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RAINFALL AND AGRICULTURE IN CENTRAL WEST AFRICA SINCE 1930

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RAINFALL AND AGRICULTURE IN CENTRAL WEST AFRICA SINCE 1930

A Dissertation APPROVED FOR THE
DEPARTMENT OF GEOGRAPHY

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"Let your light shine before men, that they may see your good deeds and praise your father in heaven"

- Matthew 5:16

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Subsaharan West African rainfall is highly variable. This variability is related to changes in the tropical Atlantic sector and circulation regimes that alter the preferred location of tropical convection along with the Intertropical Convergence Zone (ITCZ). Rainfall variations and their influence on crops need to be assessed. Although many studies have been conducted on the effects of rainfall on agriculture in various parts of the world, few studies have focused on Central West Africa. This study examines rainfall variability and its effects on crops, societies, and economies of Mali, Burkina Faso, and Côte d'Ivoire.

Rainfall is critical in determining agricultural output. Most farming systems and many aspects of crop growth are adversely affected by rainfall variability, which can have a disproportionate impact because individual crops are affected differently. Agriculture is the main mode of employment; thus, the socioeconomic well-being of Central West Africa relies on crop cultivation, which heavily depends on the vagaries of rainfall.

This analysis also investigates rainfall/crop yield relationships. The temporal focus is on recent decades spanning 1930-1998; adjustments are made, as the lengths of available data require. The aim is to determine whether rainfall fluctuations are associated with changes in crop productivity. Additionally, this study of rainfall/crop yields helps to better understand the environment, society, and economy of Central West Africa.

Studies are conducted and conclusions drawn using descriptive statistics (i.e., mean and standard deviation), Principle Component Analysis, time series, and correlation analyses as well as mapping/graphing analyses in GIS, software packages (e.g., Excel, Systat, Instat, Surfer), and comparisons with successive environmental policies. The results suggest that rainfall variations adequately account for more of the crop output than do environmental policies. It is concluded that the main influence on agriculture is rainfall and so, crop yields revolve mainly around the occurrence/non-occurrence (i.e., availability) of rains. Consequently, the understanding of rainfall variability and its induced agricultural changes is a necessity for sustainable socioeconomic development in Mali, Burkina Faso, and Côte d'Ivoire. This study recommends that environmental policies should acknowledge the importance of seasonal rainfall forecasts and incorporates the climate aspects (i.e., agroclimatologic challenge) into agricultural productivity.

CHAPTER 1

INTRODUCTION

1.1 Problem and Significance of the Study

The focus on earth resource relationships is of great relevance worldwide for better monitoring and understanding of the environment and socioeconomic well-being. This is especially true of developing regions such as tropical Africa, where more than 70 percent of the population live in rural areas and therefore depend on natural resources for their basic needs (e.g., food, wood fuel production). Research into the Subsaharan West African climate has focused on the space-time variability of rainfall and the causative climate system processes (e.g., Lamb, 1982; Folland et al., 1991; Ward, 1998). However, the link between rainfall variability and agricultural change has not been adequately researched. This linkage is important because preliminary studies strongly suggest that climate variability alone has led to a number of impacts that are perceptible in agriculture yields and crop adjustment, such as the replacement of long vegetative cycles by shorter ones, promotion of drought-resistant crops, as well as nomadic and transhumance movements (Ould Sidi, 1979; Vermeer, 1981).

Overall, most West African economic activities (e.g., farming, herding, hydroelectric production, domestic water consumption) are dependent on rainfall. Given that rainfall is obviously a weather element that plays a major role in tropical agriculture and hence socioeconomic well-being, much general research has attempted to explore and give reliable answers and solutions to rainfall variability and agricultural change, and connect them to sustained socioeconomic development policies. The inquiries for

Subsaharan West Africa mainly have focused on rainfall and its causes and variations as well as its possible seasonal forecasting (e.g., Lamb, 1978a,b; Nicholson, 1981; Hastenrath, 1990; Lamb and Peppler, 1991, 1992; Long et al., 1998; Ward, 1998). In the past two decades, studies also have included the impacts and consequences of rainfall variability (e.g., Agfoni, 1979; Nicholson, 1981; Ballo, 1989; Glantz, 1994; Mollah and Cook, 1996; Phillips et al., 1998; Chmielewski and Köhn, 1999). Although these papers are indicative of ongoing efforts to assess the effects of rainfall variations on the environment in a number of areas (e.g., agriculture, society, and economy), much research needs to be done for many Subsaharan West African countries, including Mali, Burkina Faso, and Côte d'Ivoire. The aforementioned studies do lay the framework for consideration of agricultural output as being very rainfall sensitive; yet, these previous climate-crop yield investigations treat crop productivity as one of the basic environmental issues with emphasis only on plant growth and development. These analyses do not provide full assessments of agricultural change, as would an approach that couples rainfall variability with crop acreage, production, and yield evaluations.

Therefore, this Dissertation investigates the spatial and temporal relationships between rainfall variations and agricultural changes in Subsaharan Central West Africa (Fig. 1.1), where the economies are heavily dependent on rain-fed agriculture. The study also examines the implications of rainfall variability and crop yield relationships for socioeconomic development. Indeed, farming is extremely risky in a large fraction of the study area, which is semi-arid to arid with very low rainfall reliability. Finally, this work provides information that fills a gap in the agroclimatology of Central West Africa. Note that agroclimatology in this paper includes only rainfall and agriculture. By definition, agroclimatology shall be understood as the relationships that rainfall variability and its seasonal forecast information have with the assessment of crop acreage, production, and yields. The other climatic factors (e.g., temperature, humidity, solar radiation) are relatively constant and are not limiting for crop growth in most parts of Central West Africa, which spans an environment ranging from humid (mostly Côte d'Ivoire and south Burkina Faso) to semi-arid and even arid (largely north Mali) (Fig. 1.2).

This chapter provides background information on Central West Africa that introduces the study. It first describes the physical settings, including climate, topography, vegetation, hydrology, and soil. Then, information on the human and economic situations of the study area is provided.

1.2 Background: Location and Climate

The Republics of Mali, Burkina Faso, and Côte d'Ivoire lie between latitudes 4°38' and 25°00' North, and longitudes 12°24' West and 4°25' East (Fig. 1.1). Mali and Burkina Faso (formerly Upper Volta) are both landlocked countries with no coastline. The Ivorian territory is located on the western bulge of the African continent and is the only one with a shoreline, bordered to the south by the Atlantic Ocean with 515 km of coastline. Mali and Burkina Faso show interesting contrasts between African and Western civilizations, while Côte d'Ivoire is among the most developed West African countries with more influence from the Western World. All three are former French colonies that obtained their independence from France in 1960. Table 1.1 summarizes some geographical facts (characteristics) of the three Central West African countries.

Table 1.1: Basic characteristics of Central West Africa in 2002 (developed from http://www.cia.gov, 2002; http://www.worldbank.org, 2002).

Basic Characteristic	Mali	Burkina Faso	Côte d'Ivoire
Size (km^2)	1,240,200	274,200	322,500
Population Total (millions)	11.34	12.60	16.80
Population Density (persons/km^2)	9	41	50
Population Growth Rate (% yr^{-1})	2.97	2.64	2.45
Capital City	Bamako	Ouagadougou	Yamoussoukro*
Area Comparison with U.S. States	Less than Alaska but twice Texas	Approximately the size of Colorado	Slightly larger than New Mexico

***Although Yamoussoukro has been the official capital since 1983, Abidjan remains the administrative center and houses all government and administrative services.**

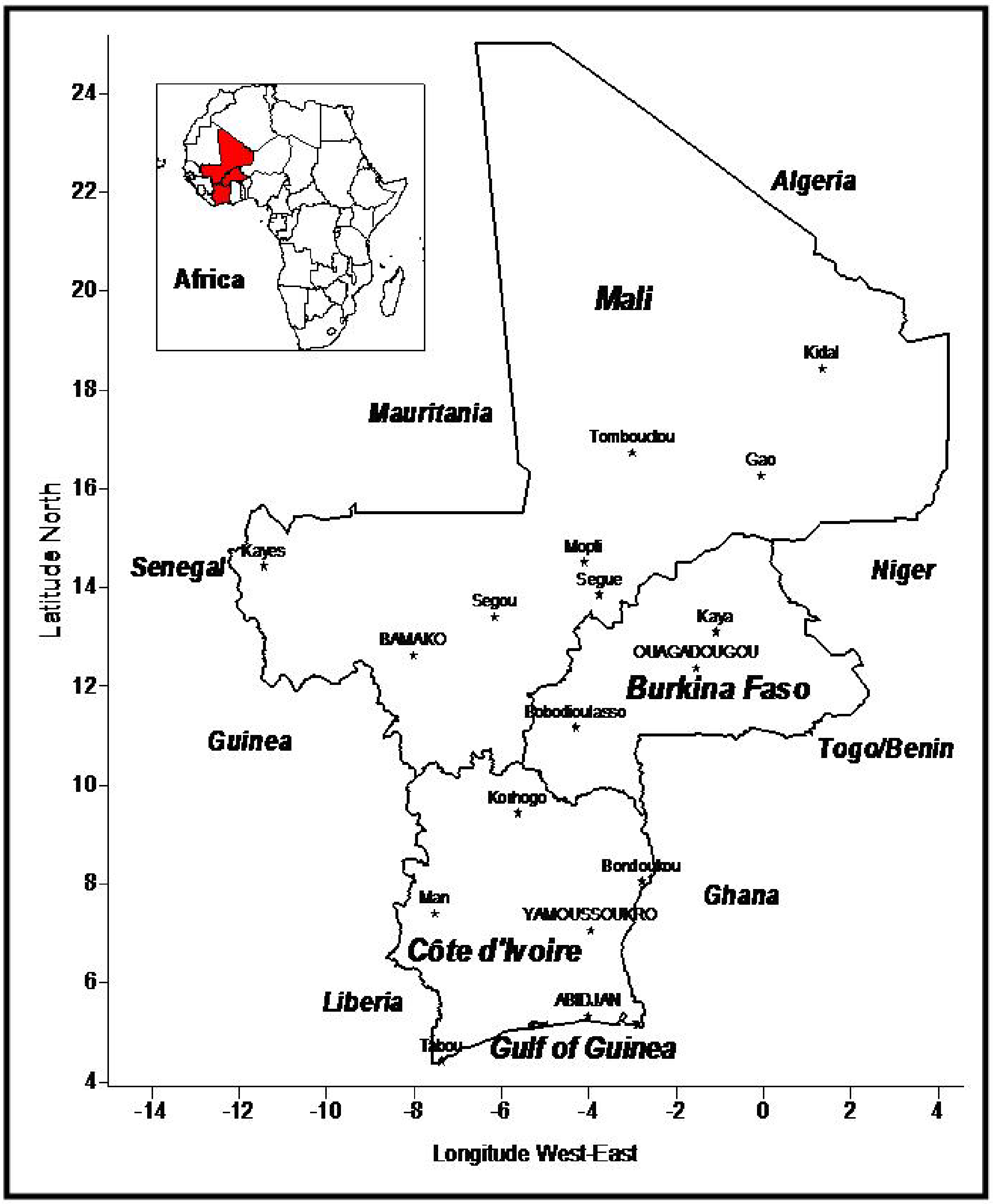


Figure 1.1: Geographic location of study area (Central West Africa).

Burkina Faso and Mali are located within the Soudano-Sahel and desert ecological zones (Fig. 1.2). They are characterized by pronounced wet and dry seasons with vegetation ranging from tropical savanna to tropical arid. Their annual rainfall (concentrated in July-September) varies from approximately 1000 mm in the south to less than 250 mm in northern Burkina Faso and almost no rain in the extreme north latitudes of Mali, where hot northeasterly desert winds prevail year-round (Bérété, 1986; Lamb and Peppler, 1991). Except in northern Mali, three distinct seasonal weather patterns can be discerned -- warm and dry (November-March); hot and dry (April-May); and warm and wet (June-October).

In contrast, Côte d'Ivoire largely lies within the humid tropical forest region, with an overall warm and moist climate for which the annual rainfall cycle changes from tropical wet (four seasons in the south) to tropical subhumid (two seasons in the north) (Fehr, 1979; Paturel et al., 1996) (Fig. 1.2). Heavy rains in the north usually occur from June to October (similar to the Soudano-Sahel zones) and provide about 1100 mm yr^{-1}. Along the equatorial coast (south), there is rain in most months, but it is heaviest between April-May and September, giving an average of 1800-2000 mm yr^{-1}. Here, there is a major dry season from December to March-April and a "little dry season" from mid-July to mid-September during years with the appearance of the coastal ocean upwelling that inhibits lower tropospheric convergence and cloud formation. When an El Niño-like suppression of coastal upwelling occurs, there is no "little dry season" during mid-July to mid-September. The mountain regions along the western border record considerable amounts of rain (ten out of twelve months, excepting December-January) that accumulate to an average total of 2500 mm yr^{-1}. It is in this region that orographic uplifting is best developed because of the influence of the spur of the Guinean mountain range.

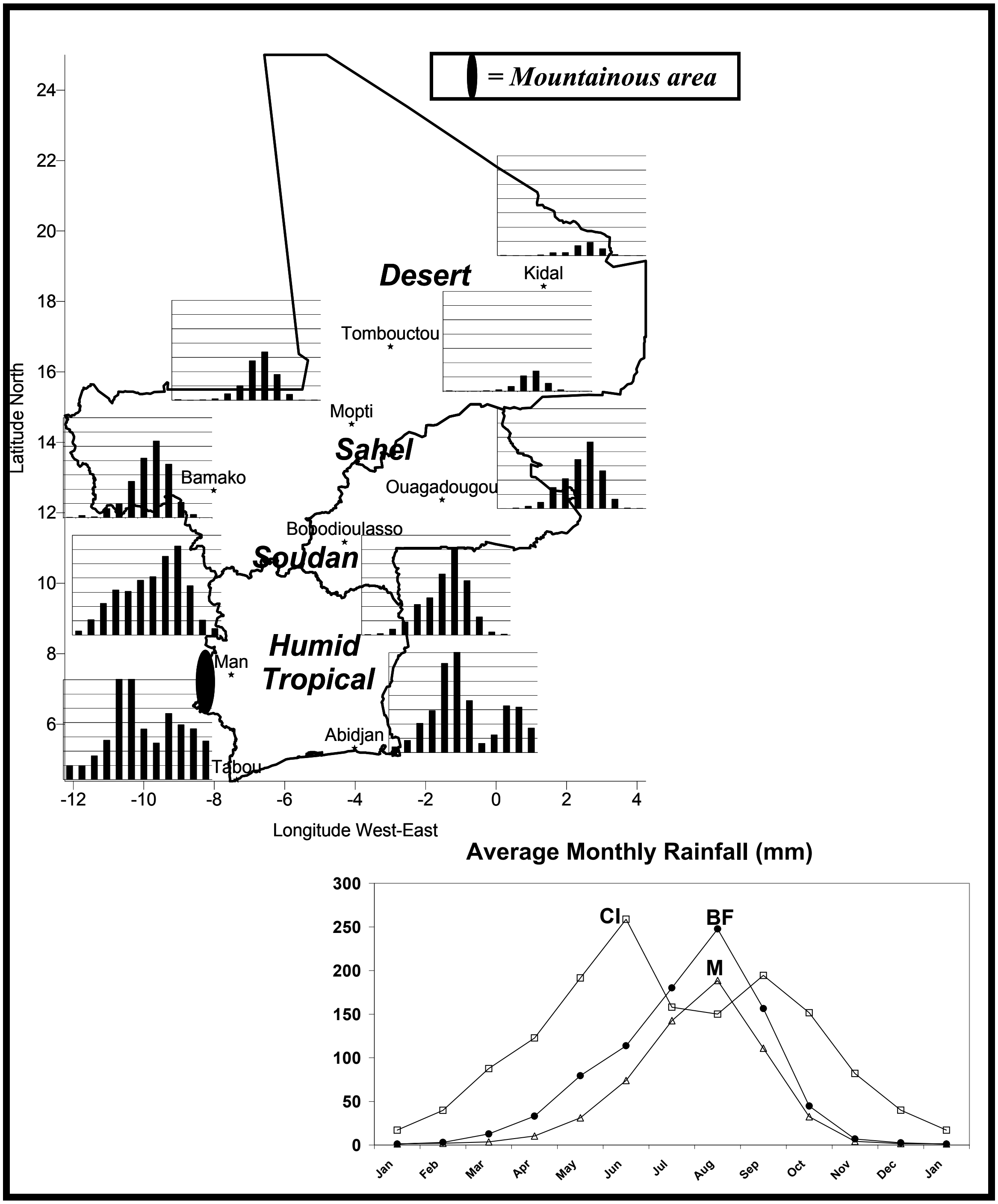


Figure 1.2: General climatic regions and annual rainfall cycles for selected stations on top (depiction is based on rainfall data sets for 1930-1998 developed for this study) and average rainfall climatology for each country on bottom (M is Mali, BF is Burkina Faso, and CI is Côte d'Ivoire).

Of the climate variables, rainfall is by far the most important because of its influence on agricultural productivity, water availability, disease, and famine. Temperatures usually support reasonably constant potential evapotranspiration and do not limit plant growth. Indeed, like the rest of the tropics, average temperatures are generally uniform and vary little from one season to another and from year to year. Seasonal mean temperatures vary between 25-30ºC, whereas daily temperatures can range from 10ºC to 45ºC (e.g., Landsberg, 1972, pp. 20, 102-104, 196, 283; CNRS/IGN, 1978, p. 14). Thus, diurnal temperature variations can exceed those of the seasonal mean temperatures (Hastenrath, 1991). In contrast, rainfall totals are more variable and provide the basis for identifying seasonal, interannual, and regional climates. Furthermore, the small seasonal temperature variations are related to rainfall, since temperatures are cooler during the rainy season because of cloud cover and evapotranspirative heat consumption. The spatial and temporal variations in tropical region rainfall reflect the space-time characteristics of the rain producing (i.e., Intertropical Convergence Zone, ITCZ) and inhibiting (i.e., subtropical anticyclones) mechanisms, which are described in Chapter 2 (see also Landsberg, 1972; Adams et al., 1996; Aryeetey-Attoh, 1997).

1.3 Physical Features: Topography, Soils, Vegetation, and Hydrologic Systems

1.3.1 Topography: Relief and Geology

The topography of Central West Africa is largely flat and uniform (Fig. 1.3, top). It consists of a mix of plains and low hills that form part of a vast lateritic plateau rising gradually from sea level in the south to almost 500 m in the north. The highland regions, which are in Côte d'Ivoire and Mali, are localized and discontinuous. The mountains rise to between 300 and 1750 m and are extensions of the Fouta Djallon and Guinean highlands of Guinea. The western border of Côte d'Ivoire is shaped by these mountain ranges, whose highest point is Mount Nimba (1752 m). The plateaus of south and southwest Mali attain heights approaching 700 m (e.g., Mount Mina, Mandingue Plateau). Hills (150-250 m above surrounding topography) rise in southeast and southwest Burkina Faso (e.g., Banfora Escarpment), as well as in southeast and southwest Côte d'Ivoire, where two spurs of hills exist along with the conspicuous 250 km long Baoulé range of hills oriented from east to west in the central part of the country. Very old pre-Cambrian rocks with a complex basement formation of severely eroded rocks (including schists, phyllites, and granites) dominate the geology. The bedrock appears at the surface in riverbeds and along steep hillsides, but elsewhere is covered with a lateritic (i.e., removal of top/rich soil) soil layer of varying depth.

1.3.2 Soils

Several soil types cover the study area (Fig. 1.3, bottom) and each responds differently to crop cultivation. Many soils tend to lose their fertility in reaction to intensive cultivation and excessive leaching, thus turning into infertile lateritic soils (red, leached, iron-bearing). Central West African soils have traditionally been classified according to a French comprehensive system, which is based on the influence of rainfall on soil formation processes (MAB, 1982). There is also a recent classification based on the soil taxonomy system originally developed by the United States Department of Agriculture, which is more strongly based on vegetation and retains three categories of soils, namely ultisols, alfisols, and aridisols (Dingman, 1994; Aryeetey-Attoh, 1997).

