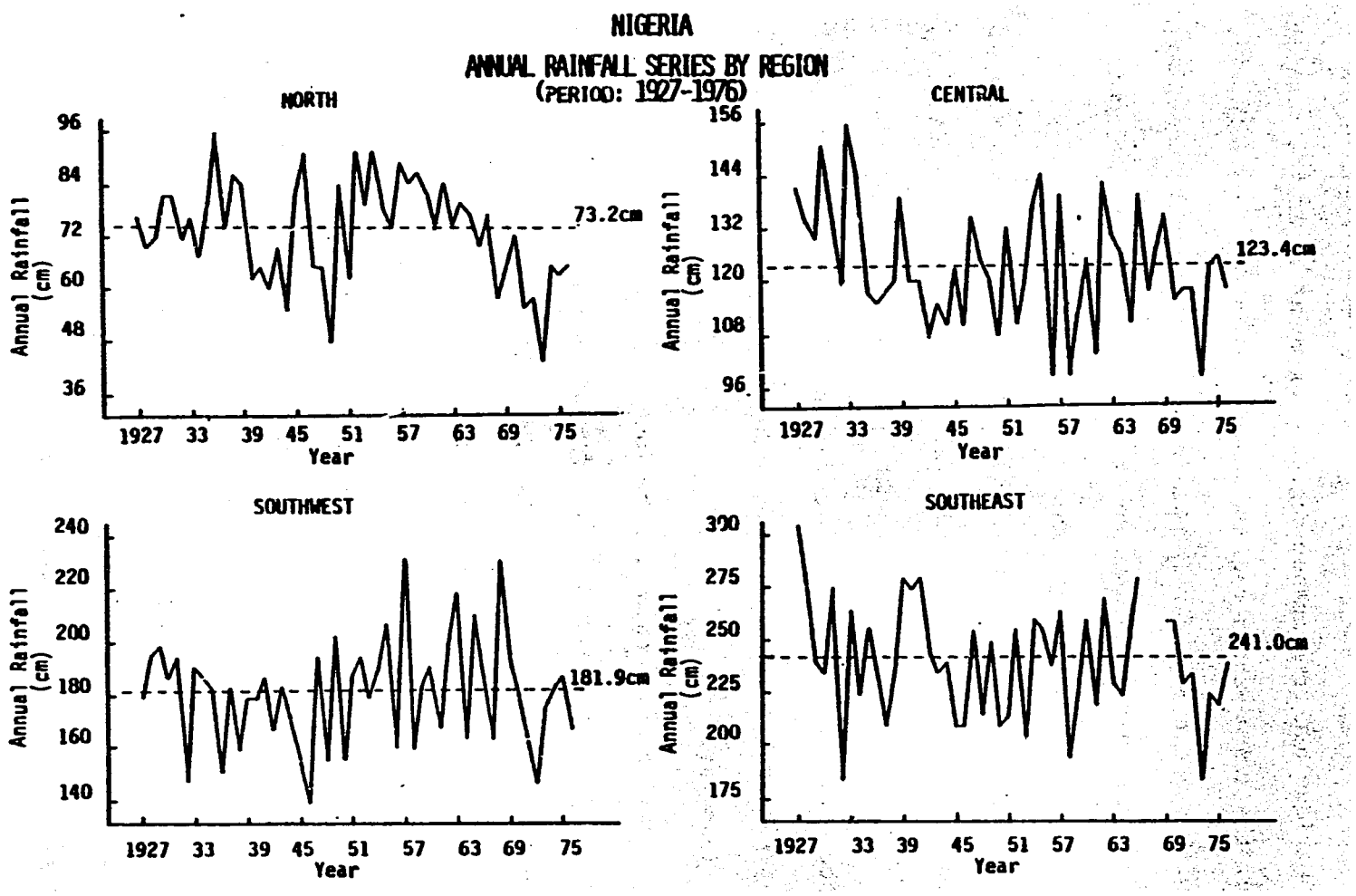


Figure 4.54. Annual rainfall series for the period 1927-1976 for the North, Central, Southwest, and Southeast regions of Nigeria.

The corresponding rainfall series for the Central Region (Figure 4.54) shows similar tendencies toward below normal rainfall during these two periods but to a lesser degree. Examination of the rainfall records for the two southern regions shows no consistent year-to-year patterns with respect to the rainfall series for the Northern Region. There are several years within these drought periods, however, which show below normal rainfall throughout most of Nigeria (i.e., 1942, 1943, 1944, 1948, 1971, 1972, 1973, and 1976). These results suggest a strong association between abnormal rainfall and anomalous large scale circulation patterns in this subtropical region during these years, especially since rainfall data for the 1971-1973 period indicated widespread drought conditions throughout the entire West and Central African regions.

The annual rainfall data for the four regions of Nigeria, expressed in terms of percentage departures from 50-year normals (1927-1976), are also presented in tabular form in Table 4.3. The drought periods of the 1940's and 1968-1976 are identified in this table. Table 4.3 shows an interesting feature with respect to comparisons between the Northern and Southern Regions. Notably, during the years 1936, 1938, 1945, 1946, 1950, 1958, and 1964, the Northern Region experienced above normal rainfall while the Southwestern Region experienced below normal rainfall. Conversely, during the years 1941, 1947, 1949, and 1968, the opposite pattern prevailed with respect to these two regions. These conditions are believed to be associated with the ITCZ as discussed below.

As many climatologists (e.g., Trewartha, 1961; Nieuwolt, 1977) have explained, the seasonal and yearly rainfall variations in West Africa

TABLE 4.3

NIGERIA ANNUAL RAINFALL

PERCENTAGE DEPARTURES FROM NORMAL (1927-1976)

	YEAR	REGION NORTH	CENTRAL	SOUTHWEST	SOUTHEAST
	1927	6	15	-1	27
	1928	-6	8	8	15
	1929	-2	5	10	-1
	1930	11	23	4	-2
	1931	11	11	8	13
	1932	-2	-2	-18	-23
	1933	4	27	5	9
	1934	-8	16	4	-7
	1935	8	-4	2	7
	1936	32	-7	-15	-2
	1937	1	-6	1	-12
	1938	18	-3	-13	-2
	1939	16	12	-1	17
Drought-North	1940	-16	-3	-1	13
Drought-North	1941	-13	-3	4	17
Drought-North	1942	-19	-12	-8	3
Drought-North	1943	-3	-7	1	-3
Drought-North	1944	-24	-10	-6	-1
	1945	13	-1	-14	-14
	1946	26	-10	-24	-14
Drought-North	1947	-10	10	7	6
Drought-North	1948	-10	1	-14	-11
Drought-North	1949	-34	-3	12	3
	1950	14	-13	-15	-14

	YEAR	REGION NORTH	CENTRAL	SOUTHWEST	SOUTHEAST
	1951	-14	6	4	-11
	1952	24	-10	7	5
	1953	9	-2	-2	-15
	1954	23	11	6	7
	1955	8	16	14	7
	1956	1	-20	-13	1
	1957	20	14	27	10
	1958	16	-19	-12	-18
	1959	16	-8	2	-5
	1960	10	1	6	9
	1961	3	-17	-8	-9
	1962	15	14	11	13
	1963	2	5	22	-5
	1964	8	2	-10	-7
	1965	4	-11	16	7
	1966	-5	13	4	17
	1967	4	-5	-9	
Drought-North	1968	-21	3	29	
Drought-North	1969	-11	8	7	9
Drought-North	1970	-2	-7	-1	8
Drought-North	1971	-23	-4	-9	-5
Drought-North	1972	-23	-5	-18	-3
Drought-North	1973	-42	-19	-3	-24
Drought-North	1974	-11	-2	1	-7
Drought-North	1975	-15	1	4	-8
Drought-North	1976	-11	-6	-8	-1

are associated with the movements of the ITCZ. During an average year the ITCZ moves far enough north to cause a "little dry season" in the southwestern portion of Nigeria. During some years with below normal rainfall in the Northern region, the ITCZ may not have penetrated far enough into the Sahelian zone thereby causing above normal rains in the Southwestern region. Similarly, during some years of above normal rainfall in the Northern region, the ITCZ may have travelled further north than normal resulting in a prolonged "little dry season" in the southern portion.

The seasonal rainfall distributions were examined to determine what, if any, consistent patterns were associated with these abnormal rainfall years. Specifically, the following questions were addressed: "Was there a delayed onset in the wet season which could seriously disrupt agricultural activities in the Sahelian zone during those below normal rainfall years?", "Was there a prolonged dry season in the Southwestern Region during abnormally high rainfall years in the Northern Region?" and finally, "During anomalous rainfall years, did all stations within the Northern Region show consistent rainfall patterns or were the regional results weighted by anomalous patterns at select stations?"

Concentrating on those years which showed contrasting annual rainfall patterns (i.e., above or below normal) between the Northern and Southwestern Regions, a consistent tendency became evident. Above normal annual rainfall in the Northern Region was associated with above normal rainfall during the months of July and August. Similarly, there was a prolonged "little dry season" with below normal rainfall during July through September in the Southwestern Region of Nigeria. These results suggest that the

zone of maximum rainfall activity associated with the ITCZ was displaced farther north than usual. There were no indications, however, of significant early season rainfall to signal an above-normal rainfall year in the Sahelian zone during these select years.

During those years of below-normal annual rainfall in the Northern Region, rainfall amounts during the peak wet season were also below normal. However, the Southwest Region experienced virtually no "little dry season" during these years, but instead had abnormally high rainfall amounts during July through September. Thus, the zone of maximum rainfall activity did not penetrate into the Northern Region with its normal intensity. During those select years of below-normal rainfall in the North and correspondingly high rainfall in the Southwest (i.e., during the months of July, August, and, to a lesser degree, September), there were no indications of a delayed onset of the wet season in the Northern Region.

Finally, during anomalous rainfall years, stations within each region were compared to see if these anomalies were caused by extreme station-specific fluctuations and not evident throughout the region, in general. This is important because of the sporadic nature of convective rainfall in frequency, intensity, and duration. These comparisons revealed no pecularities in any of the stations.

Thus, the examination of seasonal rainfall distributions during these abnormal years in the Northern Region of Nigeria indicates that there is a relatively strong relationship between the position of the ITCZ with its associated zone of maximum rainfall and the regional

rainfall patterns in both the Sahelian zone and the more humid subtropical zone in West Africa. This analysis is based upon surface data, and therefore needs the support of upper-air data analysis to further substantiate these results.

H. Crop Calendars

The major subsistence and cash crops grown in the semiarid regions of the drought prone countries of Central Africa are depicted on the maps in Figures 4.55 through 4.57. These maps showing the predominant agricultural regions were assembled from numerous sources, including FAO publications, WMO publications, Area Handbooks, USDA reports, AID reports, and personal communications with research institutes and local government officials.

The intent of presenting these maps is to show, in general, the major crop growing regions in each country. In some instances the agricultural zones are well-documented and consistent among different sources (e.g., Senegal, Niger and Sudan); however, in other cases, these zones were not well documented in the available sources. Therefore it must be emphasized that these maps present only a generalized summary of major crop regions. They are not all inclusive and do not reflect any changing agricultural patterns due to irrigation schemes or technological changes.