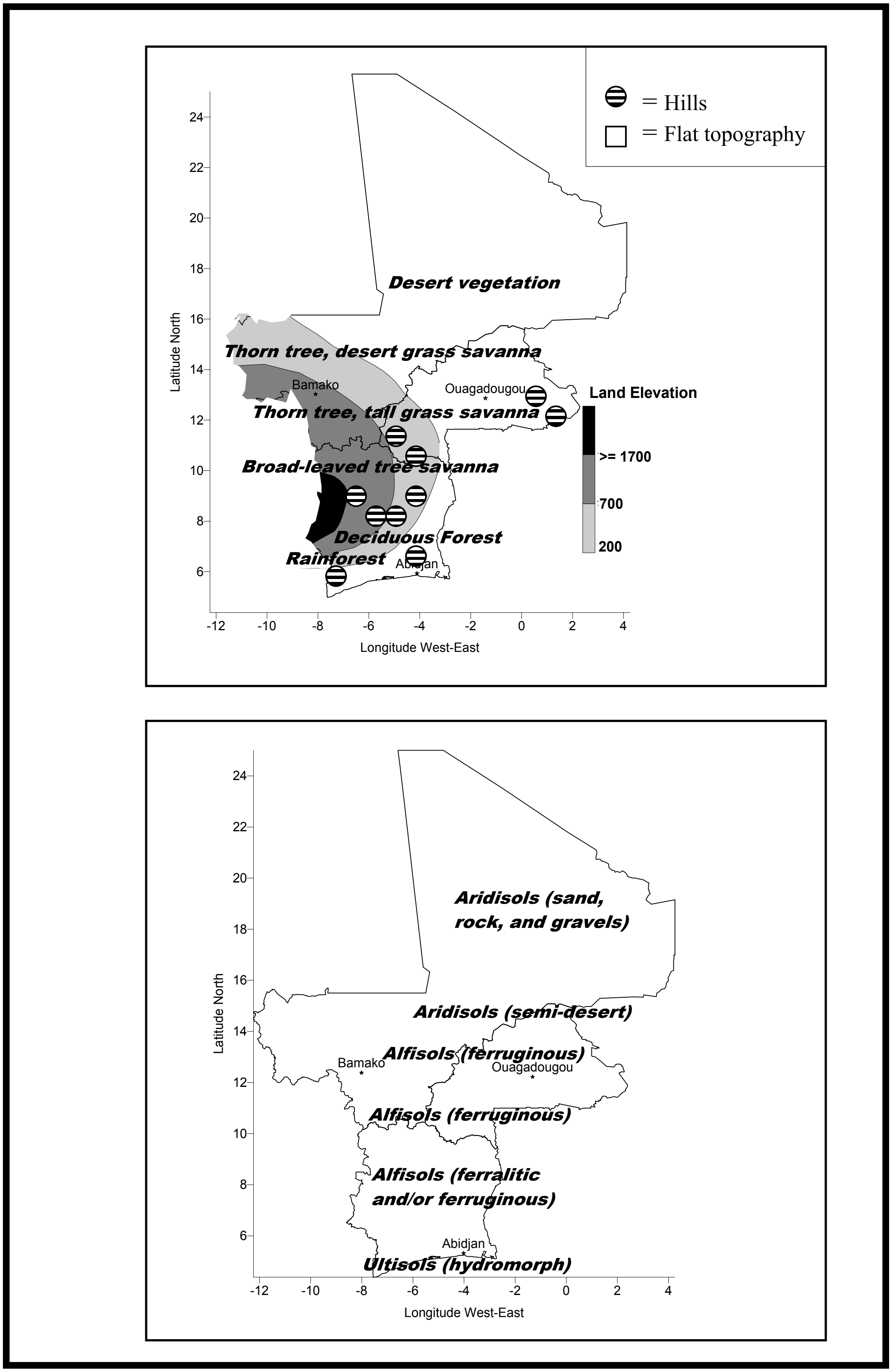


Figure 1.3: General topography of study area: elevation and basic vegetation types (top) and major soils (bottom). Developed for this study (see text for sources).

As shown in Figure 1.3 (bottom), the combination of these two classification systems accommodates the influence of climate (e.g., temperature, rainfall) and vegetation, as well as the distribution of crop types, in the study area. In the extreme south, the hydromorph (ultisols) soils (around rivers and streams), the poorly drained soils, and the swampy soils all maintain their fertility and rich reddish/yellowish silico-argillaceous character in their surface horizons due to their greater iron content. These ultisols support better, naturally irrigated cultivations, which are not widespread in the region and "are suitable for rubber, coffee, and banana plantations" (Aryeetey-Attoh, 1997, p. 31). They are relatively less weathered and occur in humid and subtropical or tropical climatic areas under forest and woodland conditions, where soil-forming processes are intense, as in southwest Côte d'Ivoire.

The second group of soil types predominates in central and northern Côte d'Ivoire and south-to-central Burkina Faso-Mali. They range from highly (ferruginous or extreme alfisols) to moderately (ferrallitic or moderate alfisols) leached and are classified as relatively productive lands because they are naturally fertile (Fig. 1.3, bottom). These soils develop in humid to subhumid and semiarid areas under hardwood forests, grasslands, and savannas. In central Côte d'Ivoire, crust-like shields alternate with rich black silico-argillaceous soils. The alfisols (both ferruginous and ferrallitic) form mainly where the precipitation averages 500-1300 mm yr^{-1} and thus also cover northern Côte d'Ivoire and south-to-central Burkina Faso-Mali. The tropical ferruginous (extreme alfisols) soils occur in northeast Côte d'Ivoire and part of south Burkina Faso, with a transition between ferrisol and ferruginous soils in northwest Côte d'Ivoire and part of south Mali. Although these soils are usually moist, they are extensively weathered because they "are widely cultivated, supporting a range of crops…including cocoa, coffee, rubber, bananas, maize, cassava, sorghum, millet, and oil palm.…In the drier belts of alfisols, cotton, groundnuts, [and] tobacco are farmed. Pastoralism is also a major activity in the drier sections" (Aryeetey-Attoh, 1997, p. 31). The mountain ferrallitic (moderate alfisols) types appear in west Côte d'Ivoire and south Mali.

Finally the aridisols, composed of sand, rock, and gravel, occur in semi-desert and desert regions such as extreme north Burkina Faso and central to north Mali where vegetation hardly covers the bare soil (Fig. 1.3, bottom). They contain low biomass densities and organic matter content. These aridisols also are subject to eolian erosion and are less favorable to farming practices without the use of irrigation technologies. Nevertheless, "in other parts of the world, such soils have been widely utilized for agricultural purposes, with new technologies in irrigation...sorghum, and millet are restricted…and nomadic grazing is quite extensive. Irrigation opportunities and… drought-resistant crops can make the aridisols productive" (Aryeetey-Attoh, 1997, p. 31). However, given that there is little water available for irrigation and no access to such technology in most parts of Central West Africa, these aridisols often remain infertile.

Overall, Central West African soils are generally considered "vulnerable to a range of surface conditions and human activities" (Aryeetey-Attoh, 1997, p. 32). Indeed, the described soils have been overused for agricultural purposes, which in turn have affected the soils resulting in the well-known phenomenon of land degradation and gully development (Späth and Francis, 1994). Crop production is greatly influenced by soil properties such as texture, slope, and soil depth, which determine the suitability of a soil for agricultural purposes. Therefore, soil knowledge can assist farmers in adapting different cropping systems to different soils for maximum production. In other words, the integration of soil resources with agroclimatic data is a base for providing information and developing recommendations related to crop adaptation and production.

1.3.3 Vegetation

The vegetation of the study region changes from tropical forest in the south to savanna grassland and shrubland (including steppes) in central areas, to semi-desert and desert land cover in the north (Aubréville, 1949; Aryeetey-Attoh, 1997). The ecological zones are classified into three major types (Fig. 1.3, top):

(1) The forest occurs south of 7º30' North, extending from the Gulf of Guinea coast to some 200-400 km inland (the coast has a southwest-northeast orientation). There is a distinction between the dense rainforest (1700-2200 mm annual average rainfall) found in areas where there is almost no annual dry season and the more sparse deciduous forest (1200-1700 mm rain per year). Both forests lie in an environment where the monthly mean temperature is constantly high (25º-26ºC) year-round and the average relative humidity levels are above 60 percent (Guillaumet and Adjanohoun, 1971). This forest landscape covers one-third of southern Côte d'Ivoire.

(2) The savanna area extends from 7º30' to 14º30' North (central-to-north Côte d'Ivoire and south-to-central Burkina Faso-Mali). Savanna is a mixture of cleared forests, shrubs, and grasses, which is deliberately burned annually for both its preservation/regeneration and agricultural purposes. It is the intermediate landscape between the semi-desert scrub and tropical forest, and typically experiences an annual dry

season of three to eight months, but receives heavy rains during the rest of the year. The yearly average rainfall ranges from 500 to 1200 mm, the relative humidity drops to less than 60 percent, and the air temperature reaches an average of 30ºC (MAB, 1982).

(3) The third vegetation type (shrubs, steppes, semi-desert, desert, etc.) consists of sparse trees, grasses, and bare soils, and is less water demanding (200-500 mm yr^{-1}). It mostly lies across north Burkina Faso as well as central and north Mali where, in the extreme north, even true desert vegetation (e.g., cactus) can occur. Indeed, with nine to twelve rain-free months (e.g., extreme north Mali), this landscape gives way to pure desert (i.e., bare soils) where rainfall averages less than 200 mm yr^{-1}.

1.3.4 Hydrologic Systems

Nine major river systems (Fig. 1.4) flow generally southward to the Gulf of Guinea, forming parallel drainage basins, deeply incising the flat and uniform topography of the study area (e.g., Banque Mondiale et al., 1992; Direction de l'Eau, 1995; Ministère de l'Environnement et de l'Eau, 1998; http://www.africaguide.com/, 1999).

The drainage system in Mali comprises two important permanent rivers (Fig. 1.4) that flow northward/westward and eastward across most of its south and central regions:

- The Senegal rises in the northern slope of the Fouta Djallon highlands (Guinea) and drains a total watershed area of 525,800 km^2; and
- The Niger, the longest river (1,700 km) in Mali, also emanates in the western slope of the Fouta Djallon and drains the largest (221,000 km^2) watershed.

These two major rivers in Mali have several tributaries (e.g., Bafing, Faleme, Baoulé, Sankarani, Bani, and Bagoé) that have poor navigation potential.

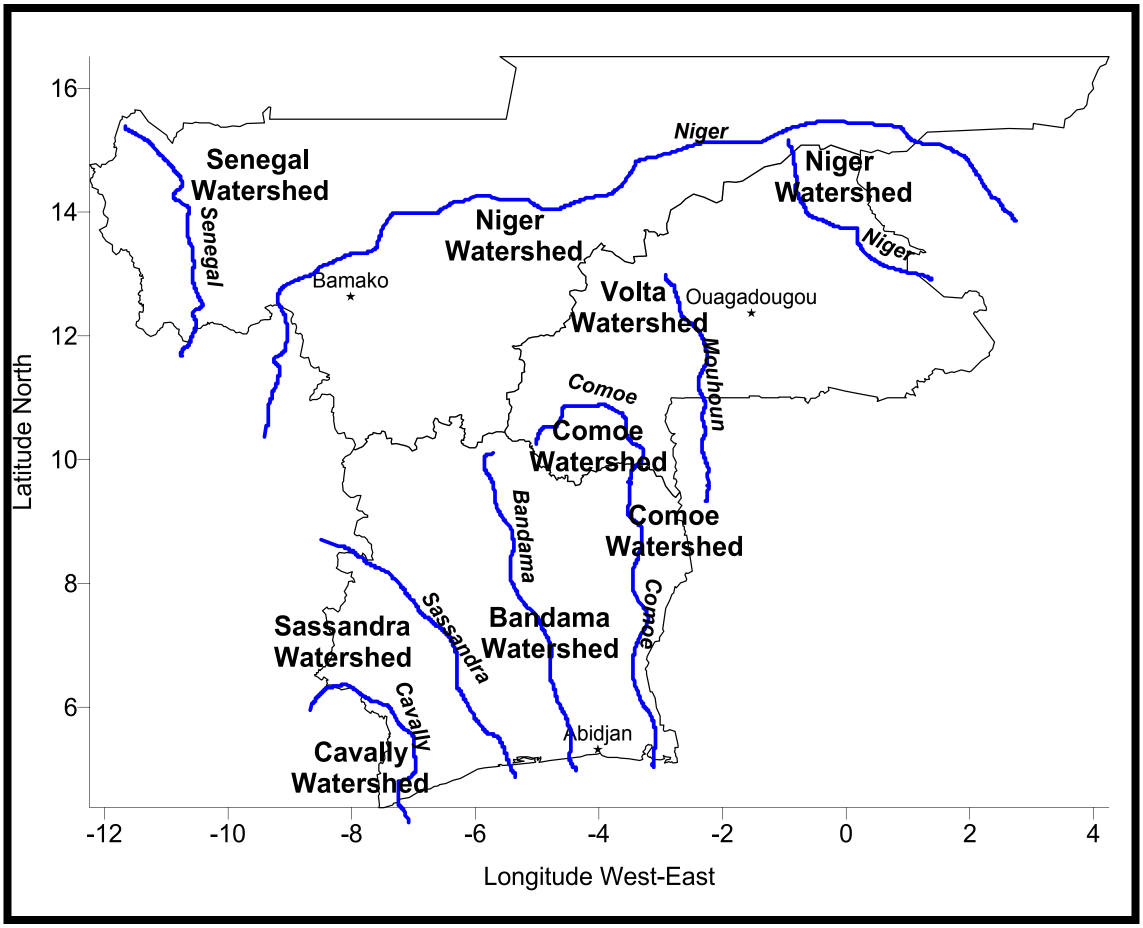


Figure 1. 4: Rivers and watershed areas in Central West Africa. Developed for this study (see text for sources).

Permanent (Mouhoun and Comoé) and temporal rivers as well as streams form the three main Burkina Faso watershed areas (Fig. 1.4):

- The Mouhoun (Black Volta), Nakambé (White Volta), Nazinon (Red Volta), and Pendjari constitute the Volta basin, which is the largest watershed and covers 178,000 km²;
- The Comoé and its substreams (Léraba and Yanon) form the Comoé watershed area of 17,000 km²; and
- Several Niger tributaries (Béli, Gorouol, Sirba, Gouroubi, Diamangou, and Tapoa) drain 79,000 km² and form part of the Niger watershed.

These Burkina Faso rivers and streams flow southward and alternately are dry (October-June) or flooded (July-September). None are navigable.

Côte d'Ivoire contains four major rivers (Fig. 1.4) that run roughly parallel from north-northwest to south-southeast throughout the country and dominate the drainage system:

- The Cavally (forming most of the Liberian frontier) begins in Guinea at an altitude of around 600 m and has 15,000 km^2 of watershed area;
- The Sassandra also rises in Guinea (Beyla region) and its watershed covers a 75,000-km^2 area;
- The Bandama lies entirely in Côte d'Ivoire and has 97,500 km^2 of watershed area; and
- The Comoé originates in Burkina Faso (Banfora region) and covers a drainage area of 78,000 km^2.

Côte d'Ivoire also possesses several slow-flowing interior and coastal streams (e.g., Néro, San Pedro, Boubo, Go, Agneby, and Bia), of which the Bia has the greatest flow rate. These rivers are broken by numerous falls and rapids, which make them difficult to navigate and low in value for transportation. They are sluggish in the dry season and subject to torrential flooding in the rainy season.

Even though all of the Central West African rivers have limited navigability due to the frequency of falls, rapids, and large annual variations in water levels, they have great potential for hydroelectric power generation and human use, especially natural irrigation. The seasonal irregularity of water resources is more considerable in the savanna area (northern Côte d'Ivoire, most of Burkina Faso, and southern Mali). Indeed, the long dry season coupled with low humidity and high solar radiation cause high evaporation/ evapotranspiration rates, which reduce savanna rivers to small pools or beds of moist clay soil prior to the rainy season onset. Therefore, the availability and management of water resources are of great concern for most of the study area. In southern Côte d'Ivoire on the other hand, the streams have a better supply of rain and soils (mostly hydromorph -- ultisols) have a relatively high retention capacity.

1.4 Economy: Dependence on Agriculture

The environmental conditions (rainfall, topography, soils, vegetation, and water resources) treated in previous sections constitute the basis for the agriculture and thus economy of the study area. Mali, Burkina Faso, and Côte d'Ivoire are classified as agrarian countries because they are quite agriculturally oriented and rely to a great extent on farming activities for economic development and societal progress. Agriculture is the main activity and around 80 percent of the study area's labor forces are engaged in forestry, crop cultivation (both staple and cash crops in labor-intensive farming), and raising livestock or animal husbandry (Ministère de l'Environnement, 1997). Cropland occupies a relatively large portion of each country -- 26% in Mali, 33% in Burkina Faso, and 51% in Côte d'Ivoire (http://www.fao.org/, 2000). In 2001, the Gross Domestic Product (GDP) of the three countries varied from US $9.2 billion in Mali to US $12.8 billion in Burkina Faso and US $25.5 billion in Côte d'Ivoire (http://www.cia.gov, 2002), and the agricultural contribution to each country's GDP ranged from 24% to 61% during 1977-2002, as summarized in Table 1.2.

Table 1.2: Contribution (percent) of agriculture to the Gross Domestic Product (GDP) of Central West Africa (developed from http://www.africaguide.com/, 1999; http://www.fao.org/, 2000; http://www.cia.gov, 2002).

Country	1977	1987	1997	1998	2000	2002
Mali	61.3	45.2	44.0	44.9	51.0	45.0
Burkina Faso	34.3	31.5	31.8	32.0	34.8	31.0
Côte d'Ivoire	24.3	29.2	27.3	25.5	42.8	28.0

Following independence in 1960, Côte d'Ivoire achieved rapid economic growth mainly based on exports of timber, coffee beans, cocoa beans, palm oil, and cotton. Crops grown for domestic consumption include rice, maize, yams, and banana plantain, which essentially limits food imports to animal proteins and cereals (e.g., wheat, more rice). Because of its more favorable natural resources (e.g., abundant rainfall, forests), Côte d'Ivoire has developed better agricultural (including forest) productivity and a stronger economy than Burkina Faso and Mali (Table 1.3). The agricultural-based prosperity of this country was remarkable from the 1960s to the 1980s. For example, in 1975 Côte d'Ivoire gained approximately US $530 million from the export of market crops, which was 63 percent of all export earnings (CNRS/IGN, 1978). In the early 1980s it was the world's largest producer and exporter of cocoa beans, third ranked producer of palm oil, and fourth largest coffee producer.

Despite the Sahelian drought since 1968 (see Chapter 2), and particularly the resulting 1983-84 crop failures and bush fires in Côte d'Ivoire, as well as the international cash crop (coffee and cocoa) price crisis since 1986, the Ivorian agricultural sector has continued to produce remarkable results. Although it weakened during the late 1980s and early 1990s because of these natural disasters and the cash crop price collapse as well as the increased competition from Southeast Asia, the Ivorian economy began a comeback in 1994 due to improved prices for cocoa and coffee as well as growth in non-

Table 1.3: Development indicators of Central West Africa. Years between parentheses are the most recent years in each category (developed from Banque Mondiale, 1992; World Bank, 1995; http://www.worldbank.org/, 2002; http://www.cia.gov, 2002).

DEVELOPMENT CRITERIA (Basic Social and Economic Indicator)		MALI	BURKINA FASO	CÔTE D'IVOIRE
SOCIAL INDICATOR	Life expectancy at birth (years in 2002)	47	46	45
	Literacy (percent in 2002)	38	36	49
	Agricultural labor force (percent in 2000)	80	90	68
SECTORIAL COMPOSITION OF ECONOMIC ACTIVITY	Agriculture, forestry, fishing (percent in 2000)	45	31	28
	Industry, manufacturing (percent in 2000)	17	28	29
	Services, commerce (percent in 2000)	38	41	43
ECONOMIC OVERVIEW	Gross Domestic Product (GDP -- billion US $ in 2001)	9.2	12.8	25.5
	GDP growth (percent in 2001)	-1.2	+4.7	-1.0
	GDP per capita (US $ in 2001)	840	1,040	1,550
	Values of exports (US $ in 2001)	575 million	265 million	3.6 billion
	Export commodities	Cotton, gold, livestock	Cotton, animal products, gold	Cocoa, palm oil, coffee, cotton, fish, timber, pineapples,
	Values of imports (US $ in 2001)	600 million	580 million	2.4 billion
	Import commodities	Machinery, construction materials, food products, fuels, textiles	Capital goods, food products, petroleum	Food products, consumer goods, fuels, raw materials, equipment
LAND USE	Water area (km^2)	20,000	400	4,460
	Land area (km^2)	1.22 million	273,800	318,000
	Arable land (percent)	4	13	9
	Permanent crops (percent)	0	0	14
	Irrigated land (km^2)	1,380	250	730
	Other (percent in 1998)	96	87	77
PAST AND PROJECTED POPULATION GROWTH	Population (millions in 1993, 2000, 2002, and 2025 [projected])	10.0, 13.0, 11.3, 25.0	10.0, 12.0, 12.6, 22.0	13.0, 17.0, 16.8, 37.0
	Average annual growth (percent in 1970-1980, 1980-1993, 1993-2000, and 2002)	2.2, 3.0, 3.1, 3.0	2.3, 2.6, 2.6, 2.6	4.0, 3.7, 3.3, 2.5
	Crude birth rate (per 1,000 population in 1970, 1993, and 2002)	51, 50, 48	48, 46, 44	51, 49, 40
	Crude death rate (per 1,000 population in 1970, 1993, and 2002)	26, 19, 18	25, 18, 17	20, 15, 17
NATURAL RESOURCE	Forest area (1,000 km^2 in 1980 and 1990)	132, 121	47, 44	121, 109
	Annual deforestation rate (1000 km^2 in 1981-1990)	1.1	0.3	1.2
	Protected areas (1000 km^2 and number)	40.1, 11.0	26.6, 12.0	19.9, 12.0
	Freshwater resources for domestic, agricultural, and industrial uses (m^3 per capita in 1970-1992)	1.4, 3.0, 159.0	0.2, 6.0, 14.0	0.7, 15.0, 52.0

traditional primary exports such as pineapples and rubber. In spite of this economic rebound, Côte d'Ivoire has not yet fully regained the strong Central West African regional economic role that it played earlier. However, it still ranks among the most prosperous Subsaharan African countries with relatively good infrastructure and a high GDP, which reached US $1,550 per capita in 2001 (http://www.cia.gov, 2002). Unfortunately, the Ivorian economy may experience another decline because of the ongoing civil war that started in September 2002.

The agricultural production of Mali and Burkina Faso has not attained the same level of prosperity as that of Côte d'Ivoire. However, agriculture still provides the economic basis of these countries (Table 1.3), which tend to be among the poorest and least developed in the world and are heavily dependent on foreign aid. Their GDPs per capita in 2001 were US $840 (Mali) and US $1,040 (Burkina Faso) (http://www.cia.gov, 2002). Mali and Burkina Faso have not extensively developed export crops, but instead have focused on staple crops to attain self-sufficient food security goals. This situation results from a natural resource scarcity and conservative governmental priorities that emphasize protection against famine. Aridity and erosion seriously hamper agricultural development in Mali and Burkina Faso; most farming is concentrated in the more moist southern and southwestern portions of both countries. Cultivation in these savanna regions mainly consists of rain-fed subsistence farming (including maize, millet, rice, and sorghum) and is complemented by livestock raising (AGHRYMET, 1997). The main agricultural exports, which are not nearly as extensive as those exported from Côte d'Ivoire, are cotton, peanuts, soybeans, and sugar cane, which represent more than 50% of the export incomes, but also are vulnerable to world price fluctuations (see Table 1.3).