Using the format presented in the Final Report of the Study of the Caribbean Drought/Food Production Problem (CEAS, 1979), "fixed" or "normal" crop calendars were assembled for the major crops grown in the countries and/or regions shown on the maps in Figures 4.55

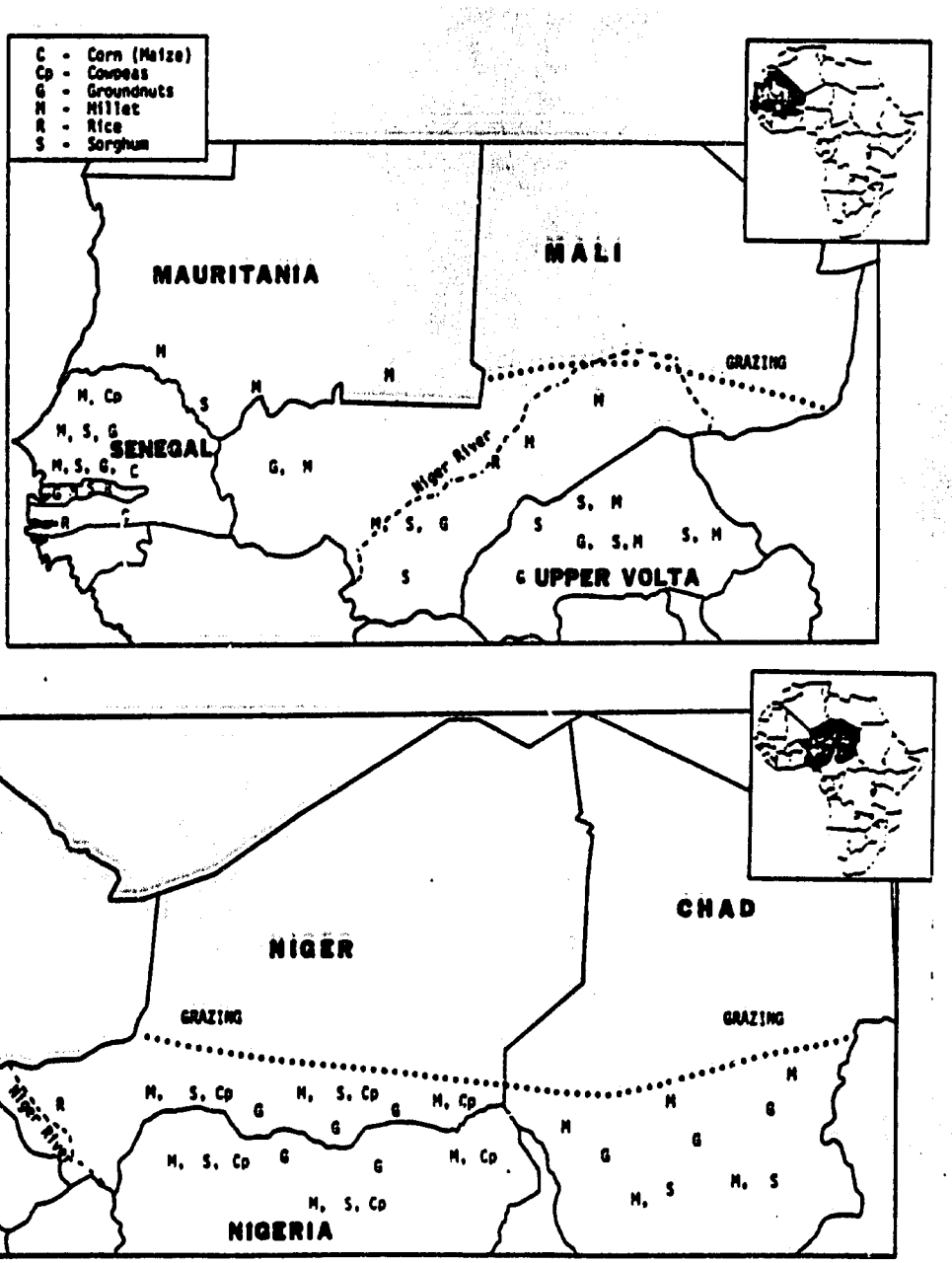


Figure 4.55. Regional maps of Senegal, Mauritania, Mali, and Upper Volta (top), and Niger, northern Nigeria and Chad (bottom) showing the predominant regions of cereal/cash crop production.

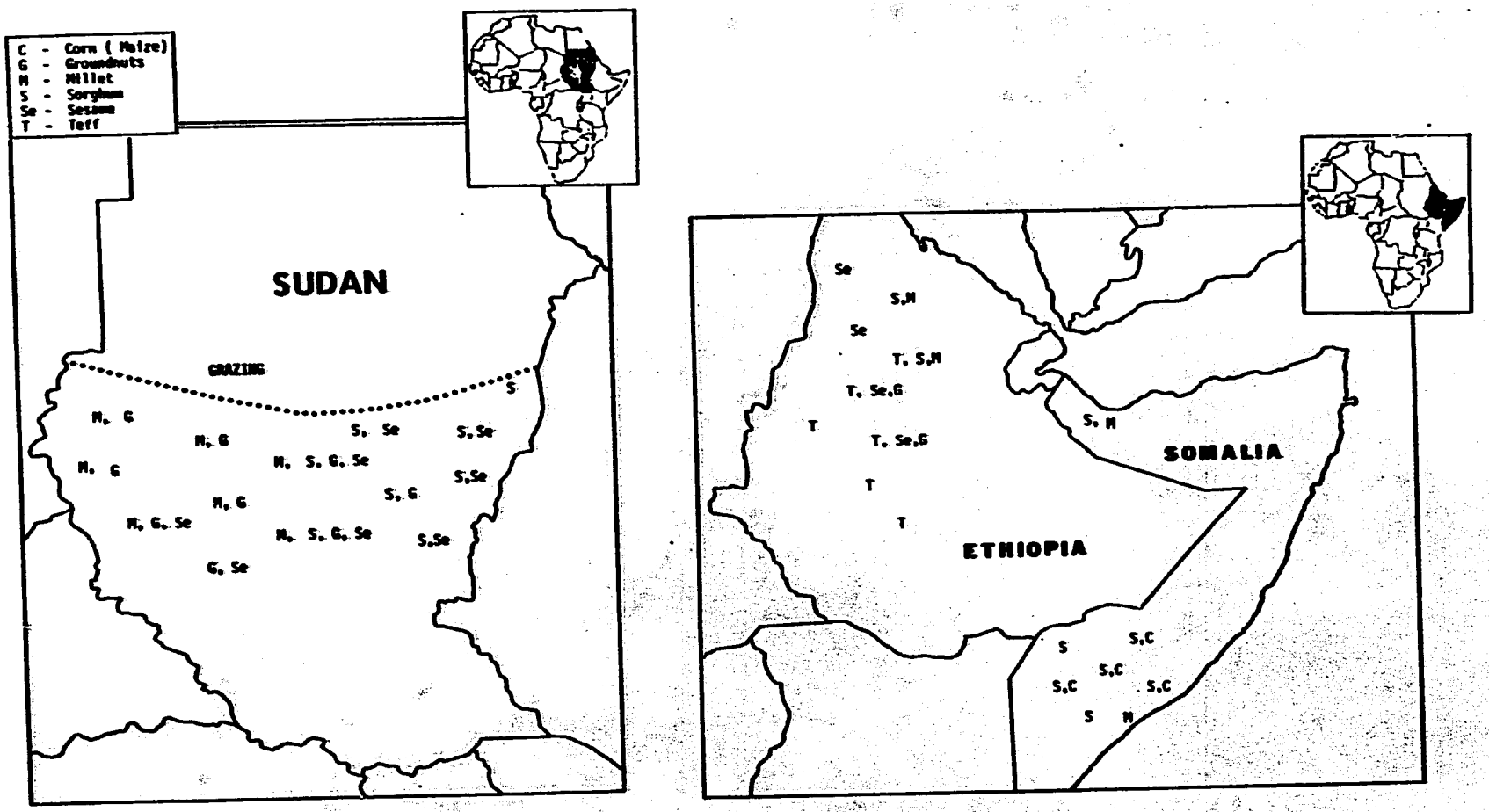
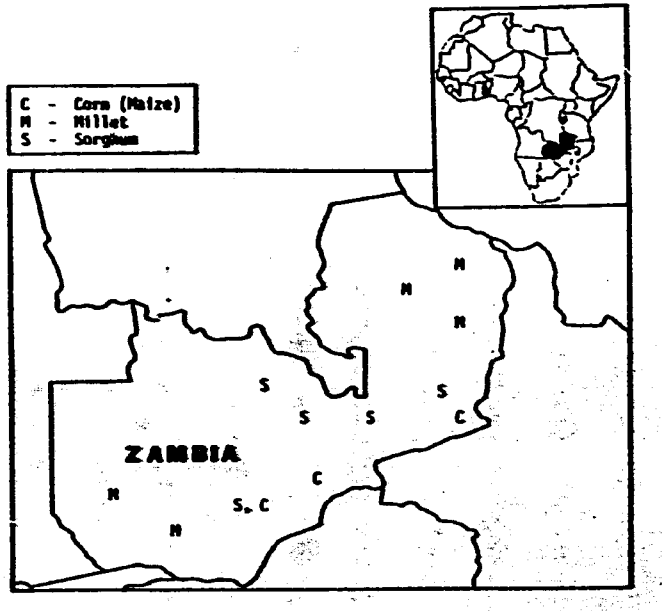


Figure 4.56. Regional maps of Sudan (left) and Ethiopia and Somalia (right) showing the predominant regions of cereal/cash crop production.



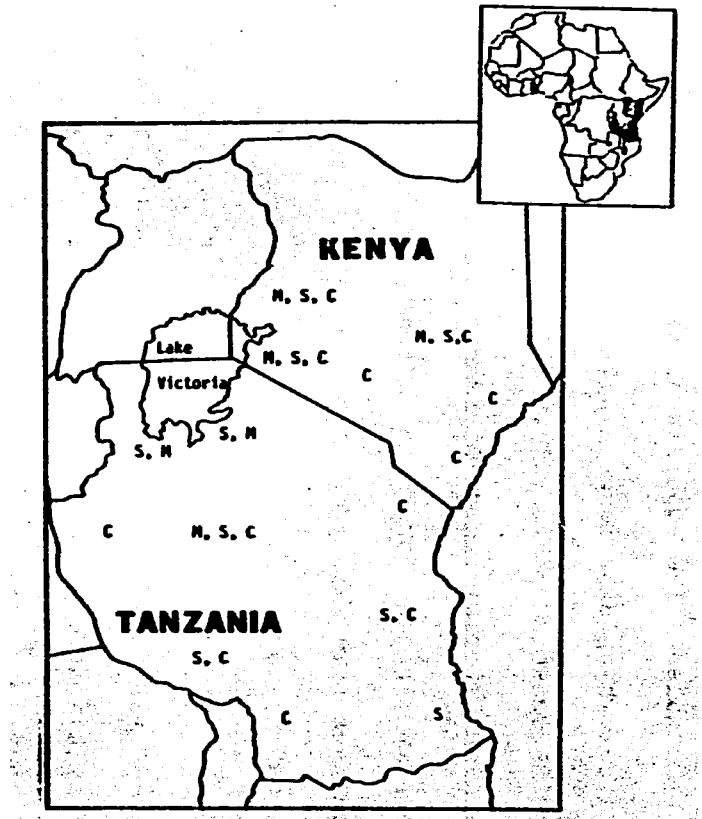


Figure 4.57. Regional maps of Zambia (left) and Kenya and Tanzania (right) showing the predominant regions of cereal crop production.