Furthermore, difficult economic conditions, made worse by prolonged and sometimes severe drought (Chapter 2) as well as decreased land fertility, have provoked considerable migration from rural to urban areas for seasonal employment within Mali and Burkina Faso and to neighboring countries such as Côte d'Ivoire and Ghana. Ultimately this situation has further reduced crop productivity in both Mali and Burkina Faso.

The World Bank and Central Intelligence Agency statistics presented in Table 1.3 summarize some of the socioeconomic and natural resource indicators for the study area. These economic overview statistics attest to the high importance of agriculture compared to the other economic sectors such as industry and administrative services. Table 1.3 indicates that these countries have few prospects (e.g., industrialization, world trade involvement) for wider economic progress in the near future. Agriculture will continue to control the primary labor force for all countries. Thus, any major disruption in the annual agricultural cycle is likely to be very detrimental to the economy. In addition, the 2000 Gross National Product (GNP) per capita in the study area rates as low-income economy. This classification has always been the case for Mali (US $240) and Burkina Faso (US $230), but not so for Côte d'Ivoire (US $660), which was among the lower-middle-income economic group in previous reports (Banque Mondiale, 1992). Côte d'Ivoire's change is due to the redefinition of the GNP criteria level that increased in 1995.

1.5 Justification and Motivation

The United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro (Brazil) in June 1992 drew attention to environmental change concerns that included biodiversity, tropical deforestation, climate change, ozone layer protection, and particularly emphasized the situation in developing countries. Proceeding with this conference in mind and through participation in an interdisciplinary project funded by the MacArthur Foundation, the need for this current study became evident. The MacArthur Foundation-sponsored multidisciplinary research, which was piloted by the Center for African Studies at the University of Illinois at Urbana-Champaign with the participation of collaborative institutions and universities in Burkina Faso, Côte d'Ivoire, Ethiopia, and Mozambique, focused on African Environments, Experiences, and Controls. Involvement in five MacArthur-funded annual workshops (1994 to 1998) organized by an interdisciplinary team of geographers, historians, economists, climatologists/meteorologists, and crop scientists, gave rise to this Dissertation. Indeed, through gaining more practice doing interdisciplinary research, the great relevance of verifying whether Central West African climate, land cover, and socioeconomic activities are interrelated emerged.

The choice of this study area provides an opportunity to assess the impacts of rainfall as it decreases and varies northward from the Gulf of Guinea to the Soudan and Sahel zones. In addition, given the geographical location, size, and orientation of Central West Africa, the study of this area provides representative information for most of West Africa concerning the relationships among rainfall-crop-socioeconomic conditions. Regardless of the economic classification of Mali, Burkina Faso, and Côte d'Ivoire, it is important to study the induced socioeconomic effects from the impacts of rainfall variability on agricultural change. With agriculture being such a prime economic parameter, the societies and economies of these countries could be severely disrupted by significant variability in rainfall, which is of considerable importance for crop production.

Thus, this Dissertation seeks to develop and enhance the degree of understanding and assessment of rainfall variability and agricultural change relationships in Central West Africa during recent decades. Further, the implications for socioeconomic development are explored. Policy recommendations are also drawn to integrate rainfall variability and crop yield adjustment in the study area.

In Chapter 2, this Dissertation reviews the results of earlier relevant studies for these Subsaharan Central West African countries as they relate to rainfall variability and agricultural productivity. The findings of these previous studies provide the focus of this research. Secondly, the Dissertation has gathered the most pertinent information, composed of daily rainfall totals as well as annual selected crop acreage, production, and yield records. This data compilation, described in Chapter 3, itself is a unique contribution to knowledge of Mali, Burkina Faso, and Côte d'Ivoire rainfall variability and crop yields. The use of each data set also is stated in Chapter 3. Then in Chapter 4, the study performs a range of analyses to evaluate rainfall and agriculture in Central West Africa as well as establish the relationships between rainfall variability and crop yields with a view toward providing comprehensive documentation on which to base socioeconomic development and policy suggestions. These analyses address questions such as:

(1) How and to what extent are rainfall variability and agricultural change (i.e., crop acreage, production, and yields) related?

(2) What are the implications of these rainfall/agriculture relationships for socioeconomic development, and which of governmental policies (from colonial to present) are directed toward establishing sustainable agriculture?

(3) Given that rainfall has very high space-time variability and most of the socioeconomic activities are extremely vulnerable to intraseasonal and interannual rainfall fluctuations, is there any clear strategy of integrated rainfall variability and agricultural changes present or possible in these countries?

Lastly, Chapter 5 of this Dissertation examines agroclimatologic histories as well as colonial-to-recent decade environmental policies in Mali, Burkina Faso, and Côte d'Ivoire in order to assess the history and relative importance of each country's governmental decision-making processes in agricultural productivity. Conclusions concerning the relationships between natural resources and environmental policies in this study provide a basis for making recommendations for the future of Central West Africa in Chapter 6.

CHAPTER 2

REVIEW OF RELATED CLIMATE, AGRICULTURAL, AND SOCIOECONOMIC LITERATURE

This chapter reviews the fairly large, but separate, literatures on the state of rainfall variability, agricultural changes, environmental policies, and socioeconomic development in West Africa. Chapter 2 shows that a variety of methods and models have been employed to make initial assessments of the patterns and causes of rainfall variations. Further, the research into the impacts of rainfall variability on agriculture and socioeconomic development reveals that researchers (e.g., geographers, climatologists, economists, crop scientists) are in general agreement that the Earth's systems (e.g., climate, land cover, socioeconomic activities) are interrelated. However, for the particular cases of Mali, Burkina Faso, and Côte d'Ivoire, the reviewed literature shows that most of the authors have focused on rainfall and its variability, and only to a lesser extent on crop productivity and agricultural changes as well as on the impacts of rainfall variability/crop yield relationships on Central West African societies and economies.

Further, this earlier research revealed that the importance and applications of environmental policies have so far been insufficiently investigated in the study region. Nevertheless, the reviewed literature brought useful information (e.g., variability, changes) on the state of rainfall and the agricultural research already performed and reinforced the premise that such study is needed for Central West Africa. In other words, the absence of extensive work on the study area rainfall variability/crop output relationships and their implications for socioeconomic development provided an opportunity for this Dissertation to make a key contribution to this topic.

2.1 Rainfall in Subsaharan West Africa

West African climate studies have centered essentially on rainfall. This atmospheric variable is important to daily-to-seasonal activities. Therefore, this chapter begins by reviewing the mechanisms that produce rain in Central West Africa, documents the rainfall trends there since 1930, and summarizes the explanations offered by researchers for the rainfall variability.

2.1.1 Rainfall Mechanisms

The atmospheric circulation mechanisms that control West African rainfall are the two quasi-stationary subtropical anticyclones centered over the Azores (30º N) and the Saint Helena (30º S) (Fig. 2.1, top). A zone of relatively low pressure, the near-equatorial trough, separates these two anticyclones. Associated with this tropical Atlantic pressure field are the northeast and southeast surface trade winds, flowing westward and equatorward from the eastern flanks of the subtropical anticyclones of each hemisphere, respectively. The trades converge in the near-equatorial trough over the tropical Atlantic and West Africa. The tropical continental air mass over West Africa, known as the Harmattan, is a northeasterly wind from the Sahara desert that varies seasonally from being very dry/warm to extremely hot (Fig. 2.1, top). This air mass can cover the whole of the study area to the Gulf of Guinea coast for at least two months between December and February, causing extensive damage to crops through desiccation. The second surface wind is the tropical maritime air mass, which is also warm but much more humid because it originates from over the tropical Atlantic Ocean (Fig. 2.1, top). Emanating from the southeasterly trades over the south Atlantic, this airflow recurves southwesterly after crossing the equator, due to the change in the Coriolis effect and the west-east pressure

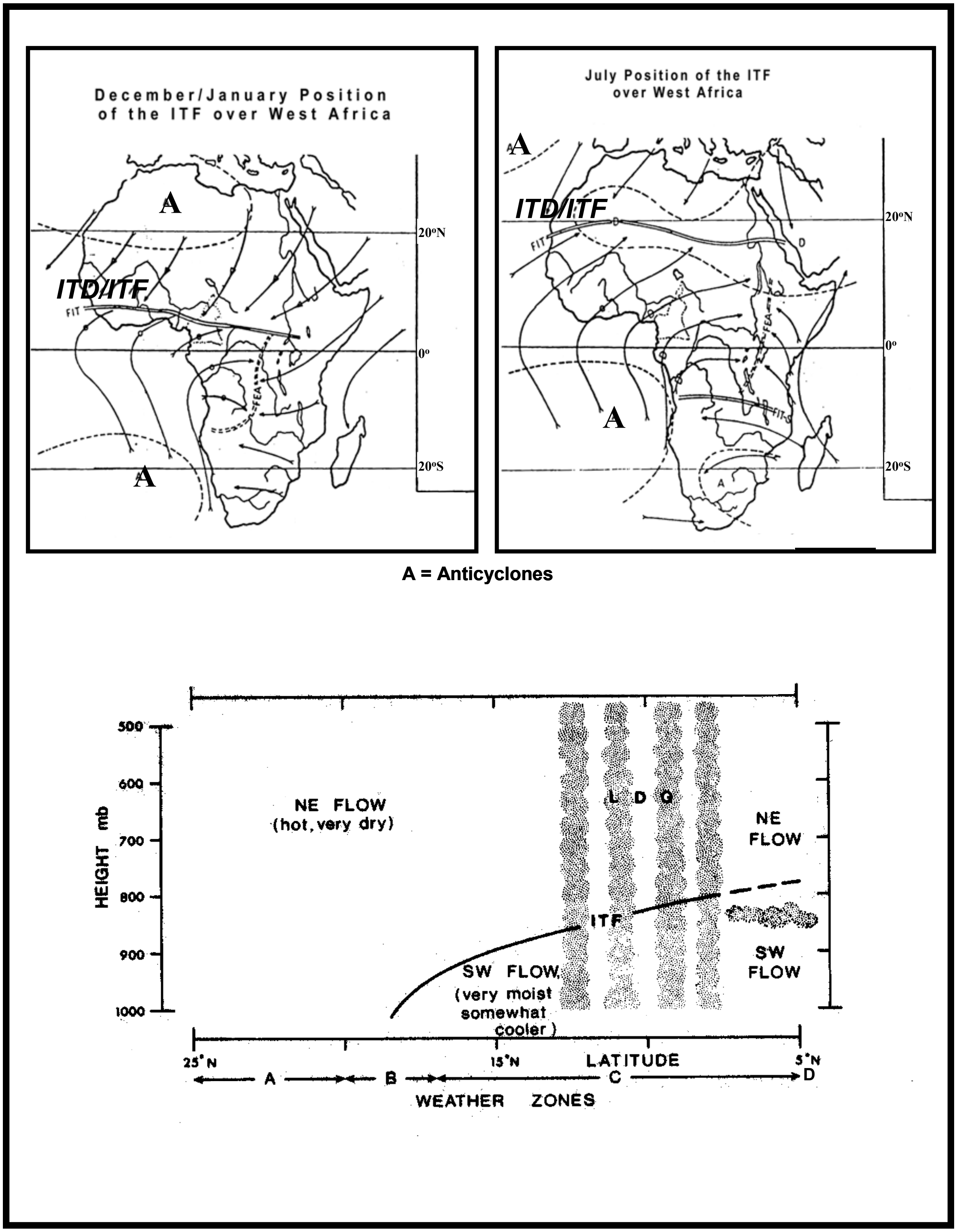


Figure 2.1: Average southernmost and northernmost positions of the Intertropical Discontinuity (ITD) or Intertropical Front (ITF) over West Africa (top) and associated weather zones (bottom): A, B, C, and D, referred to in the text. LDG denotes Ligne de Grains (adapted from Lamb, 1980, p. 13; Ballo, 1996, p. 6).

gradient into West Africa at around 15º N. This humid surface air flows to around 20º-25º N in July-September, covering most of Central West Africa with a seasonal- and monsoonal-type progression. It is therefore named the monsoon flow and produces monsoon-type rainfall as far north as the northern Sahel (around 18º N).

The mixing of the two air masses is limited because the monsoon current penetrates under the dry Harmattan flow in a wedge-like manner in the lower troposphere (Fig. 2.1). They meet in a pronounced humidity/temperature discontinuity zone called the Intertropical Discontinuity (ITD), or Intertropical Front (ITF), which extends across West Africa (including the study region) from west to east. The ITD moves seasonally due to the relative intensity of the Saharan thermal depression (heat low) and the Azores/Saint Helena anticyclones, which in turn follow the zenithal position of the sun in the tropics. The ITD reaches its extreme southern (5º N) and northern (20º-25º N) positions in December-January and July-August, respectively. As a result of these wind patterns, four weather zones (typically denoted by A, B, C, D) span the ITD and West Africa from north to south (Fig. 2.1, bottom) and determine the seasonal weather characteristics of particular locations in the study area in the following manner (e.g., Landsberg, 1972; Lamb, 1980; Motha et al. 1980; Hastenrath, 1991; Ballo, 1996):

- **Zone A** is located north of the ITD (Fig. 2.1, bottom). It is the zone under the tropical continental air mass (Harmattan) and corresponds to the dry season, having no rain or clouds and reduced visibility caused by aeolian dust. Strong Harmattan conditions prevail throughout the study region from late December-January to early February.

- **Zone B** (200-300 km from north to south) is the northernmost area of the monsoon flow, which is found both immediately north and south of the ITD; zone B straddles ITD (Fig. 2.1, bottom). It is a zone of fair weather and scarce cloudiness because the shallowness of the monsoon flow suppresses convection. Zone B also corresponds to a dry season, though with no Harmattan conditions. Except for isolated showers and thunderstorms, rain is absent in this zone. However, high nighttime temperatures and humidities are typical here, unlike the clear, cooler nights of zone A. Zone B covers the extreme southern part of the study area in February-March as well as the extreme northern part in July-August.

- **Zone C** (700-1000 km further to the south) is located south of zone B (Fig. 2.1, bottom). It contains a thicker layer of humid air and is an area of thunderstorms and heavy rains. A region experiences its wet season when this zone encompasses it. Zone C is subdivided into sub-zone C1 (northern part) and sub-zone C2 (southern part). C1 experiences frequent thunderstorms and showers due to strong lower tropospheric convergence and formation of cumulonimbus clouds. C1 also is a sub-zone of westward propagating disturbance lines known as "Lignes de Grains" (LDGs). Sub-zone C2 exhibits high humidity and moderate lower tropospheric convergence, with more continuous rainfall (called monsoon rains) associated with stratiform clouds. Zone C occupies the study region from late March-April to June and October-November for Côte d'Ivoire and from July to August-September for southern Mali and Burkina Faso.

- **Zone D** (1000-1300 km to the south of the surface discontinuity) is a zone of lower tropospheric divergence with stratiform clouds and clear skies, lower humidity, and rare rains or storms (Fig. 2.1, bottom). This zone produces a short dry season at the height of the summer in southern Côte d'Ivoire, where it temporarily interrupts the wet season from mid-July to mid-September. Thus, zone D is associated with the "little dry season" that occurs along the Atlantic coast.

The atmospheric circulation described above shows that the meridional advance and retreat of the ITD over Central West Africa brings rain; however, most occurs 700-1000 km to the south of this surface confluence. As a result of this atmospheric behavior, especially the south-north decrease gradient of monsoon layer thickness and vertically integrated water vapor, the study area rainfall displays a strong northward gradient in seasonal and annual mean rainfall (e.g., Glantz, 1977; CNRS/IGN, 1978; Lamb, 1978a; Ward, 1994). Furthermore, this south-north rainfall gradient is the product of a mono-modal annual rainfall cycle in the north and a bimodal one in the south.

As mentioned previously, the disturbance lines (squall lines, lines of thunderstorms, LDGs) are housed in the ITD weather sub-zone C1, and these mesoscale convective rain-producing mechanisms are important for the northern half of the study area (e.g., Lamb, 1982; Bolton, 1984; Omotosho, 1985; Lamb et al., 1998). Structurally, the LDGs are composed of narrow bands of active cumulonimbus clouds that are aligned from north to south (300-600 km) and move westward at the speed of the mid-tropospheric easterly flow (about 12 m s^{-1}). They are self-regenerating and last for several days, bringing rain to thousands of square kilometers. Each day, initially heavy rain is usually followed by several hours of less intense rainfall. As quantified by Finch (1998, p. 33), "…LDGs monotonically increase in size starting in early-June, and reach a maximum in either late-August…or early-September…LDGs become rapidly smaller immediately after this late-summer peak." The West African Sahel receives the majority of its rainfall from June to September each year, and LDGs are the major causes. The LDGs are therefore the most important rain-producing systems in southern Mali and Burkina Faso because they contribute to the greatest proportion of the total annual rainfall. These convective systems are also associated with the moisture and strength of the monsoon current, which play major roles in their formation (Lamb, 1982).

In other words, LDGs receive their moisture from the low-level southwesterly monsoon flow, which is overlain by easterlies that include mid-tropospheric (African Easterly Jet, AEJ) and upper-tropospheric (Tropical Easterly Jet, TEJ) maxima. These jet streams or "jet-like concentrations of wind…exert a control on the surface weather and climate" (Hastenrath, 1991, p. 124) over the study area by playing significant roles in the regional moisture and energy distributions. The mid-tropospheric AEJ is centered at around 600 mb and extends from the Red Sea to the Atlantic Ocean. The upper-tropospheric TEJ is centered at around 200-150 mb and spans from Southeast Asia across the Indian Ocean and Africa to the Atlantic (Finch, 1998). Furthermore, AEJ and TEJ show strong interannual variability. Finch (1998, pp. 12-20) assessed that the AEJ is weaker in abundant Sahel rainy seasons than in deficient rainy seasons, while the TEJ is generally stronger in the very wet seasons than in the drought ones. These strong and unstable currents of air undergo a complex annual cycle, which is well-defined from April to November for the AEJ and from late June to early September for the TEJ

(Hastenrath, 1991; Finch, 1998). The increase of easterly wind speed from the lower troposphere upward reflects the juxtaposition of warmer lower- and mid-tropospheric air over the Sahara desert to the north and cooler maritime air to the south.

Besides the ITCZ, disturbance lines, and jet streams, there are other regional (localized) rain-producing mechanisms that bring or enhance rain in parts of West Africa. For instance, orographic phenomena contribute to the rising air and development of clouds over the highlands of the border between Côte d'Ivoire and Guinea (CNRS/IGN, 1978). As a result, the windward slopes of the mountain ranges in part of the study region clearly enhance rainfall amounts, intensity, and frequency due to the orographic effect (see Chapter 1, Figs. 1.2 and 1.3, top). The tropical forests, which are mostly confined to southern Côte d'Ivoire, moderate/regulate both temperature and rainfall and may favor the occurrence of rain as well, though probably forest effects are much smaller than orographic effects (see Chapter 1, Fig. 1.3, top). In fact, forests make energy for themselves with the help of the sun's energy, and through this process of photosynthesis, water is absorbed back into the atmosphere (http://www.bsponline.org/, 2001). This way, forests produce rainfall and ensure their own water supply. Therefore, removing forests results in less rain and greater drier conditions, and eventually leads to drought. Consequently, authors such as Aubréville (1949) and Otterman et al. (1984) have estimated that regional-scale deforestation may result in a reduction in rainfall of 40-50%, down to a level comparable to that of many of the most productive savanna regions that typically have robust agrarian and livestock economies and higher human populations (e.g., southern Mali, south and central Burkina Faso, as well as central and north Côte d'Ivoire). Even though the interrelationships between forests and rainfall is an issue of some controversy that has not yet been completely investigated, the consequences of deforestation for the rest of the hydrological cycle, on the other hand, are well-known (e.g., Charney, 1975; Otterman et al., 1984; Hastenrath, 1991; http://www.bsponline.org/, 2001); Section 2.1.2.3 below addresses this latter issue.

As the immediate mechanisms (i.e., ITCZ, LDGs, AEJ, TEJ, mountains, and, perhaps, forests) that produce rain in Central West Africa have been well-explored, it is important to understand the larger-scale causes of rainfall variations in the study region. Indeed, West African rainfall now is recognized as highly variable on intraseasonal, interannual, and decadal time-scales with several consequences. The natural and human ecosystems are very sensitive to even small rainfall fluctuations, which more often than not lead to devastating effects on food production, water availability, and the economy. These deleterious societal results emphasize the need to understand the sources of this rainfall variability.

2.1.2 Hypotheses for Subsaharan Rainfall Variability on Intraseasonal, Interannual, and Decadal Time-Scales

Hess et al. (1995, p. 88) noted that the causes of West African climatic instability are "generally attributed to large-scale patterns of atmospheric circulation…[and] local land surface processes, such as change in albedo, evapotranspiration, surface temperatures and atmospheric dust." Based on these assumptions, patterns and hypotheses of Central West African rainfall variations are therefore described in the next four sections. The three factors that are emphasized in this review literature are: (1) changes in the ocean circulation regimes (i.e., sea surface temperature and El Niño-southern oscillation forcings); (2) land surface degradation (i.e., deforestation, decrease in access to land for rain-fed farming, and desertification); and (3) human activities (e.g., farming systems, increase in population, and urbanization).