through 4.57. In most instances the alternating dry and wet seasons dictate agricultural timetables. The emphasis of this discussion is placed on semiarid regions which experience single rainfall maximums during the summer growing seasons. This rainfall pattern applies to all areas except for the equatorial region of Somalia and Kenya.

The land is normally prepared for sowing at the time of the expected onset of the wet season. This preparatory period may be relatively short in areas of low rainfall and also in areas of frequent rain. Following the beginning of "expected" significant rainfall, sowing occurs. The types of crops planted and cropping practices are dictated not only by climatic variables but also by local traditions and customs, topography, and economic considerations. However, based upon climate in general, and rainfall amounts in particular, the criteria for cropping patterns follow the guidelines described by Davy et al. (1976). The lower limit of agricultural production activity is generally accepted to be along the 350 mm isohyet. Areas of lower rainfall are suited only for grazing. Short-cycle crops, primarily millet and cowpeas, which mature in 70 to 90 days, are found within the 350-500 mm zone. In the 500-700 mm zone longer-cycle millet, sorghum, groundnuts and, in some areas, sesame are the main crops with cowpeas produced as a secondary crop. The growing period is between 90 and 120 days in this zone. In addition to the above mentioned crops maize becomes an important staple food within the 700-900 mm zone, particularly in East Africa. Above 900 mm, long-cycle sorghum and maize (150 days) predominate. Rice, grown under rain-fed conditions, also requires high amounts of rain-

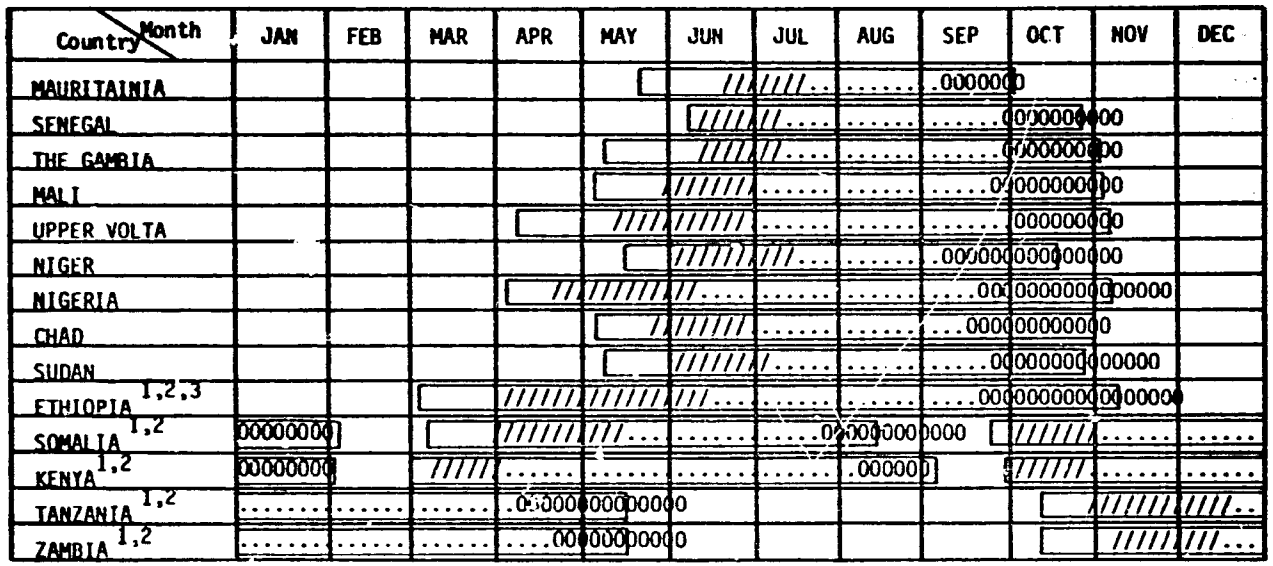
fall and is restricted to certain areas of West Africa (namely; the Casamance Region of Senegal and along the Niger River in Mali and Niger). Its importance as a staple food crop in Africa is also limited. Teff is a small-grain cereal which is found mainly in the highlands of Ethiopia; it is an important staple food crop in this area. Once established, teff is a very drought resistant plant, as is millet. Teff has a normal growing cycle of 3-4 months.

Fixed crop calendars for these rain-fed crops grown in the semiarid regions shown in Figures 4.55 through 4.57 are presented in Table 4.4. The normal duration of the wet season is included in these calendars in conjunction with normal planting and harvesting periods and with average growing cycles for the major subsistence and cash crops. The information presented in this table represents a generalized scheme for the crop growing season in different regions based upon the wet season. This fixed calendar should be adjusted according to the beginning of observed seasonal rainfall each year. The emphasis is on the primary growing season. In many areas a secondary growing season is possible due to the availability of moisture after the wet season ends, as in the case of flood-recession cultivation. These localized areas along river valleys as well as areas cultivated by irrigation schemes are not included in Table 4.4.