2.1.2.1 Patterns and Trends

Investigations of rainfall patterns and trends began with studies done by African and French scientists such as Traoré (1975), Songoré (1978), Fehr (1979), Bérété (1986), Camara (1986), Kéita (1987), Sima (1987), Sissoko (1987), and Dibi (1992) for various parts of the study region. These authors gave local perspectives and provided information on Central West African rainfall during recent decades and its year-to-year distributions (wet, normal, dry periods) and variations. This focused literature has been valuable in giving precise and detailed ideas on rainfall trends and patterns in Mali, Burkina Faso, and Côte d'Ivoire. In most of these studies, rainfall stations were assigned to one of the several climatic zones (regionalized) on the basis of each station's rainfall regime characteristics (e.g., mono-modal, bimodal). Although these studies did not extend to the larger-scale causes of the study area rainfall fluctuations, their conclusions showed a remarkable degree of coherent rainfall patterns and trends that emerged as conditions became drier everywhere in Central West Africa. Moreover, the revision of these rainfall series, as well as the station regionalization method used in these papers, were useful for this Dissertation when identifying characteristic patterns or modes of rainfall variations. However, this present study goes beyond these previous methods to detect Central West African climatic regions (i.e., regionalizations) by using more objective techniques such as Principal Component Analysis (PCA) and correlation estimates. Further, this Dissertation uses several scale analyses (e.g., annual, seasonal, decadal, monthly, and daily) in order to examine the trends and patterns of rainfall in the study area.

The patterns and causes of West African rainfall variability have also been well explored worldwide over the past 25 years (e.g., Lamb, 1978a,b, 1982; Motha et al., 1980; Folland et al., 1986a; Hastenrath, 1991; Lamb and Peppler, 1991, 1992; Janicot, 1992; Servat et al., 1997; Nicholson, 1998; Ward et al., 1999). Indeed, prompted by the highly publicized severe Sahel drought that occurred in the late-1960s to mid-1970s and reappeared in the mid-1980s, numerous articles focused on West Africa's persistent rainfall anomalies. Authors such as Lamb (1978a,b, 1982, 1985), Nicholson (1979, 1982, 1998), Lamb and Peppler (1991, 1992), Servat et al. (1997), and Ward et al. (1999) presented spatial and temporal analyses of West African rainfall variability. They demonstrated that the rainfall trend of the latter twentieth century is dominated by a pronounced Sahelian (11º-18º N) rainfall decrease that began in the late 1960s and continued until the mid-1980s, followed by only a partial recovery since then (Fig. 2.2). In some years, even Côte d'Ivoire, which mostly belongs to humid Africa, was affected by this climatic disaster in ways comparable to what was observed further north in the Sahelian region (Servat et al., 1997). This widespread drought (especially, the well-known 1968-1973 and 1982-84 episodes) caused large-scale destruction of plants, animals, and human life throughout Central West Africa.

In addition, these authors showed that the causes of rainfall variability in Subsaharan West Africa are interannual variability in tropical Atlantic sea surface temperature (SST) anomaly patterns, the behavior of the tropical Pacific El Niño-southern oscillation (ENSO) phenomenon on time-scales of several years, and extratropical interhemispheric SST anomaly differences. Hastenrath (1990), Palmer et al. (1992), Ward (1992, 1994, 1998), Janicot et al. (1998), and a website devoted to climate variability and predictability (http://www.clivar.com/, 2001) have also recognized these features as important among the key climate anomaly factors responsible for the interannual-to-decadal scale variability of Central West African regional climate.

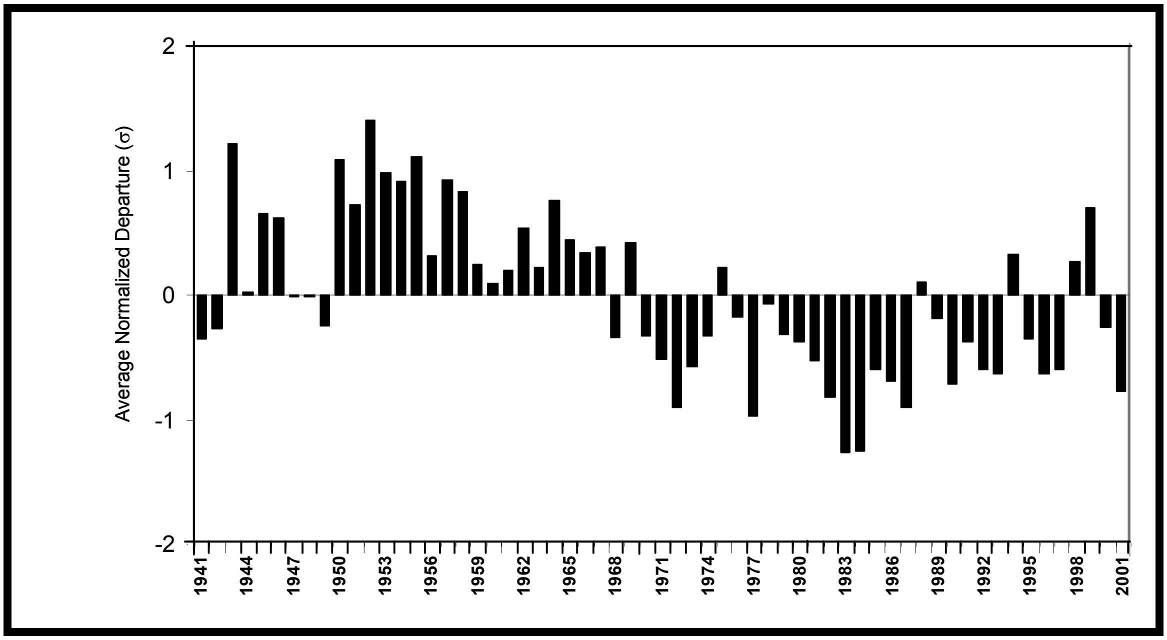


Figure 2.2: Time series for 1941-2001 yearly averaged, normalized April-October rainfall departures for 20 Sahelian West African stations between 11º-18ºN (Lamb, 1978a, 1980, 1985; Lamb and Peppler, 1991, 1992; Tarhule and Lamb, 2003).

2.1.2.2 Sea Surface Temperature and El Niño-Southern Oscillation Forcings

Janicot et al. (1998, p. 1875) noted, "the…widespread reduction or increase in rainfall occurring throughout the entire region is possibly associated with large-scale tropical circulation features." Thus, deficient rainy seasons over Subsaharan West Africa tend to be associated with three distinct SST anomaly patterns: (1) Tropical Atlantic

(North and South Atlantic); (2) El Niño-Southern Oscillation; and (3) Interhemispheric SST gradient (e.g., Lamb 1978a,b; Lamb and Peppler, 1992; Ward, 1998; http://www.cpc.ncep.noaa.gov/, 2002).

Tropical Atlantic Ocean SST anomalies affect moisture fluxes and contribute to Central West African interannual rainfall variability, as well as changes in the circulation regimes that also alter the preferred location of tropical convection and the ITCZ, which is the major rain-producing system (Palmer et al., 1992). Although several studies have focused on the correlations between rainfall and SSTs over the Sahelian regions, little attention has been given to areas south of the Sahel (Opoku-Ankomah and Cordery, 1994). However, Ward (1998, p. 3167) suggested that "tropical Atlantic SSTs are connected to out-of-phase rainfall anomalies in the Sahel and Guinea coast regions," meaning that SST anomalies are associated with dipole rainfall patterns in Central West Africa (e.g., Sahel drought versus Gulf of Guinea wetness). Also, in his comparative 1967 and 1968 case studies, Lamb (1978a) showed that rainfall was more frequent and abundant immediately south of the Gulf of Guinea coast during the 1968 Sahel drought than in the 1967 wet year. He concluded that during July-September of 1968, positive SST anomalies occurred south of 10^{o}N, while negative SST anomalies occurred immediately to the northwest.

Consequently, rainfall in the study region is characterized by a contrasting behavior (dipole feature) that is sometimes the opposite and sometimes the same based on large-scale associations with SST. Furthermore, "when sea surface temperature is warmer than normal in the northern tropical Atlantic (and/or colder than normal in the southern tropical Atlantic), the sea surface difference between the Northern and Southern Hemispheres (the SST gradient) generates a north-south surface pressure gradient in the atmosphere" (http://www.ocean.tamu.edu, 1998, n. pag.). Thus, the dipole situations of the Sahel drought versus the Gulf of Guinea coast wetness is associated with warm/cold water south/north of about 10°N in the tropical Atlantic.

Another large-scale climatic anomaly that can affect rainfall in Central West Africa is ENSO (i.e., seesawing between the south Pacific Ocean subtropical high pressure and the Indonesian equatorial low pressure). Warm (El Niño) events in the Equatorial Pacific are associated with warm, dry conditions over much of Africa (e.g., Janicot et al., 1998; Phillips et al., 1998; Barnston et al., 1999; http://www.clivar.com/, 2001). ENSO processes over the Tropical Pacific induce circulation and convective anomalies through a decline in moisture confluence and, therefore, convective rainfall over significant parts of eastern and southern portions of Africa. However, El Niño events enhance Sahelian subsidence, which further decreases Sahel rainfall in those years and diminishes rainfall in the Gulf of Guinea coast. In a few words, ENSO warm events tend to be associated with tropospheric subsidence over West Africa that contributes to drought in the region (e.g., 1972-73, 1983-84 droughts).

In addition, the rainfall variability in Central West Africa is not just related to SSTs in the Atlantic, but also strongly connected to extratropical interhemispheric SST anomaly differences in which relative changes involve changes in ocean currents in both the Atlantic and Indian Oceans (Folland et al., 1986). Thus, Ward (1998, p. 3167) noted that, "the known change in the north-south inter-hemispheric gradient of sea temperature

(SST) has accompanied climate fluctuations not just in the Sahel, but through much of the tropics, including a modest decline in July-September." Further, Wagner (1996, p. 2018) confirmed, "the pattern of SST anomalies strongly influences the latitude position of the ITCZ, whose variability is most closely related to the interhemispheric SST gradient rather than to surface temperature in either the North or South Atlantic." However, the pattern of interhemispheric SST anomalies contributes to rainfall fluctuations on the multidecadal time-scales. Therefore, the long downward trend in Central West African rainfall is attributed to the interhemispheric SST gradient.

Overall, both SST anomalies (i.e., dipole years and multidecadal fluctuations) and El Niño events (drought) are significantly correlated to rainfall throughout Central West Africa. In detail, SSTs and ENSO are associated with three rainfall anomaly scenarios in Mali, Burkina Faso, and Côte d'Ivoire (e.g., Lamb 1978a,b; Lamb and Peppler, 1992; Fontaine and Janicot, 1996; Ward 1998): (1) drought limited to the Sahel (i.e., dipole years) is associated with tropical Atlantic SST; (2) drought all over the study area corresponds to El Niño events; and (3) long downward trend of Central West African rainfall is associated with extratropical interhemispheric SST gradient. Further, in their West African monsoon and SST anomaly relationship investigations, Janicot et al. (1998, p. 1874) confirmed parts of the above conclusions and stated "positive SST anomalies in the eastern equatorial Pacific…coincide with negative rainfall…over West Africa…for …1972, 1976, 1982, and 1983. By contrast, positive SST anomalies in the eastern equatorial Atlantic are accompanied by…negative rainfall…in the Sahel and positive rainfall…in the Guinean region…in 1987." Thus, Central West African dipole situations, drought, and the long downward trend imply that a modification of regional atmospheric moisture fluxes has direct impacts on temperature and pressure gradients and then on rainfall. Therefore, skillful predictions of El Niño events and SSTs for the study area are very useful in agriculture, water resource management, and all rainfall-dependent applications.

2.1.2.3 Land Surface Change

An additional hypothesis for Central West African rainfall variability that emphasized land surface-atmosphere interactions and dealt with vegetation depletion (e.g., deforestation, desertification, soil degradation) is land surface change (e.g., Charney, 1975, 1977; Otterman et al., 1984; Hastenrath, 1991; Nobre et al., 1991; http://www.bsponline.org/, 2001). Accordingly, Hastenrath (1991, p. 374) noted, "a variety of human activities can alter…surface properties, wholesale deforestation having particularly drastic effects." Indeed, vegetation destruction can decrease the tropospheric ascent (i.e., deforestation reduces and eliminates photosynthesis, as explained earlier in Section 2.1.1) associated with the reduced cloudiness that alters or suppresses rainfall occurrence.

Clearly, certain land use patterns could affect the vegetation cover and modify surface albedo (i.e., amount of incident solar radiation reflected) in a relatively short time. Furthering this idea, Hastenrath (1991, p. 374) asserted that "properties of the Earth's surface, such as soil moisture, surface roughness, and albedo, are pertinent to the regional heat and water budget, and hence climate." Indeed, an increased albedo reduces convection currents in the atmosphere and suppresses the production of rainfall. Thus, Charney's (1975) desertification feedback hypothesis of land-surface processes proposed the effects of changes in surface albedo on rainfall. He anticipated that an increase in surface albedo through overgrazing could have significant impacts on other climate processes (especially increased tropospheric subsidence) and lead to rainfall suppression that, in turn, would further hamper the plant cover. Similarly, Charney (1977, p. 1366) suggested, “in the high evaporation case, an albedo change from 0.14 to 0.35 caused large decreases of rainfall.” In addition, Hastenrath (1991, p. 377) reported, “when the Subsaharan drought was intensifying, a moderate increase of surface albedo is indicated…[and] the dry season albedo in the Sahel [savanna] reached a maximum of about 0.30 in 1973, but then decreased to values close to 0.20 in 1979.” Comparatively, in their investigation of the albedo of Amazonian forest and ranch land, Culf et al. (1994) showed that the mean albedo for forest area is 0.13, whereas that of ranch land is 0.18.

Extending this land surface-atmosphere interaction hypothesis, Henderson-Sellers (1988), Hastenrath (1991), Nobre et al. (1991), and Culf et al. (1994) focused on tropical deforestation, a very noticeable environmental change. They showed that clearance of tropical forest represents a significant change on the Earth’s surface that generally should be considered in the quest for understanding climate system behavior in order to better assess the impacts of climate instability. As a result, Nobre et al. (1991, p. 957) noted, “…when the Amazonian tropical forests were replaced by degraded grass (pasture) in the model, there was a significant increase in the mean temperature (about 2.5^{o}C) and a decrease in the annual evaporation (30% reduction), precipitation (25% reduction), and runoff (20% reduction) in the region.” Furthermore, the biodiversity support program of the USAID (http://www.bsponline.org/, 2001, p. 2 of issue brief No. 8) concluded that “research in West Africa suggests that though deforestation in the Sahelian region may have little impact on rainfall, large-scale clearing of dense coastal forests may disrupt movement of the intertropical convergence, causing a collapse of monsoon rains and an overall reduction of rainfall in the region". In fact, the changes in the land surface have contributed to the long lasting downward rainfall trend, which has worsened severe drought year situations (e.g., Otterman et al., 1984; Hastenrath, 1991; Nobre et al., 1991; Culf et al., 1994).

2.1.2.4 Human Activities

In the pursuit of climate science development and application, authors such as Turner et al. (1990), Hastenrath (1991), and Koli Bi (1992) have related human activities (e.g., farming, population growth, and urbanization) to the causes of worldwide environmental changes and hence hypotheses for climate changes (i.e., rainfall variability and vegetation changes). Using bibliographic investigation, field observations, questionnaire surveys (interviews), and correlation analyses, these authors demonstrated that the increase in population density leads to a need for augmentation in crop production at the expense of protected natural domains (e.g., forests), which in the short run involves deforestation, soil degradation, and modification of the microclimate processes. Indeed, with regard to environmental-population studies, themes such as population pressure (i.e., crop distribution can be mapped in relation to rural population), agriculture intensification, deforestation, and land degradation emerged. However, Turner et al. (1990) and Koli Bi (1992) reached pessimistic conclusions when their recommendations focused on the fact that humanity has to adapt to degraded environment and climate variations. Indeed, for these authors, widespread deforestation and land degradations, which are barely reparable, are also combined with the uncertainty of how to describe nature the way humans have affected it. Thus, Turner et al. (1990) and Koli Bi (1992) concluded that there is limited availability of information on the consequences of environmental population interactions.

This Dissertation goes beyond these authors' assumptions by: (1) encouraging more research on climate-related impacts such as socioeconomic crises, environmental change issues; and (2) suggesting adaptive strategies such as the use of shorter vegetative cycle crops, drought-resistant crops, and seasonal rainfall forecasts to cope with rainfall variability (see Chapter 6 for elaboration). Nevertheless, the correlation analyses or analogies between population, agriculture, and environment used by Turner et al. (1990) and Koli Bi (1992) were helpful in understanding and interpreting Central West African rainfall and agriculture relationships undertaken in this study. Furthermore, Hastenrath (1991, p. 374) noted, "there is a two-way interaction between the climatic environment and human activities." Indeed, Hastenrath (1991) raised awareness of acknowledging not only the impact of climate variations on human activities but also the impact of humanity on the climatic environment. This interesting statement guided this study when addressing some of its recommended policies that deal with rainfall variability and agricultural change and emphasize the human activity impacts (Chapter 6).

Finally, studies such as Compaoré (1987), Aktar (1998), and Brou et al. (1998) showed that significant progress has been made in conceptualizing the problem of human activity impacts (e.g., population growth versus overexploitation of lands). Through worldwide bibliographic reviews and field investigations, these authors demonstrated that the causes and consequences of population pressure are related to demographic growth and several aspects of land use including urbanization, farming systems, and water resource management. Their studies also showed that these aspects of human activities are in competition with each other and with the natural vegetation as well. Indeed, human activities and their relationships to the environment are sufficiently established to link them to the more recent rainfall variability and then agricultural change in Central West Africa. Furthermore, for Compaoré (1987), Aktar (1998), and Brou et al. (1998), human activities (i.e., demographic growth, increasing search of new lands, and shorter fallow) caused drought and enhanced the downward (i.e., southward) migrations of lower rainfall isohyets during recent decades. These authors finally explained how and why the concentrated areas of cultivations were undergoing social and economic modifications (e.g., massive rural exodus, increased delinquency and unemployment rates). Their analyses helped clarify some of the migration patterns of rainfall isohyets throughout Central West Africa. Moreover, these studies were also taken into account when recommending environmental policies (Chapter 6) that should include rainfall variations as well as public participation and involvement.

Overall, the reviewed literature that focused on West African rainfall trends and variability helped design the methodology for this Dissertation (i.e., PCA, determination of annual rainfall index/totals, multidecadal isohyetal trends, monthly rainfall patterns, number of rain days per year/season/month, and rainy season onset/cessation dates; see Chapter 3 for complete methodology and Chapter 4 for results) in order to describe Central West African rainfall patterns and variations during recent decades. The SSTs, ENSO phenomenon, land surface changes, and human activities were the sources of rainfall fluctuations throughout Mali, Burkina Faso, and Côte d'Ivoire. The primary purpose of this study is to illustrate this information as it relates to crop output in this part of the world. Thus, studies that described agriculture in Central West Africa and assessed the causes and consequences of agricultural productivity and change are examined in Section 2.2. Further, research that centered on the impacts of rainfall variability and agricultural change relationships for socioeconomic development as well as the importance and application of environmental policies are reviewed.

2.2 Agriculture in Central West Africa

2.2.1 Crop Types and Cultivation Calendars

Information on the origins, water needs, and phenologic cycles of the major crops in the study area was obtained from AGRHYMET Center (1997) and Britannica (http://www.britannica.com/, 2001) catalogs, as well as local unpublished agricultural bulletins (i.e., reports from agricultural ministries and related agencies, such as Agence Nationale d'Appui au Dévelopment Rural, ANADER). Table 2.1 presents and summarizes these crops, which were selected for study based on each country's dietary habits and available data (e.g., completeness and length). Table 2.1 also shows that each plant is associated with a particular range of annual rainfall total needed for its growth and development. Table 2.2 presents annual crop calendars that reflect crop water needs and phenologic cycles. The crop cultivation calendars (months given) apply to the area where each crop is widely grown (see Chapter 4, Section 4.2.1).

Table 2.1: Crop origin, water requirement, and phenology in the study area. Developed from AGRHYMET (1997), http://www.britannica.com/ (2001), and local unpublished reports from Ministries of Agriculture and related agricultural agencies (e.g., ANADER, CSSPPA, PNR) within each country. P = mean annual rainfall, T = mean annual temperature, and RH = mean annual relative humidity (which is not always relevant and is only available for a few crops).

Crop	**Region of Origin**	**Annual Climatic Environment**	**Phenologic Cycle (to maturation)**	**Processed Product**
Cocoa* (*Theobroma cacao* -- short tree: 2-6 m high)	South and Central American tropical forests	P = 1,300-2,000 mm T = 24-28°C RH = 85-90%	Tree/flowers = 2-4 years Beans = 160-200 days	Cocoa powder and chocolate
Coffee* (*Coffea ssp*. -- shrub, small tree: ≤ 3 m high)	Africa (Ethiopia)	P = 1,500-1,800 mm T = 18-26°C RH = 80%	Tree/flowers = 3-5 years Beans = few weeks	Brewed coffee beverage
Cotton (*Gossypium ssp*. -- seed, fiber, herb)	India and most subtropical areas	P = 700-1,300 mm T = 27-32°C RH = 85-90%	150-180 days	Textiles and oil
Peanuts (*Arachis hypogaea* -- also called groundnuts)	Bolivia	P = 400-700 mm T = 25-35°C	90 days = short cycle 105 days = medium 120 days = long	Peanut butter and oil
Sugarcane (*Saccharum officinarum* -- perennial grass)	South Pacific Islands	P = 1,000-2,000 mm T = 32-38°C	9-24 months	Juice and sugar
Soybeans (*Glycine max* -- legume)	Central China	P = 450-700 mm T = 18-35°C	100-130 days	Vegetable proteins and milk
Maize (*Zea mays* -- Indian corn, Turkish or Spanish wheat, cereal)	The Americas	P = 500-800 mm T= 18-20°C	60-90 days = short cycle 90-120 days = medium 120-150 days = long	Grain and flour
Millet (*Penninisetium typoides* -- cereal, grass)	Asia and Africa	P ≤ 1,000 mm T = 27-30°C	60-90 days = precocious 90-120 days = tardy	Grain and flour
Plantain (*Musa Paradisiaca* -- flowering plant)	India and Southern Asia	P = 1,300-2,000 mm T = 24-28°C RH = 85-90%	Annual plant Tall tree: 3-10 m high	Starch
Rice (*Oryza sativa* -- cereal, grain, grass)	Southeast Asia	P ≥ 1,000 mm T = 22-30°C	90-150 days	Grain and flour
Sorghum** (*Sorghum sativa* -- cereal, grass)	Tropical West Africa	P = 450-650 mm T ≥ 20°C	90-120 days	Grain and flour
Yams (*Brachiara lata* -- root plant)	Warmer tropical regions of both hemispheres	P = 700-1,300 mm T = 27-32°C RH = 80%	Annual plant	Starch

*** The cultivation of cocoa and coffee crops starts a year before in a form of tree nursery.**
**** Sorghum is cultivated in hot/arid areas and is thus quite drought resistant.**

Table 2.2: Crop cultivation calendars in Central West Africa. Developed from local unpublished reports from Ministries of Agriculture and related agricultural agencies (e.g., ANADER, CSSPPA, PNR) within each country. The construction of crop cultivation calendars is based on latitudinal locations of main agricultural regions for each crop.