Intercropping is a standard and practical cropping practice throughout the region. Millet and sorghum are often intercropped with cowpeas which provide a valuable source of nitrogen fertility to the soil. Thus, it can be assumed that in areas identified as major millet/sorghum producing regions, cowpeas are also planted. Further-

TABLE 4.4

ESTIMATED FIXED CROP CALENDAR INFORMATION FOR
CEREAL CROPS/PULSES[1]/OIL CROPS[2]



[1]Extent of cowpea production in these countries is unknown at this time.
[2]Extent of groundnut and/or sesame production in these countries is unknown at this time.
[3]In Ethiopia, crop calendar includes teff production.

[ ]	WET SEASON	CEREAL CROPS:	MILLET, SORGHUM, MAIZE, RICE
///////	PLANTING PERIOD	PULSES	: COWPEAS, PIGEON-PEAS
.....	GROWING SEASON	OIL CROPS	: GROUNDNUTS, SESAME
000000	HARVEST PERIOD		

174

more, as noted in Chapter II, there may be competition between subsistence food crops such as millet, sorghum and maize, and cash crops such as groundnuts and sesame. This competition for cultivated land developed into a serious problem as the economic impact of the recent prolonged drought on producers became severe. Notably, groundnut production and acreage declined considerably in Niger as a result of deficit food production. The overall effect on future production remains to be seen.

Finally, the information provided in Table 4.4 should be considered as the best available synthesis for crop calendars by countries throughout Central Africa. Improvements to the generalized scheme in Table 4.4 should be possible as additional information is obtained and verified in the future.

I. Proposed Operational Assessment Program for Central Africa

a. Background

The Climatic Impact Assessment Division, Center for Environmental Assessment Services (CEAS/CIAD) prepares a weekly assessment publication, entitled "Environmental/Resource Assessment" report, that relates weather events to a number of societal functions in many of the countries of the world. This report, which is now in its fourth year of publication, provides governmental and private subscribers with a description of the week's meteorological events and their societal effect in each of seven major agriculture regions of the world outside of the U.S., e.g., Canada, the Soviet Union, China, India, Australia, Argentina and Brazil. Of particular concern in these assessments are precipitation amounts, temperatures, droughts, floods, and sudden destructive

weather; their purpose is to provide timely qualitative evaluations of the societal impact of these climatic/weather events. The Environmental/Resource Assessment report also contains detailed quantitative temperature analysis for the states and regions of the U.S. in terms of heating and cooling degree days. It provides assessments of natural gas use derived from CIAD natural gas consumption models as well as temperature-related power consumption. Further, this weekly publication outlines major weather anomalies (and their impact on societies throughout the world) and, for AID/OFDA, provides detailed weekly and season-to-date analysis, precipitation summaries and qualitative assessments for 21 Central African countries. The models described in the AID/CIAD Africa project are expected to input into and significantly enhance the agriculture effects section of this assessment. A separate CIAD assessment report covering 26 regions in the Caribbean Basin was designed to satisfy the specific disaster assistance needs of AID/OFDA. This weekly report, which identifies the extent and intensity of drought and flood areas in the Caribbean, is distributed through OFDA mailing lists. The output from the Caribbean models which were developed under AID/CIAD contract, are, after testing, expected to enhance the agricultural effects section of this report.

Collectively, these assessment publications provide timely impact assessments of the effects of the variabilities of climate and weather on agriculture, energy consumption, disaster assistance, and in the future, a number of other societal events. The assessment reports are based on two primary meteorological sources; 1) the synoptic weather observations obtained from over 8000 weather stations, worldwide, that

are channeled through the Global Telecommunications Network under the auspices of the UN affiliated World Meteorological Organization and 2) the circumpolar TIROS, geostationary GOES and DMSP weather satellite imagery from which CEAS/CIAD estimates precipitation amounts. Special CIAD programs and satellite imagery interpretation techniques evaluate, synthesize and summarize this meteorological data into operationally usable climate/weather information designed to support CIAD's assessment mission. It is then applied to the assessment process along with societal event information using a combination of judgmental and statistical tools. Expansion of the weekly assessment support provided to OFDA, recently agreed upon, will extend assessment coverage to all of Africa south of the Sahara and to South Asia.

b. Operational Utility of the Weather/Crop Yield Relationships in Central Africa

The agroclimatological techniques presented in this report will be used to provide readily usable qualitative potential yield information. This information will incorporate knowledge of the stage of crop development to estimate conditions of the major subsistence food crops. Weather impact assessments will be made on a timely basis during the crop season based upon available meteorological data from weather observations and satellite imagery.

Following the format established in the Final Report: A Study of the Caribbean Basin Drought Food Production Problem (CEAS, 1979), weekly weather/crop impact statements will continue to be issued for specific Central African regions and countries. These reports will be augmented by crop development and qualitative yield information

acquired from the crop models described in this paper when drought conditions (i.e., cumulative precipitation less than 60 percent of normal for at least a two month period) are indicated by analysis of precipitation data or if model projections suggest abnormal yield.

On a monthly and growth-stage basis, statistical weather/crop impact estimates will be incorporated into the weekly assessment report. These will be based upon real-time monthly meteorological data and utilize the traditional linear regression yield models, analogue yield models and historical yield indices. If a complete data base is not available for all stations used in the specific model, an initial estimate will be made based upon the available data and "revised" when more complete data become available. A statement will appear in the appropriate weekly weather/crop impact assessment report to indicate data availability and the types of agroclimatic techniques used for assessment.