Crop	Field Preparation (clearing-plowing)	Sowing or Planting	Field Care (thinning-weeding-hoeing)	Harvest (earliest & main harvest)
Cocoa beans	Feb-Apr	May	Jul-Aug	May-Jun & Oct-Dec
Coffee beans	Dec-Apr	Mar-Jun	Mar-Oct	Sep-Jan
Cotton	Mar-May	Jun	Jun-Sep	Nov-Dec
Peanuts	Mar-May	Late Jun to Jul	Aug-Sep	Late Oct to Early Nov
Sugarcane	Mar-May	May-Jun	Jun-Nov	Dec
Soybeans	Mar-May	Apr-Jul	May-Aug	Jul-Oct
Maize	Feb-May	Apr-Jun	Mar-Aug	Jul-Oct
Millet	May-Aug	May-Jul	Mid-Jun to Mid-Sep	Oct
Plantain	Dec-Mar	Mar-Jul	Jul-Oct	Oct-Apr
Rice	Mar-Jun	Mar-Jul	Apr-Oct	Jul-Nov
Sorghum	Apr to Mid-Jun	Mid-Jun	Jul-Sep	Oct
Yams	Jan-May	Jan-Jun	Mar-Dec	Jun-Feb

2.2.2 Dependence of Agriculture on Rainfall

Rain-fed agriculture dominates the study area; therefore, life revolves around the occurrence or non-occurrence of rainfall and its distribution patterns (e.g., Sivakumar, 1992; Sivakumar et al., 1992, 1993). Thus, Sivakumar (1988, p. 295) noted "a significant relationship exists between the onset of rains and the length of the growing season….Rainfall analysis has important applications in crop planning…[and] disaster planning…for drought prone West Africa." The author further stated, "the unpredictable and variable nature of rainfall in this region…is often given as the reason for the frequent crop failures" (Sivakumar, 1988, p. 296). As a result, any variation in the timing or amount of rainfall can cause serious problems for crop productivity (i.e., crop failures and food shortages).

For this Dissertation, several studies (e.g., Semenov and Porter, 1995; Easterling, 1996; Peiris et al., 1996; Phillips et al., 1998; Chmielewski and Köhn, 1999) that examined different parts of the world provided insights and guidance (i.e., methodology including regression estimates, correlation analyses, and model simulations) in order to analyze drought, crop failures, food shortage, water availability, and socioeconomic disruptions/crises. However, most of the aforementioned agrometeorological methods and results were more applicable to the United States and Europe than to developing countries such as Central West Africa. Nevertheless, a few articles directly focused on the practical importance of agrometeorology in Central West Africa (e.g., Sivakumar, 1992; Sivakumar et al., 1992, 1993; Olufayo et al., 1998).

Overall, all of these reviewed literatures helped conceptualize and develop the methods of spatial distributions, time series, and correlation analyses that were employed in this Dissertation, particularly in analyzing crop data and then the relationships between rainfall variability and agricultural change. Further, the review of some of this relevant literature showed that scientific interest in West African agrometeorology is growing due to the effects of increasing variability of rainfall there, even in countries that border the Gulf of Guinea that were long considered to be humid (Sivakumar, 1988; Servat et al., 1997). Accordingly, authors such as Sivakumar (1988, p. 296) have noted that "recommendations in the past for agricultural development in West Africa were based more on soil management…[and that] among the factors controlling agricultural productivity in West Africa, the most important are soil fertility and rainfall." However, agrometeorological skills and applications are still at an emerging phase and differ from one Central African country to another (e.g., Sahel versus Gulf of Guinea regions), depending on the severity of the consequences of climate variability (i.e., rainfall variations). Thus, Olufayo et al. (1998, p. 227) concluded, "there are much more needs than deeds in operational agrometeorology in tropical Africa because the agricultural environment is endangered in many places and in many ways." As a result, crop yields are studied here to identify their vulnerability to rainfall variability.

In order to support the growing awareness of the importance of agrometeorology in West Africa, Sivakumar (1988) and Olufayo et al. (1998) described its progress and applicability. They contributed to relevant support for the methods of time series, (graphs), spatial distributions (maps), and correlation analyses that were developed for this Dissertation. Sivakumar (1988) and Olufayo et al. (1998) also showed that the agricultural zones and crop cultivation calendars are associated with the crop water requirement, the vegetative cycle, and the quality and quantity of crop productivity. Further, they added that the preferred habitats of plants are sensitive to rainfall distribution and variability. In other words, Sivakumar (1988) and Olufayo et al. (1998) helped formulate the concept of agrometeorology and build the methodology (time series and correlation analyses) used in this study to examine rainfall variability and crop output relationships. Therefore, this Dissertation addresses agrometeorology issues and focuses on the extent to which rainfall variability impacts agricultural change (i.e., crop acreage, production, and yields), and hence socioeconomic development in Central West Africa. Moreover, with the recurring droughts and decreased crop productivity in the study area, the need for a better and enhanced use of agrometeorology is recommended in Chapter 6.

2.2.3 Use of Seasonal Rainfall Forecasts to Improve Crop Productivity

Recognition of the importance of rainfall to agriculture has, in recent decades, led to rainfall impact analyses as well as to the development of seasonal rainfall forecasts for the assessment and management of agricultural production and other resources, such as dams (e.g., Dancette, 1978; Stern et al., 1982; Sivakumar, 1988, 1992; Sivakumar et al., 1992; Antle, 1996; Mollah and Cook, 1996; Hubert et al., 1998; Wilks and Wolfe, 1998; Camberlain and Diop, 1999; Fox et al., 1999). Also, Glantz (1977), Sonka et al. (1982), and Hill et al. (1999) noted that reliable climate forecasts, especially rainfall, might be used to improve planting schedules, as an efficient input substitute for other more expensive agricultural inputs (i.e., fertilizer and pesticide consumptions, number of seeds planted, and energy/labor), and to seek international assistance in advance of food shortages. Most of these authors used sophisticated statistical analyses (e.g., time series, regression estimates, correlation analyses) of observational data, economic decision models that included biophysical simulations, and Global Climate Model (GCM) simulations in their climate-impact assessments. Their statistical analyses were inspirational to the rainfall/crop relationship methodology of this Dissertation, which is mainly based on time series and correlation analyses.

In addition, concerns about the future food supply justify the interest in predicting rainy season quality involving the onset, cessation, length, distribution, and variability of rains, which are critical for agricultural monitoring and production. Centers such as the African Centre of Meteorological Applications for Development (ACMAD), the Centre Régional de Formation et d'Application en Agrométéorologie et Hydrologie Opérationnelle (AGRHYMET), the Cooperative Institute for Mesoscale Meteorological Studies (CIMMS), and the International Research Institute for Climate Prediction (IRI), in collaboration with West African national meteorological services, have recently organized seasonal prediction workshops and conferences like the PREdiction Saisonnière en Afrique de l'Ouest (PRESAO) I in 1998 (Abidjan), II in 1999 (Dakar), III in 2000 (Ouagadougou), and IV in 2001 and V in 2002 (both in Niamey). The goals of these meetings were to capitalize on the development of statistical and GCM models and to exploit the rainfall dependence on SSTs and ENSO to skillfully predict the seasonal rainfall in West Africa. These forecasts are intended to help a variety of climate information users, such as farmers, hydrologists, decision-makers in governments, and people involved in marketing/investing agricultural decisions.

In other words, in order to minimize the detrimental crop dependence on climate effects (i.e., rainfall variability), empirical and dynamical methods are emerging in operational meteorology through early warning systems or forecasts of seasonal rainfall. For instance, Folland et al. (1991), Aligbe et al. (1997), and Ward (1998) estimated a regression between a cereal index (e.g., maize) and SST anomaly index, then used the results to forecast seasonal rainfall and crop yield. These authors concluded that on average there is more skill in predicting crop index than seasonal rainfall total because the index effectively estimates the amount (both excess and deficit) of water stress suffered by the crop (Aligbe et al., 1997). Further, forecasts of crop production are more often based on data collected from farm operations and field observations. Therefore, the estimates are more accurate, objective, reliable, and timely (Aligbe et al., 1997; http://www.usda.gov/, 2003).

As already noted, agriculture is strongly dependent on rainfall, an understanding of which is useful for better planning and management of farming activities, thus enhancing crop productivity as well as improving the economy. However, the publications dealing with this topic for Central West Africa are only three general agronomic reports (i.e., Albergel et al., 1984; Ministère du Logement, du Cadre de Vie et de l'Environnement and Ministère de l'Enseignement Supérieur, de la Recherche et de l'Innovation Technologique, 1996; Ministère de l'Environnement, 1997), which are reviewed next.

For the case of Mali, Ministère de l'Environnement (1997) has listed the ongoing governmental and national institute projects on biodiversity conservation and the effects of global warming in arid lands. These governmental tasks suggest the development of natural resource management systems. These are ambitious and futuristic works that aim to reduce land degradation and to stabilize animal production at a level that is sufficient to fulfill the needs of the rapidly growing population. To date, absence of completed agrometeorology and seasonal rainfall prediction studies provides the opportunity for this Dissertation to contribute to such research for Mali.

So far, for Burkina Faso, Albergel et al. (1984) focused on the interrelations between climate variations, water resources, and agricultural production by means of worldwide bibliographic reviews, questionnaires (e.g., surveys of farmers, local scientists), and field observations. Their brief study concluded that the variability of climate elements on intraseasonal and interannual time-scales is the essence of dry areas, which is an obvious assessment since the dryness is caused by these climate variations. Also, these authors assumed that rainfall variability is strongly correlated with water resources and crop productivity but did not give detailed information on the methodology used to test rainfall sensitivities of various economic sectors. Indeed, Albergel et al. (1984) did not provide much specific information on the understanding of rainfall variability and agriculture change relationships in Burkina Faso before making the above assumptions. Therefore, the existence of only one study, and that lacking detail, for Burkina Faso justifies the relevant and regional work undertaken in this Dissertation.

The 1996 research conducted in Côte d'Ivoire at the Adiopodoumé Research Station (17 km west of Abidjan) concentrated on a distinct experimental field observation in the southern part of the country in order to analyze the vulnerability of the agricultural sector to climate change (Ministère du Logement, du Cadre de Vie et de l'Environnement and Ministère de l'Enseignement Supérieur, de la Recherche et de l'Innovation Technologique, 1996). Although the report only used a single experimental field study performed in 1996, it concluded that the effects of rainfall variability on agriculture varied from one location to another and speculated that impacts would be more severe in the drier central and northern regions of the country than in the humid coastal regions. The focus of this Adiopodoumé Research and the recognition that rainfall variability there also causes crop failures were used as baseline research for this study. However, because the performed research is based on a single field observation, it cannot give scientifically based, generalizable conclusions for the whole country. Further, the assessments between central-north versus south-east-west are more speculative (i.e., theories and hypotheses). Therefore, the rainfall impacts on agriculture, and thus on the Ivorian economy, remains in question; this Dissertation takes a further step into this topic.

Overall, rainfall variability/agricultural change relationships have not yet been completely investigated in Mali, Burkina Faso, and Côte d'Ivoire. The few focused studies do not provide enough specific information. Thus, the absence or insufficiency of such research for Central West Africa provided the opportunity for this Dissertation to contribute to this matter significantly.

2.2.4 Socioeconomic Development

The strong societal and economic dependence of Central West Africa upon market and subsistence agriculture compounds the sensitivity of the region to rainfall extremes. Researchers such as Agfoni (1979), Ould Sidi (1979), Vermeer (1981), Coulibaly (1986), Guitteye (1986), Simparana (1987), Sow (1987), Ballo (1989), Ouédraogo (1990), and Ministère du Logement, du Cadre de Vie et de l'Environnement and Ministère de l'Enseignement Supérieur, de la Recherche et de l'Innovation Technologique (1996) studied the effects of climatic uncertainties, drought, adaptive strategies, and socioeconomic systems (i.e., agriculture comprised of both farming and raising livestock) in Africa. Through their methods of questionnaire surveys and field observations, these authors drew attention to the critical dependence of socioeconomic activities on the highly variable rainfall in West Africa (e.g., agricultural productivity as it relates to rainfall magnitude and frequency). Indeed, based on their identifications and descriptions of rainfall variations and impacts, these authors derived emerging themes that were directly related to socioeconomic consequences of drought: (1) human and livestock deaths; (2) crop failures (i.e., famine and severe food shortages); and (3) water shortages. These previous works also showed that the primary economic goal of increased agricultural production to sustain the high population rates, which is reasonable, also carried with it negative potential environmental impacts. Indeed, non-supportive cultural practices, coupled with poor forest preservation and rainfall variations, defeat the well-intentioned aims, resulting in deforestation and overgrazing.

However, very few of these investigations included the adaptation mechanisms required by rainfall variability, such as how to adapt or learn to cope with the constraints of the environment (e.g., transhumant or nomadic movement) and the adjustment or change in dietary habits (replacement of long vegetative cycle crops by short ones or promotion of drought-resistant crops) as well as more involvement of women in crop cultivation (Vermeer, 1981; Ballo, 1989), particularly in cash crops and large cultivation efforts. Overall, these previous works helped in understanding that West African rainfall variations have caused both social and economic crises (e.g., famines, water shortage), and helped in developing the adaptive methods to cope with rainfall variations suggested in Chapter 6.

Furthermore, various aspects of the linkage between agriculture and socioeconomic growth have been researched extensively for developed nations, while almost nothing has been done for developing countries (Antle, 1996; Wilks and Wolfe, 1998). Though these works did not focus on the study region, the data used (e.g., rainfall, crop), methods of analyses (e.g., time series, correlation analyses), as well as the interpretations of results were adapted for use in this Dissertation. Indeed, Antle (1996) and Wilks and Wolfe (1998) focused mainly on economic variables such as farm income, value of farm assets, and farming systems or technologies. They utilized a modeling approach that allowed environmental indicators, such as the productivity or value of the ecosystem and its components, to be included in impact assessments. These authors also showed in their analyses of agriculture-environment interactions how rainfall change affects both crop production and the physical processes that determine environmental impacts on agriculture. These recent developments in agricultural economics have enhanced the understanding of climate-related impacts and the potential for adaptation in developing countries.

2.2.5 Environmental Policies

Walling (1984) and Dezetter et al. (1998) studied river flow regimes and water resource variability impacts to describe how the river flow variability in Africa is due to rainfall change. These studies used the methodology of bibliographic references and field observations to enhance the understanding of rainfall variability and its effects on the whole environment, even though their conclusions focused on rivers in particular. Other investigations (FAO/UNDP, 1994; Kini, 1995) dealt with forest management and environmental preservation for wood fuel production in Burkina Faso. These analyses presented Burkina Faso's natural resource management as one of the most innovative and successful in the Sahel because this country achieved a significant breakthrough in the management of forests for wood fuel production (e.g., an increased supply of forest products, such as firewood and a control of deforestation/environment degradation). However, Kini (1995) commented that this success must be understood as relative to past project failures. Overall, these studies did not fully address environmental (i.e., agricultural) policies in regard to rainfall variations and provided little information on adaptive strategies to cope with environmental change (especially directed toward farmers). Further, they were too broad and provided little help for the assessment of agricultural change policies in Burkina Faso. Nevertheless, the focus on one of the study area countries reinforced the need for such research on Burkina Faso and thus, the whole of Central West Africa.

Moreover, environmental policies have to be implemented correctly for development of better natural resource management strategies. Thus, the most urgent effort in Central West Africa is a published emerging national plan to re-establish a sustainable use of natural resources. The highly publicized 1992 Rio de Janeiro Conference that led to the drafting of Central West African environmental policies is relatively recent. Indeed, Pouchepadass (1993) and Ibo (1993) argued that there were environmental policies such as natural resource preservation (e.g., forest) in Central West Africa before the 1990s. These authors demonstrated that policies have existed since colonial times, but were more in the form of idle recommendations than practical engagements. Therefore, both the governments and population had little application of these policies. Given the importance of the population's socioeconomic well-being, Vermeer (1981, p. 297) suggested that "development policy and efforts must be guided by the fact that carrying capacity fluctuates sharply with climatic pulsation." The implications of this statement are taken into account in Chapter 6.

In summary, the reviewed literature in Chapter 2 showed that while the rainfall mechanisms, patterns, and variability of Central West Africa have been reasonably well-investigated, more studies need to be done for the assessments of agricultural change as well as for the socioeconomic impacts of rainfall variability/crop yield relationships. Though rainfall variability, agriculture, and sustainable socioeconomic development recently captured public attention in Mali, Burkina Faso, and Côte d'Ivoire (i.e., workshops/conferences organized by ACMAD, AGRHYMET Center, CIMMS, IRI, and West African environmental services), few studies have focused on these topics. Indeed, by visiting universities and main agricultural institutions in these countries, several unexpected documents were found and reviewed for the present study. Unfortunately, these papers primarily tended to be anecdotal and provided little scientific information for crop variations. However, they helped create many of the tables and maps developed for this Dissertation. Thus, the absence or insufficiency of such works offered the opportunity for this Dissertation to contribute to expanding knowledge about rainfall/crop yield relationships in Central West Africa.

Indeed, Mali, Burkina Faso, and Côte d'Ivoire are experiencing a subsequent decline in their crop productivity, and their societies and economies are at a critical stage. The resulting environmental imbalance (i.e., disrupted by rainfall variability) significantly influences a reorientation of sustainable socioeconomic development goals. Hence, this Dissertation addresses all of these issues, with its present objectives and directions focusing on deficiencies revealed by previous works. Chapter 3 gives detailed information on four research objectives and their related components; the data sources and records used, as well as the various methods of analyses, are also described.

CHAPTER 3

RESEARCH OBJECTIVES, DATA, AND METHODS

The difficulties encountered when collecting complete data (especially for crops) in Africa led scientists to make statements such as "there is little reliable information on trade, agricultural production, marketing, size of livestock herds, or number of livestock deaths" (Glantz, 1977, p. 156). Therefore, the acquisition and compilation of Central West Africa's rainfall and crop records undertaken for this study are significant contributions to scientific knowledge and research advancement. Since the data originate from diverse agencies that, more often than not, fail to collaborate, the study crops and rainfall records are of maximum possible reliability because they were directly acquired from individual agricultural and weather service headquarters in Mali, Burkina Faso, Côte d'Ivoire, and Niger. These data, especially for crops, are the most complete and longest ever compiled for the study area. However, these rainfall and crop records vary in number as well as in length, and contain some incomplete and missing years. Despite the missing information, these data consist of the essential records needed for this research and provide the basis for the unique results obtained.

Chapter 3 reveals four research objectives and their related components. It presents the rainfall and crop data sets (sources and records) as well as the various methods of analyses developed for this Dissertation to study rainfall variability, document agricultural change, analyze rainfall/crop yield relationships, and assess the socioeconomic impacts of these relations. Chapter 3 also lays the groundwork to compare agroclimatologic histories and environmental policies in Central West Africa.

Each section gives detailed descriptions of the quantitative methods used on the collected data from the entire study region.

3.1 Rainfall Data and Analyses

Research Objective I: To analyze rainfall characteristics and trends in Central West Africa from the Guinea Coast to the Sahel zone. The rainfall analyses are particularly tailored to the needs of agriculture. This first objective has the following five components:

- Use representative rainfall stations to study annual, decadal, seasonal, monthly, and daily rainfall patterns since 1930 and uncover strong rainfall variability (i.e., drought/wetter conditions) over time and space;
- Verify that rainfall patterns suggest a climatic dipole in Central West Africa;
- Analyze rainfall isohyetal migrations at multidecadal time-scales to reveal a decrease in rainfall since the 1960s for both the Soudano-Sahelian region (north of 9.3º N) and the Gulf of Guinea Coast area (south of 9.3º N);
- Show fluctuations in the number of rain days; and
- Determine onset and cessation dates of the rainy seasons (lengths of rainy seasons).

3.1.1 Rainfall Data

3.1.1.1 Mali Rainfall Data

Mali daily rainfall data for 1930-1997 were provided by both the Centre Régional de Formation et d'Application en Agrométéorologie et Hydrologie Opérationnelle (AGRHYMET Center) for synoptic stations and the Institut de Recherche pour le Développement (IRD), formerly the Institut Français de Recherche Scientifique pour le

Développement en Coopération (ORSTOM) for all other stations (i.e., rainfall, climatological, and agrometeorological). AGRHYMET is a Sahelian regional center for agrometeorological and hydrological research and application headquartered in Niamey, Niger; IRD is a French scientific research institute for development headquartered in France but with a presence in most former French colonies. Daily data for 1998 were obtained from the Direction de la Météorologie Nationale (DMN), the Mali national weather service. The resulting data set contains 34 evenly distributed stations (Fig. 3.1, top). With the exception of Douentza (1995) and Kayes (1997), which cease earlier, the Malian rainfall records all end in 1998 (Table 3.1*a*). The missing data range from a few days to several years for all of the 34 rainfall stations (Tables 3.2*a*-*c*).