Using the crop calendars established for various crops in specific countries (See Table 4.4, Section IV.H), agroclimatic techniques will be used in the following manner:

Regression Models:	Senegal	-	Millet
			Rice
			Groundnuts
			Cowpeas
			Maize
	Niger	-	Millet
			Sorghum
	Sudan	-	Millet
			Sorghum

Regression Models: (cont.)	Sudan (cont.)	-	Sesame
Analogue Models:	The Gambia	-	Millet
			Rice
	Mauritania	-	Millet
	Mali	-	Millet
Historical Yield Indices:	Chad	-	Millet
	Upper Volta	-	Millet

The percentiles of the historical yield indices will provide qualitative information on current crop conditions relative to past conditions (i.e., good or poor crop seasons). These indices can be used in conjunction with crop calendars to provide information on various crops according to the phenological stage of development. They can also be used in support of crop yield models since the models key on specific growth-stage data. The yield indices can supply information before and after the key stages of crop development in these countries.

An additional, but significant, objective will be to rigorously test and evaluate developed climate/crop yield models and other agro-climatic techniques. Invariably historical weather data are far more complete and reliable than corresponding crop information. Therefore, the ability to test and evaluate these models depends largely upon the acquisition of qualified yield data and/or reliable and accurate appraisals of actual field conditions by knowledgeable persons. Where feasible, revised yield estimates from the countries of interest will be used for independent testing of the regression models used for assessment. Also, the verification of assembled crop calendar information is a major task.

The statistical assessment procedures proposed in this report are believed to represent a substantial improvement on any other known crop specific model for these countries or any drought measuring technique that does not consider crop calendar information and plant-water requirements by growth stage. Limitations in the statistical regression system are recognized and will be considered in the weekly assessment reports. Finally, the weekly assessment reports should be used to complement other sources of information such as field observations, probability or non-probability sampling surveys, agricultural attache reports, AID Mission sources such as private volunteer organizations, etc. In addition to providing additional information on weather impact, these sources are necessary to provide information on significant changes in crop location or acreage, impact of disease, pests, and destruction brought about by political instability and substantial changes in technology.

CHAPTER V

SUMMARY

The specific objectives of this project include:

(1) the development of a complete meteorological data base for drought-prone countries of Africa

(2) the development of agroclimatic techniques to be utilized operationally for assessment of subsistence food crop production and drought conditions in sub-Saharan Africa.

Considerable success was achieved in gathering meteorological data bases throughout West Africa. These data bases were processed and analyzed to study the severity of the recent meteorological drought in the Sahelian region of Africa. Seasonal and annual rainfall variations in sub-Saharan Africa are associated with the movements of the Intertropical Convergence Zone (ITCZ). Below normal rainfall patterns in the Sahelian zone often coincided with above normal rainfall in the humid zone which suggests that the frontal position was located further south than normal during these anomalous rainfall years.

Agricultural data bases were assembled for Senegal, Niger, Sudan, Nigeria and Upper Volta. Except for Upper Volta, weather-crop yield models were developed for the major subsistence food/cash crops grown in these countries. The agricultural data base for Upper Volta had to be eliminated from analysis due to inherent problems in data quality. After careful screening, relatively strong signals were found relating year-to-year crop variability to the selected weather elements.

The crop moisture ratio (CMR) was developed as the predictor variable for model development. The CMR is a measure of available moisture under rainfed conditions for successive growth stages of specific crops. There was a good relationship between crop yields and CMR for both the vegetative and reproductive stages. During the vegetative growth stage a linear relationship was observed between crop yields and CMR. However, during the reproductive stage, there was a general tendency for optimum conditions to be reached beyond which yields leveled off with continued increases in moisture availability. Unique patterns in this relationship during the reproductive stage were found for different countries, however. The advantage of using such a parameter as the CMR is that when yield data are not available an agroclimatic analysis can still be performed. This analysis must be oriented toward key phases of crop development during which a climatic variable may become a limiting factor for growth processes. Historical crop yield indices do provide the basis for objective analysis of crop conditions at successive growth stages based upon meteorological data and crop calendar information. These indices were developed for Chad, Upper Volta, Mali, Kenya and Tanzania.

In the northern parts of the Sahelian region where grazing is the predominant form of agriculture, deser encroachment has posed a severe problem for herdsmen. Percentile rankings of historical climatic data were generated to provide a qualitative assessment of rangeland conditions. An attempt to quantify vegetative information and/or carrying capacity for the rangelands is an important task in future work on the rangeland index.

The results of the agroclimatic analysis conducted during this project illustrate the operational utility of the agroclimatic techniques. Climate/crop yield models need to be rigorously tested and evaluated using independent yield estimates for the most recent years. Revisions of these models may be necessary as additional data is gathered. Verification of assembled crop calendar information will also be a necessary task in future work.

In general, these techniques can provide significant information which will allow estimation of crop variability from an adequate flow of current meteorological data.

CHAPTER VI

DATA SOURCES

A. Meteorological Data

Meteorological data were obtained from a variety of sources including records from the World Meteorological Organization, the National Oceanic and Atmospheric Administration, official publications of individual countries, and official records obtained through the cooperation of National Meteorological Services of several African nations. These data include both monthly precipitation and temperature. Special recognition must be given to the following agencies: Agence pour la Securite de la Navigation Aerienne en Afrique et a Madagascar (ASECNA), Senegal; National Meteorological Service, the Gambia; Meteorologie Nationale, Cameroon; and, Nigerian Meteorological Service, Nigeria.

After quality control checks, historical meteorological data bases for individual countries were developed. A total of seventy-seven WMO meteorological stations were used for crop-climate analysis in eight countries over the period 1951-1977 (Table 4.5). Further, a total of 785 precipitation recording stations in ten countries (Appendices I and II) were used for the meteorological drought analysis for the years 1968-1975. Monthly precipitation data at each location were combined into growth stage, seasonal and annual values for analysis purposes. These data were further aggregated into regions within each country for the drought analysis. Finally, a total of 28 national meteorological stations were available for the study of agroclimatic patterns of

184

TABLE 4.5

LIST OF WMO STATIONS

The following is a list of the countries, stations, and WMO station I.D.'s which will be used to provide operational assessments for Central Africa.

COUNTRY	STATION NAME	WMO #
Senagal	Ziguinchor	616950
	Kolda	616980
	Linguere	616270
	Diourbal	616660
	Kaolack	616790
	Tambacounda	616870
	Kedougou	616990
	Kitam	616300
	Saint-Louis	616000
	Dakar/Yoff	616410
	Podor	616120
Niger	Agadas	610240
	Tillabery	610360
	Tahoua	610430
	N'Guigmi	610490
	Niamey-Aero	610520
	Birni-N'Konni	610750
	Maradi	610800
	Zindar	610900
	Gaya	610990
	Maine-Soroa	610960
	N'Guigma	610490
Sudan	El Obeid	627710
	En Nahud	627810
	El Fasher	627600
	Geneina	627700
	Ed Duaim	627500
	Kosti	627720
	Sennar	627620
	Wadi Medani	627510
	Nyala	627900
	Damazine	628050
Upper Volta	Boromo	655160
	Ouagadougou	655030
	Fada N'Gourma	655070
	Dori	655010
	Ouahigouya	655020
	Bobo-Dioulasso	655100
	Gaoua	655220
Nigeria	Maiduguri	650820
	Kano	650460
	Katsina	650280
	Nguru	650640

TABLE 4.5 (cont.)

COUNTRY	STATION NAME	WMO #
Nigeria (Continued)	Sokoto	650100
	Yelwa	650010
	Kaduna	650190
	Zaria	650300
	Potiskum	650730
Mali	Kayes	612570
	Menaka	612500
	Gao	612260
	Tombouctou	612230
	San	612770
	Segou	612720
	Mopti	612650
	Koutiala	612930
	Bamako	612910
	Hombori	612400
	Nara	612330
	Tessalit	612020
	Kidal	612140
Chad	Fort Lamy	647000
	Abeche	647560
	Ati	647510
	Mongo	647580
	Bokoro	647080
	Bousso	647050
	Am Timan	647540
	Mao	647010
	Faya	647530
Mauritania	Nema	614970
	Kiffa	614980
	Rosso	614890
	Aioun El Atrouss	614990
	Boutilimit	614610
	Nouakchott	614420
	Tidjikja	614500

Nigeria. Table 4.2 includes those stations which were selected for analysis after quality-control checks were made.

B. Agricultural Data

Agricultural statistics were obtained from numerous sources. The Center for Research on Economic Development, University of Michigan was a valuable source for crop production, acreage and yield statistics for several Sahelian countries. Other sources included the West African Rice Development Association (WARDA), Liberia; Ministry of Agriculture, Division of Statistics, Senegal; Mr. P. Hutchinson, WMO Agroclimatol gist, the Gambia; Institute for Agricultural Research, Ahmadu Bello University, Nigeria; Food and Agriculture Organization (FAO) production yearbooks; and World Bank Agricultural Sector Surveys.

In addition to crop statistics, agronomic information which is needed to develop proper crop calendars for specific crops in specific regions was gathered from numerous qualified sources from both the United States and individual countries. Special recognition should be given to the following personnel and their respective institutions:

Mr. Joe Hartman, AID agricultural specialist for Senegal;

Dr. Brown Enyi, Head of Research, WARDA;

Mr. Van Henderson, AID agricultural specialist for Liberia, formerly for Chad;

Mr. Gene Chivaroli, Acting Director, AID Mission, Senegal;

Mr. Robert Rousell, AID Food for Peace Officer, Chad;

Dr. B. N. Okigbo, Deputy Director General, International Institute of Tropical Agriculture (IITA), Nigeria;

Mr. E. Jones, Project Manager of the Rice Research Station, Sierra Leone;

Mr. P. Hutchinson, WMO Agroclimatologist, the Gambia;

Mr. V. Lateef, presently NE/Tech/AD, Department of State, formerly, FAO officer, Senegal;

Mr. S. Skinner, agricultural economist, Foreign Demand and Competition Division, U.S. Department of Agriculture;

Mr. J. Becker, agricultural economist, AID;

Mrs. A. K. Binder, Chief, Food Security and Information Service, FAO, Rome;

Dr. M. Frere, Crop Ecology and Generic Research Unit, FAO, Rome;

Dr. Klaus Meyn, Northern Agriculture Division, The World Bank; and,

Dr. D. Stryker, Associate Professor International Economic Relations, Tufts University.

Two libraries have also been helpful in providing bibliographical information concerning the drought-prone countries of Central Africa. Mr. J. Lauer, Librarian, Sahel Documentation Center, Michigan State University, and Mr. D. Illes, Project Librarian, MUSAT, Bio-Ag Library, University of California-Riverside, have been very cooperative in this regard.

C. Regional Surveys

Bibliographic searches for major political, military, economic and social events which may have affected agricultural productivity in specific African nations were conducted by NOAA/EDIS Oceanic and Atmospheric Scientific Information System (OASIS). Data bases for these

surveys include New York Times (1969-present), Commonwealth Agriculture Bureau (1972-present), National Agriculture Library (1970-present), and Public Affairs Information Service (1976-present). Mr. Robert Walter, and Mr. Gary Adams, OASIS personnel, were most helpful.

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190

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