3.1.1.2 Burkina Faso Rainfall Data

AGRHYMET Center and IRD provided Burkina Faso daily rainfall data for 1930-1997, while the Burkinabè DMN gave the data for 1998. These data are from 36 evenly distributed stations (Fig. 3.1, top), whose records vary in length (Table 3.1*b*). All stations have complete records through 1998, except for Markoye (ends in 1990). Here also, the missing data cover a few days to several years (Tables 3.2*a*-*c*). Thus, the completion of these daily rainfall data for Burkina Faso is quite remarkable.

3.1.1.3 Côte d'Ivoire Rainfall Data

The Côte d'Ivoire daily rainfall data set contained 31 stations evenly distributed throughout the country (Fig. 3.1, top). The periods of record are given in Table 3.1*c*; note that five stations end before 1998. The data set was mostly obtained from SOciété de Développement et d'EXploitation Aéronautique aéroportuaire et Météorologique

(SODEXAM), the Ivorian national weather service, by visiting its headquarters twice in Abidjan. In addition to the SODEXAM data, some data for Côte d'Ivoire were obtained from AGRHYMET Center records, despite its little focus on the Guinea Coast countries. Even so, most of the Ivorian rainfall stations, like those of Mali and Burkina Faso, have missing data ranging from a few days to several years (Tables 3.2*a*-*c*).

Table 3.1*a*: Mali daily rainfall stations and periods covered. The stations used in Principal Component Analysis (Section 3.1.2.2) are asterisked. The stations are listed alphabetically with corresponding numbering (from 1 to 34). The station types are: A = agrometeorological, C = climatological, S = synoptic, and R = rainfall. W/A = when applicable.

WMO ID (W/A)	AGRHYMET Code	Station Number &Type	Station Name	Lat.	Long.	Elev. (m)	Period
	270031	1 -- C	Ansongo*	15.40'N	00.30'E	246	1930-98
	270084	2 -- C	Bafoulabe*	13.48'N	10.50'W	104	1931-98
	270035	3 -- R	Balle*	15.20'N	08.35'W	285	1950-98
61291	270007	4 -- S	Bamako*	12.38'N	08.01'W	331	1950-98
	270059	5 -- R	Diema*	14.33'N	09.11'W	252	1941-98
61288	270141	6 -- R	Dioila*	12.29'N	06.48'W	315	1939-98
	270045	7 -- R	Douentza*	14.59'N	02.57'W	305	1930-95
61226	270025	8 -- S	Gao*	16.16'N	00.03'W	258	1930-98
	270166	9 -- R	Goualala*	11.13'N	08.14'W	350	1945-98
	270023	10 -- R	Goundam*	16.25'N	03.40'W	269	1930-98
61240	270036	11 -- S	Hombori*	15.17'N	01.42'W	287	1936-98
	270175	12 -- R	Kalana*	10.47'N	08.12'W	379	1950-98
61257	270063	13 -- S	Kayes*	14.26'N	11.26'W	46	1930-97
61285	270118	14 -- S	Kenieba*	12.40'N	11.21'W	136	1942-98
61214	270017	15 -- S	Kidal*	18.26'N	01.21'E	458	1930-98
	270158	16 -- R	Kignan*	11.51'N	06.01'W	348	1950-98
	270117	17 -- R	Kimparana*	12.50'N	04.56'W	297	1950-98
61270	270107	18 -- S	Kita*	13.04'N	09.27'W	328	1931-98
	270089	19 -- R	Kolokani*	13.35'N	08.02'W	399	1931-98
61293	270144	20 -- S	Koutiala*	12.24'N	05.28'W	344	1930-98
	270151	21 -- R	Mahou*	12.08'N	04.38'W	330	1950-98
	270181	22 -- R	Manankoro	10.27'N	07.27'W	360	1960-98
61250	270029	23 -- S	Menaka*	15.52'N	02.13'E	288	1930-98
61265	270060	24 -- S	Mopti*	14.31'N	04.06'W	271	1930-98
	270067	25 -- A	Niono*	14.15'N	05.59'W	277	1950-98
	270072	26 -- R	Pel	14.05'N	03.16'W	259	1960-98
	270137	27 -- R	Sagabari*	12.36'N	09.48'W	332	1950-98
	270030	28 -- R	Sarafere*	15.49'N	03.42'W	261	1936-98
61272	270096	29 -- S	Segou*	13.24'N	06.09'W	288	1935-98
	270082	30 -- R	Segue*	13.51'N	03.45'W	464	1950-98
61297	270165	31 -- S	Sikasso*	11.21'N	05.41'W	374	1930-98
61202	270016	32 -- S	Tessalit*	20.12'N	00.59'E	493	1948-98
61223	270021	33 -- S	Tombouctou*	16.43'N	03.00'W	263	1949-98
61235	270042	34 -- C	Yelimane*	15.07'N	10.34'W	97	1936-98

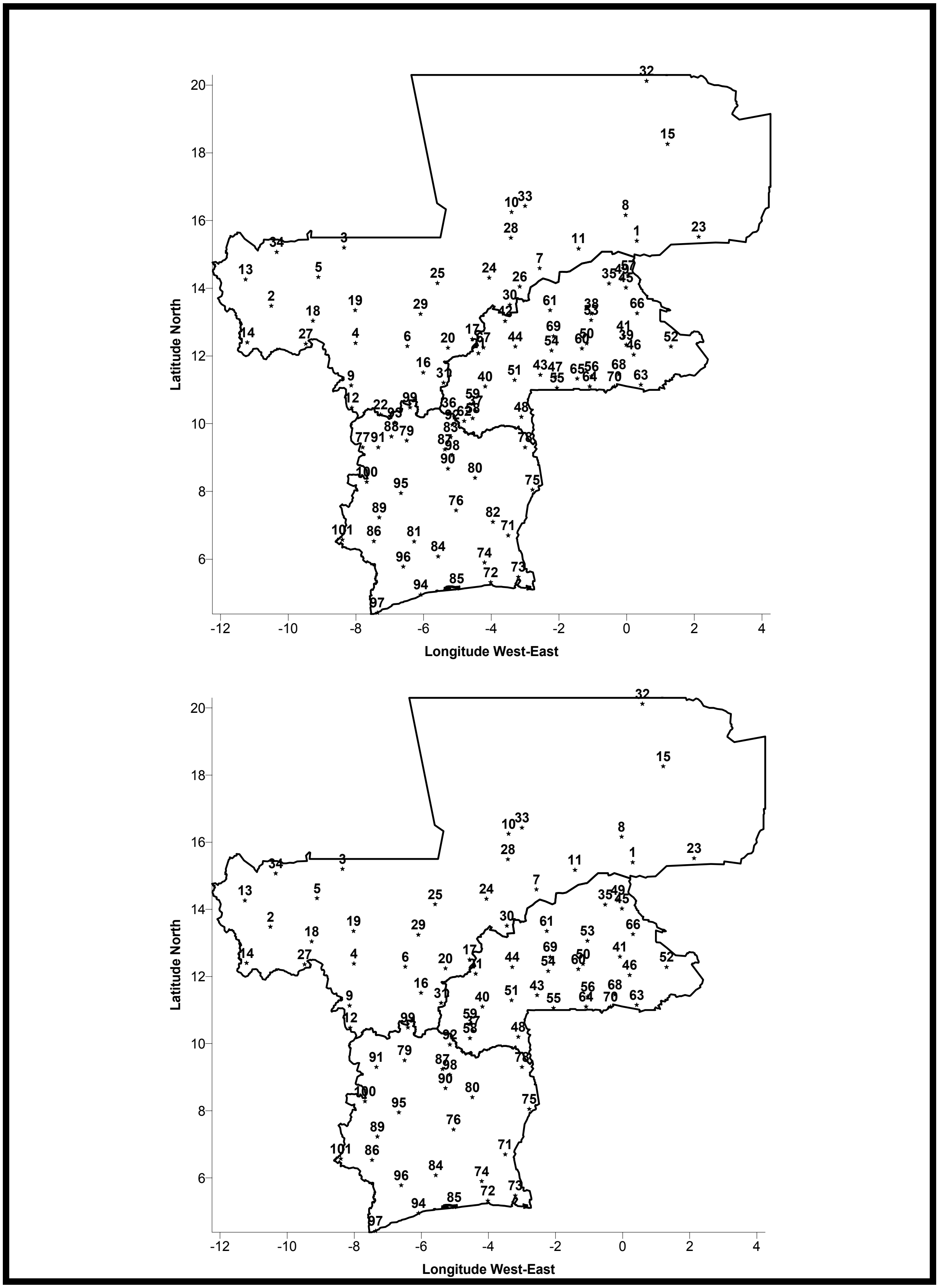


Figure 3.1: Location of study area rainfall stations for which daily rainfall totals were acquired (101 stations, top) and the stations used in Principal Component Analysis (84 stations, bottom). Numbers locate rainfall stations and refer to the listings in Tables 3.1*a-c*.

Table 3.1*b*: Burkina Faso daily rainfall stations and periods covered. The stations used in Principal Component Analysis (Section 3.1.2.2) are asterisked. The stations are listed alphabetically with corresponding numbering (from 35 to 70). The station types are: A = agrometeorological, C = climatological, S = synoptic, and R = rainfall. W/A = when applicable.

WMO ID (W/A)	AGRHYMET Code	Station Number & Type	Station Name	Lat.	Long.	Elev. (m)	Period
	200023	35 -- R	Aribinda*	14.14'N	00.52'W	370	1950-98
	200128	36 -- A	Baguera	10.32'N	05.25'W	315	1961-98
	200134	37 -- R	Banfora*	10.38'N	04.46'W	284	1930-98
	200045	38 -- R	Barsalogho	13.25'N	01.04'W	330	1959-98
	200088	39 -- R	Bilanga	12.33'N	00.01'W	281	1968-98
65510	200099	40 -- S	Bobo Dioulasso*	11.10'N	04.18'W	432	1930-98
	200085	41 -- S	Bogande*	12.59'N	00.08'W	250	1948-98
	200028	42 -- R	Bomborokuy	13.03'N	03.59'W	279	1961-98
65516	200107	43 -- S	Boromo*	11.44'N	02.55'W	264	1930-98
65505	200054	44 -- S	Dedougou*	12.28'N	03.29'W	299	1930-98
65501	200026	45 -- S	Dori*	14.02'N	00.02'W	276	1930-98
65507	200089	46 -- S	Fada N'gourma*	12.04'N	00.21'E	292	1930-98
	200110	47 -- R	Gao	11.39'N	02.11'W	331	1964-98
65522	200140	48 -- S	Gaoua*	10.20'N	03.11'W	333	1930-98
	200025	49 -- R	Gorom Gorom*	14.27'N	00.14'W	380	1950-98
	200078	50 -- R	Guilongou*	12.37'N	01.18'W	315	1950-98
	200103	51 -- R	Hounde*	11.29'N	03.31'W	324	1930-98
	200008	52 -- R	Kantchari*	12.28'N	01.31'E	270	1943-98
	200044	53 -- C	Kaya*	13.06'N	01.05'W	313	1930-98
	200061	54 -- C	Koudougou*	12.16'N	02.22'W	250	1930-98
	200111	55 -- A	Leo*	11.06'N	02.06'W	347	1930-98
	200115	56 -- A	Manga*	11.40'N	01.04'W	286	1949-98
65500	200027	57 -- A	Markoye	14.38'N	00.04'E	295	1955-90
	200133	58 -- A	Niangoloko*	10.16'N	04.55'W	320	1950-98
	200132	59 -- R	Orodara*	10.59'N	04.55'W	523	1950-98
65503	200003	60 -- S	Ouagadougou*	12.22'N	01.32'W	296	1930-98
65502	200035	61 -- S	Ouahigouya*	13.35'N	02.26'W	329	1930-98
	200154	62 -- R	Ouanglodougou	10.08'N	04.80'W	280	1975-98
	200125	63 -- A	Pama*	11.15'N	00.42'E	230	1949-98
65518	200114	64 -- S	Po*	11.10'N	01.09'W	326	1942-98
	200112	65 -- R	Sapouy	11.33'N	01.46'W	330	1959-98
	200050	66 -- R	Sebba*	13.26'N	00.31'E	212	1950-98
	200051	67 -- R	Tansilla	12.25'N	04.23'W	430	1963-98
	200121	68 -- C	Tenkodogo*	11.46'N	00.23'W	302	1930-98
	200063	69 -- C	Yako*	12.58'N	02.16'W	294	1942-98
	200119	70 -- R	Zabre*	11.10'N	00.36'W	296	1950-98

3.1.1.4 Criteria for Rainfall Station Inclusion

When evaluating the data of the three study countries, it is important to note that not all of the original 101 rainfall stations (Tables 3.1*a*-*c* and Fig. 3.1, top) were suitable for all of the subsequent analyses for two reasons. First, the series were required to have long successive records for the period covering 1930 to 1998 (Section 4.1.2). Second, the stations needed to be operational from 1950 to 1998 (Section 4.1.1). Therefore, in order to perform the Principal Component Analysis (PCA), which helped select representative rainfall stations, the above criteria had to be verified (Fig. 3.2). The information revealed in Figure 3.2 also guided the choice of the study period and rainfall stations (84 out of the 101 stations) that were used in the PCA.

Table 3.1*c*: Côte d'Ivoire daily rainfall stations and periods covered. The stations used in Principal Component Analysis (Section 3.1.2.2) are asterisked. The stations are listed alphabetically with corresponding numbering (from 71 to 101). The station types are: A = agrometeorological, C = climatological, S = synoptic, and R = rainfall. W/A = when applicable.

WMO ID (W/A)	SODEXAM Code	Station Number & Type	Station Name	Lat.	Long.	Elev. (m)	Period
	1090000400	71 -- A	Abengourou*	06.70'N	03.50'W	201	1930-98
65575	1090000100	72 -- S	Abidjan*	05.31'N	04.01'W	8	1936-98
	1090001000	73 -- R	Aboisso*	05.47'N	03.20'W	39	1930-98
	1090002200	74 -- C	Agboville*	05.90'N	04.20'W	54	1930-98
65545	1090004600	75 -- S	Bondoukou*	08.05'N	02.78'W	370	1936-98
65555	1090005600	76 -- S	Bouake*	07.44'N	05.04'W	376	1930-98
	1090005800	77 -- R	Bougousso	09.30'N	07.80'W	472	1965-98
	1090006100	78 -- R	Bouna*	09.30'N	03.00'W	319	1930-98
	1090006400	79 -- R	Boundiali*	09.50'N	06.50'W	421	1930-98
	1090007300	80 -- R	Dabakala*	08.40'N	04.48'W	258	1930-98
65560	1090008000	81 -- S	Daloa	06.52'N	06.28'W	277	1966-98
	1090008500	82 -- R	Daoukro	07.10'N	03.95'W	230	1955-98
	1090009900	83 -- S	Ferkessedougou	09.60'N	05.20'W	325	1930-87
65557	1090010300	84 -- S	Gagnoa*	06.08'N	05.57'W	210	1930-98
	1090010900	85 -- R	Grand Lahou*	05.13'N	05.02'W	4	1930-98
	1090011200	86 -- R	Guiglo*	06.53'N	07.47'W	217	1930-98
65536	1090012000	87 -- S	Korhogo*	09.24'N	05.37'W	381	1944-98
	1090013900	88 -- R	Madinani	09.62'N	06.95'W	516	1962-98
65548	1090014200	89 -- S	Man*	07.23'N	07.31'W	340	1930-98
	1090015700	90 -- R	Niakaradougou*	08.67'N	05.28'W	386	1950-98
65528	1090016000	91 -- S	Odienne*	09.30'N	07.34'W	421	1930-98
	1090016300	92 -- R	Ouanglodougou*	09.97'N	05.15'W	309	1950-98
	1090017900	93 -- R	Sanhala	10.03'N	06.85'W	380	1962-98
65599	1090017200	94 -- S	Sassandra*	04.95'N	06.08'W	66	1930-98
	1090017500	95 -- C	Seguela*	07.95'N	06.67'W	351	1930-96
	1090018100	96 -- A/R	Soubre*	05.78'N	06.60'W	134	1940-98
65592	1090018400	97 -- S	Tabou*	04.42'N	07.37'W	21	1930-98
	1090018700	98 -- R	Tafire*	09.07'N	05.15'W	409	1950-98
	1090019300	99 -- R	Tengrela*	10.48'N	06.40'W	356	1950-96
	1090020500	100 -- R	Touba*	08.28'N	07.68'W	494	1938-92
	1090020800	101 -- R	Toulepleu*	06.57'N	08.40'W	270	1930-97

3.1.2 Rainfall Analyses

Governed by the conditions of completeness and length, 84 out of 101 rainfall stations (83%) -- 32 out of 34 for Mali (94%), 27 out of 36 for Burkina Faso (75%), and 25 out of 31 for Côte d'Ivoire (81%) -- covering the period 1950-98 were selected from the original data for use in this study when performing PCA (Fig. 3.1, bottom). 1950 was retained as first year of analysis for the PCA because it is a prominent year when the data sets of each country register more rainfall stations that show a relative consistency of less missing data (Fig. 3.2). PCA was then performed after the detection and replacement of the missing data (see Sections 3.1.2.1 and 3.1.2.2 for description of procedures).

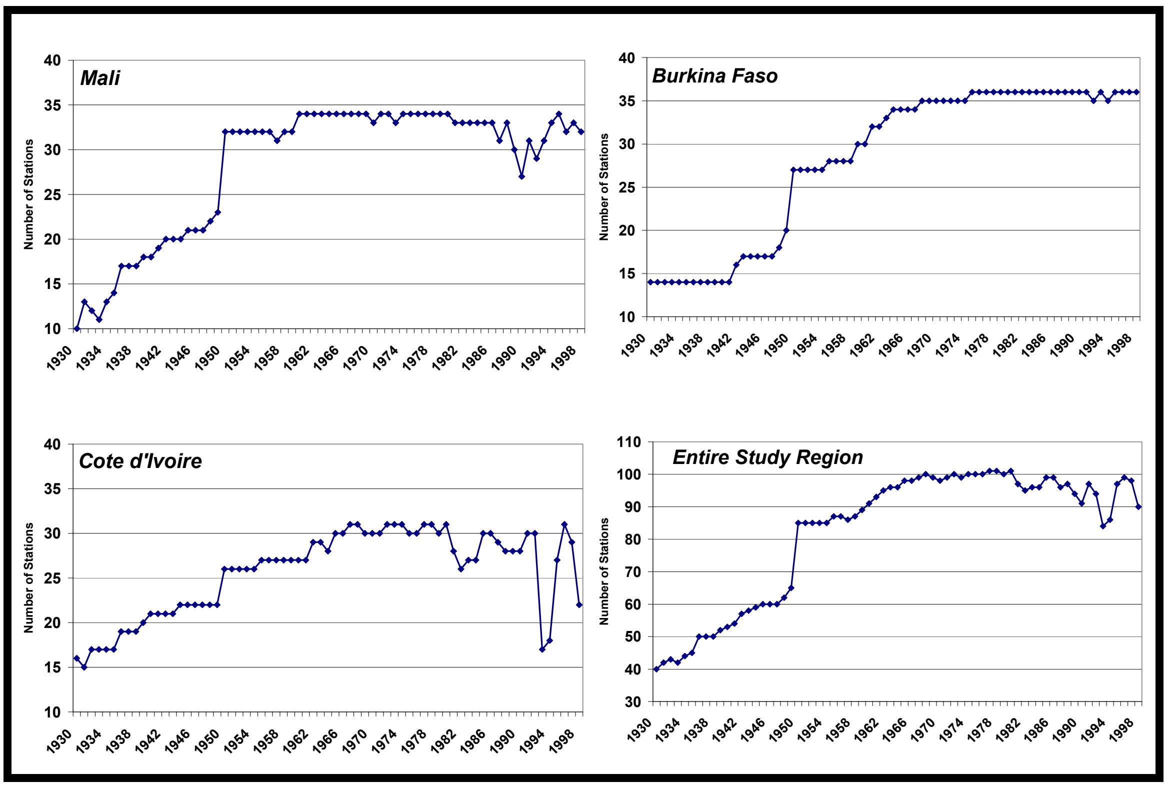


Figure 3.2: Total number of daily rainfall stations available in each year (1930-1998), from which one or more observation(s) were received for Mali, Burkina Faso, Côte d'Ivoire, and for the entire study region.

The rationale for use of PCA is to determine homogenous climatic regions objectively by defining the principal components, which account for the maximum amount of variation in the whole data used. Then, based on PCA results, representative rainfall stations (i.e., complete and longest sets) were selected for the pursuit of the remaining rainfall analyses in Chapter 4, which focused on annual rainfall index/totals, multidecadal isohyetal trend determination, monthly rainfall patterns, number of rain days per year/season/month, and finally, the determination of the onset and cessation dates of the rainy seasons. These analyses, using a reduced number of rainfall stations (i.e., representative rainfall stations), covered the whole study period from 1930 to 1998 (see Section 4.1 for results and discussion of rainfall analyses).

3.1.2.1 Missing Data

The missing values (Tables 3.2*a*-*c*) detected and counted as part of this investigation do not constitute a problem in the pursuit of the analyses. Using the standard technique of station climatology, the incomplete data were supplied. The method consists of using the appropriate mean rainfall value for a calendar day/month to fill in the missing values of that day/month for the whole period. Katz and Glantz (1986, p. 767) used a similar technique and describe it in the following terms: "when individual station rainfall observations are missing, an adjustment is made.…This adjustment involves replacing the divisor N by the number of the stations actually available and, in effect, taking rainfall for the missing stations to be average." In cases where the missing data comprise more than five years, the SYSTAT 9 software has a Missing Value Analysis command, which, when applied, automatically estimates and fills in the missing values. SYSTAT 9 treats all selected variables as continuous (numeric) data. It selects a matrix (e.g., correlation, covariance) to compute and a method (e.g., regression substitution) for handling missing data (to predict values for the missing variables). The representative stations that were retained for analyses in Chapter 4 have less than 15% missing values.

Table 3.2*a*: Summary of missing data for Central West African rainfall stations. Years that registered more than 15 days of missing data as fractions of total number of years of collected data. Highest and lowest percentages are put in bold.

Mali	**Missing Data**	**Burkina Faso**	**Missing Data**	**Côte d'Ivoire**	**Missing Data**
Ansongo	48/69 (≈ 70%)	Aribinda	13/49 (≈ 27%)	Abengourou	4/69 (≈ 6%)
Bafoulabe	52/68 (≈ 76%)	Baguera	4/38 (≈ 11%)	Abidjan	3/63 (≈ 5%)
Balle	21/49 (≈ 43%)	Banfora	31/69 (≈ 45%)	Aboisso	1/69 (≈ 1%)
Bamako	18/49 (≈ 37%)	Barsalogho	5/40 (≈ 13%)	Agboville	8/69 (≈ 12%)
Diema	33/58 (≈ 59%)	Bilanga	7/31 (≈ 23%)	Bondoukou	3/63 (≈ 5%)
Dioila	40/60 (≈ 67%)	Bobo Dioulasso	29/69 (≈ 42%)	Bouake	0/69 (≈ **0%**)
Douentza	54/65 (≈ **83%**)	Bogande	18/51 (≈ 35%)	Bougousso	4/34 (≈ 12%)
Gao	51/69 (≈ 74%)	Bomborokuy	9/38 (≈ 24%)	Bouna	7/69 (≈ 10%)
Goualala	35/54 (≈ 65%)	Boromo	33/69 (≈ 48%)	Boundiali	2/69 (≈ 3%)
Goundam	50/69 (≈ 72%)	Dedougou	33/69 (≈ 48%)	Dabakala	2/69 (≈ 3%)
Hombori	45/63 (≈ 71%)	Dori	31/69 (≈ 45%)	Daloa	1/33 (≈ 3%)
Kalana	33/49 (≈ 67%)	Fada N'gourma	32/69 (≈ 46%)	Daoukro	14/44 (≈
Kayes	52/68 (≈ 76%)	Gao	8/35 (≈ 23%)	Ferkessedougou	1/58 (≈ 2%)
Kenieba	43/57 (≈ 75%)	Gaoua	30/69 (≈ 43%)	Gagnoa	0/69 (≈ **0%**)
Kidal	51/69 (≈ 74%)	Gorom Gorom	11/49 (≈ 22%)	Grand Lahou	1/69 (≈ 1%)
Kignan	23/49 (≈ 47%)	Guilongou	10/49 (≈ 20%)	Guiglo	1/69 (≈ 1%)
Kimparana	31/49 (≈ 63%)	Hounde	32/69 (≈ 46%)	Korhogo	3/55 (≈ 5%)
Kita	51/68 (≈ 75%)	Kantchari	23/56 (≈ 41%)	Madinani	2/37 (≈ 5%)
Kolokani	52/68 (≈ 76%)	Kaya	36/69 (≈ 52%)	Man	0/69 (≈ **0%**)
Koutiala	51/69 (≈ 74%)	Koudougou	37/69 (≈ 54%)	Niakaradougou	2/49 (≈ 4%)
Mahou	29/49 (≈ 59%)	Leo	40/69 (≈ **58%**)	Odienne	3/69 (≈ 4%)
Manankoro	15/39 (≈ 38%)	Manga	20/50 (≈ 40%)	Ouanglodougou	2/49 (≈ 4%)
Menaka	50/69 (≈ 72%)	Markoye	15/36 (≈ 42%)	Sanhala	4/37 (≈ 11%)
Mopti	51/69 (≈ 74%)	Niangoloko	10/49 (≈ 20%)	Sassandra	1/69 (≈ 1%)
Niono	37/49 (≈ 76%)	Orodara	8/49 (≈ 16%)	Seguela	8/67 (≈ 12%)
Pel	14/39 (≈ 36%)	Ouagadougou	30/69 (≈ 43%)	Soubre	0/59 (≈ **0%**)
Sagabari	15/49 (≈ **31%**)	Ouahigouya	31/69 (≈ 45%)	Tabou	2/67 (≈ 3%)
Sarafere	41/63 (≈ 65%)	Ouanglodougou	2/24 (≈ **8%**)	Tafire	3/49 (≈ 4%)
Segou	46/64 (≈ 72%)	Pama	14/50 (≈ 28%)	Tengrela	5/47 (≈ 11%)
Segue	31/49 (≈ 63%)	Po	20/57 (≈ 35%)	Touba	5/54 (≈ 9%)
Sikasso	50/69 (≈ 72%)	Sapouy	3/40 (≈ **8%**)	Toulepleu	3/68 (≈ 4%)
Tessalit	32/51 (≈ 63%)	Sebba	11/49 (≈ 22%)		
Tombouctо	25/50 (≈ 50%)	Tansilla	3/36 (≈ **8%**)		
Yelimane	50/63 (≈ 79%)	Tenkodogo	37/69 (≈ 54%)		
		Yako	26/57 (≈ 46%)		
		Zabre	9/49 (≈ 18%)		
Range	From **31%** (Sagabari) to **83%** (Douentza)		From **8%** (Ouanglodougou Sapouy, Tansilla) to **58%** (Leo)		From **0%** (Bouake, Man, Gagnoa, and Soubre) to **32%** (Daoukro)

Table 3.2*b*: Summary of missing data for Central West African rainfall stations. Years that registered more than 60 days of missing data as fractions of total number of years of collected data. Highest and lowest percentages are put in bold.

Mali	Missing Data	Burkina Faso	Missing Data	Côte d'Ivoire	Missing Data
Ansongo	48/69 (≈ 70%)	Aribinda	8/49 (≈ 16%)	Abengourou	4/69 (≈ 6%)
Bafoulabe	52/68 (≈ 76%)	Baguera	1/38 (≈ 3%)	Abidjan	3/63 (≈ 5%)
Balle	21/49 (≈ 43%)	Banfora	23/69 (≈ 33%)	Aboisso	1/69 (≈ 1%)
Bamako	18/49 (≈ 37%)	Barsalogho	3/40 (≈ 8%)	Agboville	8/69 (≈ 12%)
Diema	33/58 (≈ 59%)	Bilanga	1/31 (≈ 3%)	Bondoukou	3/63 (≈ 5%)
Dioila	40/60 (≈ 67%)	Bobo Dioulasso	22/69 (≈ 32%)	Bouake	0/69 (≈ **0%**)
Douentza	54/65 (≈ **83%**)	Bogande	15/51 (≈ 29%)	Bougousso	4/34 (≈ 12%)
Gao	51/69 (≈ 74%)	Bomborokuy	1/38 (≈ 3%)	Bouna	7/69 (≈ 10%)
Goualala	24/54 (≈ 44%)	Boromo	28/69 (≈ 41%)	Boundiali	2/69 (≈ 3%)
Goundam	50/69 (≈ 72%)	Dedougou	30/69 (≈ 43%)	Dabakala	2/69 (≈ 3%)
Hombori	45/63 (≈ 71%)	Dori	31/69 (≈ 45%)	Daloa	1/33 (≈ 3%)
Kalana	25/49 (≈ 51%)	Fada N'gourma	30/69 (≈ 43%)	Daoukro	14/44 (≈ **32%**)
Kayes	50/68 (≈ 74%)	Gao	3/35 (≈ 9%)	Ferkessedougo	1/58 (≈ 2%)
Kenieba	40/57 (≈ 70%)	Gaoua	9/69 (≈ 13%)	Gagnoa	0/69 (≈ **0%**)
Kidal	51/69 (≈ 74%)	Gorom Gorom	6/49 (≈ 12%)	Grand Lahou	1/69 (≈ 1%)
Kignan	19/49 (≈ 39%)	Guilongou	6/49 (≈ 12%)	Guiglo	1/69 (≈ 1%)
Kimparana	28/49 (≈ 57%)	Hounde	27/69 (≈ 39%)	Korhogo	3/55 (≈ 5%)
Kita	49/68 (≈ 72%)	Kantchari	19/56 (≈ 34%)	Madinani	2/37 (≈ 5%)
Kolokani	48/68 (≈ 71%)	Kaya	32/69 (≈ 46%)	Man	0/69 (≈ **0%**)
Koutiala	42/69 (≈ 61%)	Koudougou	35/69 (≈ **51%**)	Niakaradougou	2/49 (≈ 4%)
Mahou	27/49 (≈ 55%)	Leo	32/69 (≈ 46%)	Odienne	2/69 (≈ 3%)
Manankoro	10/39 (≈ **26%**)	Manga	16/50 (≈ 32%)	Ouanglodougo	2/49 (≈ 4%)
Menaka	50/69 (≈ 72%)	Markoye	13/36 (≈ 36%)	Sanhala	4/37 (≈ 11%)
Mopti	51/69 (≈ 74%)	Niangoloko	4/49 (≈ 8%)	Sassandra	1/69 (≈ 1%)
Niono	36/49 (≈ 73%)	Orodara	6/49 (≈ 12%)	Seguela	8/67 (≈ 12%)
Pel	14/39 (≈ 36%)	Ouagadougou	30/69 (≈ 43%)	Soubre	0/59 (≈ **0**%)
Sagabari	14/49 (≈ 29%)	Ouahigouya	31/69 (≈ 45%)	Tabou	2/67 (≈ 3%)
Sarafere	41/63 (≈ 65%)	Ouanglodougou	0/24 (≈ **0%**)	Tafire	3/49 (≈ 4%)
Segou	45/64 (≈ 70%)	Pama	9/50 (≈ 18%)	Tengrela	5/47 (≈ 11%)
Segue	31/49 (≈ 63%)	Po	18/57 (≈ 32%)	Touba	5/54 (≈ 9%)
Sikasso	35/69 (≈ 51%)	Sapouy	1/40 (≈ 3%)	Toulepleu	3/68 (≈ 4%)
Tessalit	32/51 (≈ 63%)	Sebba	8/49 (≈ 16%)		
Tombouctо	25/50 (≈ 50%)	Tansilla	1/36 (≈ 3%)		
Yelimane	49/63 (≈ 78%)	Tenkodogo	32/69 (≈ 46%)		
		Yako	20/57 (≈ 35%)		
		Zabre	6/49 (≈ 12%)		
Range	From **26%** (Manankoro) to **83%** (Douentza)		From **0%** (Ouanglodougou) to **51%** (Koudougou)		From **0%** (Bouake, Man, Gagnoa, and Soubre) to **32%** (Daoukro)

Table 3.2*c*: Summary of missing data for Central West African rainfall stations. Years that registered more than 120 days of missing data as fractions of total number of years of collected data. Highest and lowest percentages are put in bold.

Mali	Missing Data	Burkina Faso	Missing Data	Côte d'Ivoire	Missing Data
Ansongo	48/69 (≈ 70%)	Aribinda	8/49 (≈ 16%)	Abengourou	4/69 (≈ 6%)
Bafoulabe	50/68 (≈ 74%)	Baguera	1/38 (≈ 3%)	Abidjan	3/63 (≈ 5%)
Balle	21/49 (≈ 43%)	Banfora	15/69 (≈ 22%)	Aboisso	1/69 (≈ 1%)
Bamako	14/49 (≈ 29%)	Barsalogho	2/40 (≈ 5%)	Agboville	7/69 (≈ 10%)
Diema	33/58 (≈ 59%)	Bilanga	1/31 (≈ 3%)	Bondoukou	3/63 (≈ 5%)
Dioila	35/60 (≈ 58%)	Bobo Dioulasso	7/69 (≈ 10%)	Bouake	0/69 (≈ **0%**)
Douentza	54/65 (≈ **83%**)	Bogande	14/51 (≈ 27%)	Bougousso	4/34 (≈ 12%)
Gao	51/69 (≈ 74%)	Bomborokuy	1/38 (≈ 3%)	Bouna	7/69 (≈ 10%)
Goualala	13/54 (≈ 24%)	Boromo	18/69 (≈ 26%)	Boundiali	2/69 (≈ 3%)
Goundam	49/69 (≈ 71%)	Dedougou	22/69 (≈ 32%)	Dabakala	2/69 (≈ 3%)
Hombori	45/63 (≈ 71%)	Dori	31/69 (≈ 45%)	Daloa	1/33 (≈ 3%)
Kalana	14/49 (≈ 29%)	Fada N'gourma	19/69 (≈ 28%)	Daoukro	14/44 (≈
Kayes	47/68 (≈ 69%)	Gao	3/35 (≈ 9%)	Ferkessedougou	1/58 (≈ 2%)
Kenieba	35/57 (≈ 61%)	Gaoua	3/69 (≈ 4%)	Gagnoa	0/69 (≈ **0%**)
Kidal	51/69 (≈ 74%)	Gorom Gorom	5/49 (≈ 10%)	Grand Lahou	1/69 (≈ 1%)
Kignan	16/49 (≈ 33%)	Guilongou	6/49 (≈ 12%)	Guiglo	1/69 (≈ 1%)
Kimparana	21/49 (≈ 43%)	Hounde	13/69 (≈ 19%)	Korhogo	3/55 (≈ 5%)
Kita	39/68 (≈ 57%)	Kantchari	17/56 (≈ 30%)	Madinani	2/37 (≈ 5%)
Kolokani	42/68 (≈ 62%)	Kaya	32/69 (≈ **46%**)	Man	0/69 (≈ **0%**)
Koutiala	34/69 (≈ 49%)	Koudougou	30/69 (≈ 43%)	Niakaradougou	2/49 (≈ 4%)
Mahou	21/49 (≈ 43%)	Leo	14/69 (≈ 20%)	Odienne	2/69 (≈ 3%)
Manankoro	7/39 (≈ 18%)	Manga	9/50 (≈ 18%)	Ouanglodougou	2/49 (≈ 4%)
Menaka	50/69 (≈ 72%)	Markoye	13/36 (≈ 36%)	Sanhala	4/37 (≈ 11%)
Mopti	49/69 (≈ 71%)	Niangoloko	2/49 (≈ 4%)	Sassandra	1/69 (≈ 1%)
Niono	33/49 (≈ 67%)	Orodara	1/49 (≈ 2%)	Seguela	8/67 (≈ 12%)
Pel	11/39 (≈ 28%)	Ouagadougou	24/69 (≈ 35%)	Soubre	0/59 (≈ **0%**)
Sagabari	10/49 (≈ 20%)	Ouahigouya	28/69 (≈ 41%)	Tabou	2/67 (≈ 3%)
Sarafere	41/63 (≈ 65%)	Ouanglodougou	0/24 (≈ **0%**)	Tafire	3/49 (≈ 4%)
Segou	40/64 (≈ 63%)	Pama	7/50 (≈ 14%)	Tengrela	5/47 (≈ 11%)
Segue	29/49 (≈ 59%)	Po	11/57 (≈ 19%)	Touba	5/54 (≈ 9%)
Sikasso	10/69 (≈ **14%**)	Sapouy	1/40 (≈ 3%)	Toulepleu	3/68 (≈ 4%)
Tessalit	32/51 (≈ 63%)	Sebba	7/49 (≈ 14%)		
Tombouctou	25/50 (≈ 50%)	Tansilla	1/36 (≈ 3%)		
Yelimane	49/63 (≈ 78%)	Tenkodogo	27/69 (≈ 39%)		
		Yako	17/57 (≈ 30%)		
		Zabre	1/49 (≈ 2%)		
Range	From **14%** (Sikasso) to **83%** (Douentza)		From **0%** (Ouanglodougou) to **46%** (Kaya)		From **0%** (Bouake, Man, Gagnoa, and Soubre) to **32%** (Daoukro)

3.1.2.2 Principal Component Analysis (PCA)

Eigenvectoral analysis is a multivariate statistical technique that has been frequently and effectively applied in climatological and meteorological research. It has several variants including Principal Component Analysis (PCA), Empirical Orthogonal Function (EOF) Analysis, and Factor Analysis (FA). PCA is used here to identify characteristic patterns (or modes) of rainfall variations allowing for regionalization and selection of representative rainfall stations in order to conduct the rainfall analyses discussed in Chapter 4. Tables 3.1*a*-*c* and Figure 3.1 (bottom) present the study area rainfall stations used in the PCA, which groups variables with similar characteristics (e.g., climatic regions) in delimitation exercises. Richman (1986, p. 314) identified six possible modes of PCA for meteorological/climatological fields that vary in space and time (Table 3.3).

Table 3.3: PCA modes (from Richman, 1986, p. 314).

PC Mode	Variable Index	Individual Index	Fixed Entity
O	Time	Field	Station
P	Field	Time	Station
Q	Station	Field	Time
R	Field	Station	Time
S	Station	Time	Field
T	Time	Station	Field

These six modes are coupled in sets of two opposite modes based on their defined indices and entities (e.g., O/P, Q/R, S/T). Thus, Richman (1986, p. 315) wrote, "a PC analysis of a meteorological field can therefore be made by varying any two of these three entities and holding the third fixed." This particular study treats three entities: (1) rainfall is the meteorological field (i.e., fixed parameter); (2) the annual/seasonal/monthly totals are the time index; and (3) the location of the rainfall stations is the variable index.

With rainfall being the fixed parameter, only T-mode (temporal observations are variables and stations are cases) or S-mode (temporal observations are cases and stations are variables) can be used. Serrano et al. (1999, p. 2899) further explained, "…T-mode identifies subgroups of observations with similar spatial patterns…S-mode compares series and identifies those stations in which rainfall varies similarly…S-mode is used for …regionalization purpose, while T-mode…for pattern detection." Because this study was interested in PCA for the regionalization of the rainfall station, the S-mode was selected.

Another important aspect of PCA is the number of significant PCs (or factors or EOFs) to be retained and (possibly) rotated. The eigenvalues associated with each PC represent the amount of variation it explains among the PC space. The larger the eigenvalue, the more variation is explained by that PC. Among the possible selection criteria for significant PCs, the following two were combined and used in this analysis: (1) the scree plot method and (2) the eigenvalue sampling errors test (Richman, 1986; Serrano et al., 1999). The first approach, which is graphical, defines that "the point where the tail of the [eigenvalue as a function of EOF number] plot becomes linear is where no further EOFs are retained, since the linear tail with nearly equal eigenvalues theoretically represents random noise" (Richman, 1986, p. 294). The second procedure is the North et al. (1982) test that uses the sampling errors and their associated eigenvalues. They recommended that significant PCs could be kept if the difference between neighboring eigenvalues λ_i and λ_{i+1} is larger than the sampling error $\lambda_i(\sqrt{\frac{2}{n}})$, i.e., if:

$$\lambda_i - \lambda_{i+1} > \lambda_i(\sqrt{\frac{2}{n}})$$

where n is the total number of observations (cases). The key point is that this method focuses on eigenvalue separations. It generally checks the difference between the concerning eigenvalue and the one preceding and identifies the last pronounced "step" in the eigenvalue plot before it flattens out as recognized by the scree plot method.

In order to have a more uniform distribution, to identify clusters in the data, and to capture more clearly the real shape of patterns (for the explained variance across significant PCs), the next step, perhaps, is to perform their rotation. This method consists of linear transformations of the retained unrotated PCs by the same number of derived variables, called rotated principal components (RPCs). Further, the rotation method realigns the eigenvectors to fit clusters in the data better (if they exist). After reviewing and examining conclusions of articles such as Richman and Lamb (1985) and Serrano et al. (1999), Kaiser's Varimax orthogonal rotation was chosen from among others (e.g., quartimax, oblimax, maxplane) for use here. Varimax is generally accepted as being "the most accurate orthogonal rotation when applied to known data sets" (Richman, 1986, p. 318). Therefore, Varimax identifies homogeneous groups of variables and simplifies the PCs. The Varimax rotated PCs' spatial loadings are then plotted and isoplethed to define the study area climatic regions.

S-mode rotated PCA was employed to delineate several regions within Central West Africa and the resulting regionalization was used to select representative stations. The PCA was performed on a seasonal basis and the seasons were determined based on preliminary monthly analyses and previous work by Ward (1994) and Aligbe et al. (1997). For Burkina Faso and Mali, July-September (JAS) and May-October (MJJASO) are the chosen seasons; while for Côte d'Ivoire, March-June (MAMJ), July-September (JAS), and October-November (ON) are retained separately. These stations were used in a range of rainfall analyses reported in Chapter 4 -- annual rainfall index/totals, multidecadal isohyetal trend determination, monthly rainfall patterns, number of rain days per year/season/month, and, finally, the determination of the rainy season onset/cessation dates. As already mentioned in Section 3.1.2, for the selected 42 representative rainfall stations, data from 1930-1949 was added to cover the whole study period. The new data set covering the period from 1930 to 1998 is presented and analyzed in Chapter 4.

3.1.2.3 Average Annual Rainfall Index and Totals

Annual rainfall totals are obtained by summing the daily values for each station. These totals were then mapped to display spatial patterns of Central West African rainfall. The totals show the rainfall gradients and differences that are reflected in the diversity of cropping, which allow useful comparison of agricultural potential within the study area. On the other hand, calculations and plots of normalized rainfall index time series (i.e., temporal deviations above or beyond the long-term average) are also performed to monitor the study area rainfall conditions. The rainfall index is calculated from the well-defined standardized departure index (e.g., Lamb, 1978, 1982; Katz and Glantz, 1986; Nicholson et al., 1988; Servat et al., 1997) that has been widely used to assess the interannual rainfall variation. "The construction of this index involves standardizing the annual…total rainfall for an individual station by subtracting the station's mean and dividing by its standard deviation, with the mean and standard deviation being computed from the station's historical record" (Katz and Glantz, 1986, p.

114). The following formula was used to calculate this reduced centered variable (i.e., standardized rainfall deviations or anomalies) for each station and then averaged over all stations within the same region to obtain a single annual value for the index:

$$Normalized\ Departure\ (X_j) = \frac{1}{N_j}\sum_{i=1}^{N_j}\frac{x_{ij} - \bar{x}_i}{\sigma_i},$$

where x_{ij} is the annual rainfall total for year $_j$ at station i , $\bar{x}_i$ and σ_i are respectively the mean and standard deviation of annual rainfall total at station i over the period 1930-1998.

The standardized index quantifies the rainfall departure from the long-term average using standard deviations. For all stations, means ($\bar{x}$) and standard deviations (σ) were calculated across the entire 69-year study period. With the whole period under scrutiny, the rainfall deviations can be explained with less bias toward dry or wet periods. When $\bar{x}$ and σ were computed with a standard WMO 30-year normal period (e.g., 1931-60 or 1961-90), the means were either significantly larger or smaller than the 1930-98 average. Thus, realistic patterns emerge only if the whole 69-year period is considered.

3.1.2.4 Multidecadal Isohyetal Trend Determination

The next focus is on multidecadal analyses of rainfall using the mean value of annual rainfall index/totals. The decades of 1930s, 1940s, 1950s, 1960s, 1970s, 1980s, and 1990s are used for the study period extending from 1930-98. Note that 9 (rather than 10) years constitute the decade of the 1990s. These decades happen to coincide with Central West African decadal rainfall regime changes and were chosen to document in detail the rainfall trends that are characterized by five major features -- high rainfall in the

1930s, low rainfall in the 1940s, abundant rainfall in the 1950s, drought in the late 1960s and early 1970s, and decreased rainfall in the 1980s and 1990s (Figs. 2.2 and 4.3) -- in spite of extreme wet (e.g., 1943, 1950, 1969, 1975, 1988, 1994, 1998) and dry (e.g., 1949, 1968, 1972, 1977, 1982-1984, 1990) individual years that have sometimes been observed within the decadal time-scale trends (e.g., Lamb, 1978a,b, 1982, 1985; Nicholson, 1982, 1998; Lamb and Peppler, 1991, 1992; Servat et al., 1997; Ward et al., 1999). Further, the inspection of the complete time series for 1930-98 verified that the use of these standard decades captured the interannual and decadal trends. For each of the seven decades, the isohyets are computed and plotted to depict their inter-decadal movements or shifts that show where and when the isohyets have migrated during these recent decades. Special attention is paid to the positional changes in the 250 mm, 500 mm, 750 mm, 1,000 mm, 1,250 mm, and 1,500 mm annual isohyets, since they are the annual average amounts of rainfall (i.e., threshold values) that are considered important for the growth of most of the crops treated in Sections 4.2 and 4.3.

3.1.2.5 Monthly and Daily Rainfall Analyses

As for the annual totals, the mean monthly rainfall totals, together with their standard deviations, maxima, and minima are computed from the daily rainfall data. Histograms showing the long-term average rainfall regimes explain the average monthly rainfall variability as well as the average contributions of each month to the yearly totals. The month-to-month patterns are analyzed to verify whether they vary between decades. This monthly analysis also displays the spatial distribution of monthly rainfall that indicates the role of each month for plant growth and development, as well as agricultural practices.

Daily rainfall records, on the other hand, are very large with a variety of uses. Here, the issues that are important in planning agricultural operations, such as plowing, planting, weeding, and harvesting are considered. In other words, plans for cropping strategies should be consistent with rainfall patterns and planting times should be adjusted to the probable rainfall so that stages of crop growth do not synchronize with periods of limited rainfall. Thus, the number of yearly, seasonal, and monthly rain days are determined and mapped. Rain days verify crop capacity to support days with no rains, decide on supplementary irrigation, and provide bases for long-term cropping strategies (Sivakumar, 1992). Conventionally, meteorological offices across the study area suggest 0.1 mm of rain day^{-1} as a rain day criterion (Stern et al., 1982; Sharma, 1996), but agricultural considerations require higher thresholds such as 0.85 mm, 2 mm, 5 mm, or 10 mm of rain day^{-1} to identify useful rains (Mollah and Cook, 1996). This Dissertation retains 0.1 mm threshold to determine the rain days and their distributions throughout Central West Africa. Further, daily rainfall data are explored to describe any changes in the start and end of the rains.

3.1.2.6 Onset and Cessation of the Rainy Seasons

With the strong rainfall variability, "the period of agronomically useful rainfall must be defined in order to consider the social and economic value of the annual rains" (Hess et al., 1995, p. 89). The rainy season onset/end is the time when there is a sudden increase/decrease in daily rainfall values. Several criteria exist to define the onset, cessation, and even false starts of the Central West African rainy seasons. Table 3.4, adapted from Hess et al. (1995, p. 90), summarizes these criteria:

Table 3.4: Definitions for onset, end, and "false start" (conditional upon the criteria for onset having been met) of rains. ET_p= potential evapotranspiration (Hess et al., 1995, p. 90).

Author	Criteria for Onset	Criteria for False Start	Criteria for End
Benoit (1977)	Rainfall of at least 0.5 ET_p over any period [presumab1y one or few days]	5 dry days immediately following [presumab1y the onset date]	None given
Kowal and Kassam (1978)	Rainfall at least 25 mm in 10 days	Rainfall less than 0.5 ET_p in the next 10 days	The last 10 day period with at least 12.5 mm of rain provided that rainfall in the preceding 10 days exceeded ET_p
Stern et al. (1982)	Rainfall at least 20 mm in 2 days	10 dry days in the following 30 [presumab1y days]	No rainfall in 15 days
Sivakumar (1988)	Rainfall at least 20 mm in 3 days	7 dry days in the next 30 [presumab1y days]	No rainfall in 20 days

Each of these rainy season onset/cessation definitions (Table 3.4) has been used in previous work as shown by Hess et al. (1995, p. 89) who concluded that "the method of Kowal and Kassam (1978) was devised for decadal (10-day) rainfall totals and is, therefore, less appropriate where daily data are available, and the method of Benoit refers more explicitly to 'growing' season rather than 'rainy' season." With the above conclusions in mind, and based on the climatic location of the study area as well as the data available (i.e., daily rainfall), the Stern et al. (1982) and the Sivakumar (1988) criteria for onset, "false start", and cessation of rains are employed in this study. "The duration of the rainy season was taken as the difference between the end and start of rains" (Hess et al., 1995, p. 89). Overall, the primary purpose of Central West African rainfall analyses (including missing data analysis, PCA, annual rainfall index/totals, multidecadal isohyetal trend determination, monthly rainfall patterns, number of rain days per year/season/month, and the determination of the rainy season onset/cessation dates) is to provide information relevant to the agriculture. Thus, data for major crops in the study area were developed and thoroughly examined.

3.2 Crop Data and Applied Methodology

Research Objective II: To detect and assess the extent to which crop acreage and production, and the impacts of rainfall variations, are valuable indicators of agricultural change. This second objective requires investigations of these three components:

- Verify that crop data display spatial and temporal variations and determine if cash crops show greater variability in acreage/production/yields than staple crops;
- Examine whether production increases are more related to acreage increases than to yield increases (i.e., where/when have the acreages of particular crops been enlarged?); and
- Analyze how agricultural changes depict impacts of rainfall variability (i.e., do variations in rain-fed agriculture, especially yields, indicate wetter/drier region?).

3.2.1 Crop Data

Visiting the headquarters of each country's Division des Statistiques Agricoles (DSA) within the Ministry of Agriculture helped the collection of crop data for Mali (M), Burkina Faso (BF), and Côte d'Ivoire (CI). This yielded data for 1984-98 for M/BF and late 1940s-early 1950s to mid-1980s for CI. The records for the remaining years (late 1960s to 1984 for M/BF and mid-1980s to 1998 for CI) were obtained on another visit by research at the headquarters of related agricultural services such as the AGHRYMET Center (Niamey) for M/BF crop data and, for CI crop data, the Agence Nationale d'Appui au Dévelopment Rural (ANADER), Caisse de Stabilisation et de Soutien des Prix des Productions Agricoles (CSSPPA), and Projet National Riz (PNR), all of which are located in Abidjan. These data comprised annual acreage and production records for both cash and staple crops across Central West African village, district, and regional subdivision levels. Yields were then derived from acreage and production values.

After compiling the above figures, it became evident that the crop data for Mali and Burkina Faso started in the late 1960s-early 1970s, while those for Côte d'Ivoire began earlier (late 1940s-early 1950s). Crop data estimations in these countries uncovered different reasons as to the importance of crop data inventories. Data for Mali/Burkina Faso have been more complete since 1984, when acreage and production estimates were based on systematic surveys at the village/district levels, which were then aggregated for each region and finally for the whole country. Earlier data for these two countries may be less reliable because they were estimated through the monitoring of the governmental self-sufficient food security goals (e.g., Pouchepadass, 1993; AGHRYMET, 1997; Ministère de l'Agriculture, 1998). Indeed, difficult economic conditions and declining land productivity in Mali/Burkina Faso (made worse by prolonged and sometimes-severe drought), have constrained their governments to estimate crop data, especially production, in order to monitor the annual crop productivity and design development policy. Since there is no evidence of any discontinuity in the crop time series for Mali/Burkina Faso, all available records were used here. In Côte d'Ivoire, the recording of crop data by the Ministry of Agriculture started in the late 1940s and early 1950s, but stopped in 1984 due to economic crises, with the drop of cash crop prices as well as the remote consequences of Sahelian drought (e.g., 1982-84 crop failures and bush fires). Since then, the Ivorian Ministry of Agriculture has not recorded any substantial data. So the missing years (especially after mid-1980s) were completed by the aforementioned related agricultural agencies (i.e., AGHRYMET Center, ANADER, CSSPPA, PNR), which unfortunately did not cover all of the selected crops because each institute focused on only the specific crops for which it was responsible. Thus, the compilation of crop record for Côte d'Ivoire post-1984 provided the opportunity for this study to pull all of these data together into long successive records (i.e., completeness/length) for this country.

The acquisition and combination of the above two sets of crop data for this study brought substantial improvement to crop records for Mali, Burkina Faso, and Côte d'Ivoire. Already, requests for the data have been received from Ministries of Agriculture and related agricultural services in the study area. Therefore, this Dissertation has produced the best available crop data set for Central West Africa.

3.2.1.1 Agricultural Regions for Central West Africa

There are 27 administrative regions in Central West Africa that comprise villages and districts for which agricultural data were collected and made available (Ministère de l'Agriculture et des Eaux et Forêts, 1984; Ministère de l'Environnement et du Tourisme, 1994; Ministère de l'Environnement, 1997). These 27 administrative regions are the agricultural subdivisions (Table 3.5 and Fig. 3.3) for which crop data were aggregated and

Table 3.5: Agricultural regions and their abbreviations in Central West Africa. Those asterisked are focuses of analysis in Chapter 4. See Figure 3.3 for locations of crop regions.

Mali (7 regions)	Burkina Faso (10 regions)	Côte d'Ivoire (10 regions)
Gao (G)	Center (Ca)*	Center (Cb)*
Kayes (Ky)*	Central-east (CEa)	Central-east (CEb)
Koulikoro (Ko)*	Central-north (CNa)	Central-north (CNb)
Mopti (Mb)	Central-west (CWa)	Central-west (CWb)*
Segou (Su)*	East (E)*	North (Nb)
Sikasso (So)*	Haut-Bassin (HB)*	Northeast (NE)
Tombouctou (T)	Mouhoun (Ma)*	Northwest (NW)
	North (Na)	South (Sb)*
	Sahel (Sa)	Southwest (SWb)
	Southwest (SWa)	West (W)*

Figure 3.3: Agricultural regions in Central West Africa. Côte d'Ivoire is darkly shaded, Mali is lightly shaded, and Burkina Faso is unshaded (top). See Table 3.4 for full names of crop regions; those hatched are focuses of analysis in Chapter 4 (bottom).

analyzed in Section 4.2. Within Mali, national authorities aggregated crop acreage and production at a regional level, while those of Burkina Faso and Côte d'Ivoire were obtained at village/district levels. Thus, the Burkinabè and Ivorian data were rearranged and aggregated at regional levels in this Dissertation as part of the agricultural analyses.

3.2.1.2 Crop Data and Missing Values Assessment

Tables 3.6*a*-*c* summarize the availability of cash crop data by region for this study. Only the three major cash crops are treated for each country.

Table 3.6*a*: Data for individual cash crops in each of the seven agricultural regions of Mali. A = acreage, P = production, and years in parentheses indicate periods covered. See Figure 3.3 for locations of crop regions.

YEAR OF AVAILABLE DATA			
Region	**Cotton (A, P = 1966-97)**	**Peanuts (A, P = 1966-97)**	**Sugarcane (A, P = 1984-97)**
Gao (G)	**A** = No data available **P** = 1966,71	**A** = 1966,68 **P** = 1966,69,71	Not grown
Kayes (Ky)	**A** =1966,68,84-85,92,94-97 **P** = 1966-69,78,92-97	**A** = 1966-68,84-97 **P** = 1966-69,71-72,74,76-78, 80-82,84-97	**A** = 1987-88 **P** = No data available
Koulikoro (Ko)	**A** = 1966-68,84-97 **P** = 1966-69,71-72,74,76, 78,81-82,84-97	**A** = 1966-68,84-97 **P** = 1966-69,71-72,74,76-78, 80-82,84-97	**A** = 1985,87-88,91 **P** = No data available
Mopti (Mb)	**A** = 1966-68,84 **P** = 1966-69,71-72,76,78	**A** = 1966-68,84-97 **P** = 1966-69,71-72,74,76-78, 80-82,84-97	Not grown
Segou (Su)	**A** = 1966-68,84-97 **P** = 1966-69,71-72,74,76,78, 81-82,84-97	**A** = 1966-68,84-97 **P** = 1966-69,71-72,74,76-78, 80-82,84-97	**A** = 1984-97 **P** =1984-97
Sikasso (So)	**A** = 1966-68,84-97 **P** = 1966-69,71-72,74,76,78, 81-82,84-97	**A** = 1966-68,84-97 **P** = 1966-69,71-72,74,76-78, 80-82,84-97	**A** = 1984,88-91 **P** = 1989
Tombouctou (T)	Not grown	**A** = 1984,86-90 **P** = 1988-90	Not grown
YEAR OF MISSING DATA			
Region	**Cotton (A, P = 1966-97)**	**Peanuts (A, P = 1966-97)**	**Sugarcane (A, P = 1984-97)**
Gao (G)	**A** = No data available **P** = 1967-70,72-97	**A** = 1967,69-97 **P** = 1967-68,70,72-97	Not grown
Kayes (Ky)	**A** = 1967,69-83,86-91,93 **P** = 1970-77,79-91	**A** = 1969-83 **P** = 1970,73,75,79,83	**A** = 1984-86,89-97 **P** = No data available
Koulikoro (Ko)	**A** = 1969-83 **P** = 1970,73,75,77,79-80,83	**A** = 1969-83 **P** = 1970,73,75,79,83	**A** = 1984,86,89-90,92-97 **P** = No data available
Mopti (Mb)	**A** = 1969-83,85-97 **P** = 1970,73-75,77,79-97	**A** = 1969-83 **P** = 1970,73,75,79,83	Not grown
Segou (Su)	**A** = 1969-83 **P** = 1970,73,75,77,79-80,83	**A** = 1969-83 **P** = 1970,73,75,79,83	No missing years
Sikasso (So)	**A** = 1969-83 **P** = 1970,73,75,77,79-80,83	**A** = 1969-83 **P** = 1970,73,75,79,83	**A** = 1985-87,92-97 **P** = 1984-88,90-97
Tombouctou (T)	Not grown	**A** = 1966-83,85,91-97 **P** = 1966-87,91-97	Not grown

Table 3.6*b*: Data for individual cash crops in each of the ten agricultural regions of Burkina Faso. A = acreage, P = production, and years in parentheses indicate periods covered. See Figure 3.3 for locations of crop regions.

YEAR OF AVAILABLE DATA			
Region	**Cotton (A, P = 1970-98)**	**Peanuts (A, P = 1970-98)**	**Soybeans (A, P = 1985-98)**
Center (Ca)	**A** = 1970-71,75-81,84-93, 95-98 **P** = 1970-82,84-93,95-98	**A** = 1970-98 **P** = 1970-98	**A** = 1985-88,90,92-98 **P** = 1985-88,93-98
Central-east (CEa)	**A** = 1970-71,75-80,84-89, 91-93,95-98 **P** = 1979,84-89,93,95-98	**A** = 1970-98 **P** = 1970-79,81-98	**A** = 1985-89,91-98 **P** = 1985-89,93-98
Central-north (CNa)	**A** = 1970-71,75-81,84-93,95-98 **P** = 1970-82,84-89,91-93,95-98	**A** = 1970-98 **P** = 1970-71,73-98	**A** = 1985-86 **P** = 1985-86
Central-west (CWa)	**A** = 1970-71,75-81,84-98 **P** = 1970-82,84-98	**A** = 1970-98 **P** = 1970-98	**A** = 1986,93,95,97-98 **P** = 1986,93,95-98
East (E)	**A** = 1970-71,75-81,85-86, 88-93,95-98 **P** = 1971-74,77,79-81,85-86, 88-93,95-98	**A** = 1970-79,81,84-86,88-98 **P** = 1970-79,81,83-86,88-98	**A** = 1985-86,88-98 **P** = 1985-86,88-89,93-98
Haut-Bassin (HB)	**A** = 1970-71,75-81,84-98 **P** = 1970-82,84-98	**A** = 1970-98 **P** = 1970-98	**A** = 1985-89,93,95-98 **P** = 1985-89,93,95-98
Mouhoun (Ma)	**A** = 1970-71,75-81,84-98 **P** = 1970-82,84-98	**A** = 1970-84,87-98 **P** = 1970-84,87-98	**A** = 1987-88,90,92-93,95-98 **P** = 1987-88,93,95-98
North (Na)	**A** = 1970-71,85-89,91-93,95-98 **P** = 1970,78,85-89,93,95-98	**A** = 1970-79,81-98 **P** = 1970-79,81-98	**A** = No data available **P** = 1993,96,98
Sahel (Sa)	**A** = 1976,93 **P** = 1993,96	**A** = 1970-73,75-79,82-86,88-98 **P** = 1970-73,75-79,81-83, 85-86,88-98	**A** = 1990 **P** = 1993
Southwest (SWa)	**A** = 1970-71,75-81,84-98 **P** = 1970-82,84-98	**A** = 1970-98 **P** = 1970-98	**A** = 1986-89,93,95-98 **P** = 1986-89,93,95-98
YEAR OF MISSING DATA			
Region	**Cotton (A, P = 1970-98)**	**Peanuts (A, P = 1970-98)**	**Soybeans (A, P = 1985-98)**
Center (Ca)	**A** = 1972-74,82-83,94 **P** = 1983,94	No missing years	**A** = 1989,91 **P** = 1989-92
Central-east (CEa)	**A** = 1972-74,81-83,90,94 **P** = 1970-78,80-83,90-92,94	**A** = No missing years **P** = 1980	**A** = 1990 **P** = 1990-92
Central-north (CNa)	**A** = 1972-74,82-83,94 **P** = 1983,90,94	**A** = No missing years **P** = 1972	**A** = 1987-98 **P** = 1987-98
Central-west (CWa)	**A** = 1972-74,82-83 **P** = 1983	No missing years	**A** = 1985,87-92,94,96 **P** = 1985,87-92,94
East (E)	**A** = 1972-74,82-84,87,94 **P** = 1970,75-76,78,82-84,87, 94	**A** = 1980,82-83,87 **P** = 1980,82,87	**A** = 1987 **P** = 1987,90-92
Haut-Bassin (HB)	**A** = 1972-74,82-83 **P** = 1983	No missing years	**A** = 1990-92,94 **P** = 1990-92,94
Mouhoun (Ma)	**A** = 1972-74,82-83 **P** = 1983	**A** = 1985-86 **P** = 1985-86	**A** = 1985-86,89,91,94 **P** = 1985-86,89-92,94
North (Na)	**A** = 1972-84,90,94 **P** = 1971-77,79-84,90-92,94	**A** = 1980 **P** = 1980	**A** = No data available **P** = 1985-92,94-95,97
Sahel (Sa)	**A** = 1970-75,77-92,94-98 **P** = 1970-92,94-95,97-98	**A** = 1974,80-81,87 **P** = 1974,80,84,87	**A** = 1985-89,91-98 **P** = 1985-92,94-98
Southwest (SWa)	**A** = 1972-74,82-83 **P** = 1983	No missing years	**A** = 1985,90-92,94 **P** = 1985,90-92,94

Table 3.6*c*: Data for individual cash crops in each of the ten agricultural regions of Côte d'Ivoire. A = acreage, P = production, and years in parentheses indicate periods covered. See Figure 3.3 for locations of crop regions.

YEAR OF AVAILABLE DATA			
Region	**Cocoa (A= 1948-98 P= 1959-98)**	**Coffee (A= 1950-98 P= 1959-98)**	**Cotton (A= 1951-98 P= 1950-98)**
Center (Cb)	**A** = 1948,50-82,96-98 **P** = 1959-98	**A** = 1950-82,96-98 **P** = 1959-98	**A** = 1964-98 **P** = 1964-98
Central-east (CEb)	**A** = 1948,50-90,96-98 **P** = 1959-98	**A** = 1950-90,96-98 **P** = 1959-98	**A** = 1991,93-96 **P** = 1991,93-96
Central-north (CNb)	**A** = 1948,50-82,96-98 **P** = 1959-98	**A** = 1950-82,96-98 **P** = 1959-88,90-98	**A** = 1951,53-54,56-58, 64-98 **P** = 1950-58,64-98
Central-west (CWb)	**A** = 1948,50-90,96-98 **P** = 1959-98	**A** = 1950-90,96-98 **P** = 1959-98	**A** = 1964-98 **P** = 1964-98
North (Nb)	Not grown	Not grown	**A** = 1951-54,56-58,64-98 **P** = 1950-58,64-98
Northeast (NE)	**A** = 1948,50-82,96-98 **P** = 1959-98	**A** = 1950-82,96-98 **P** = 1959-98	**A** = 1984-98 **P** = 1955-56,84-98
Northwest (NW)	**A** = 1955-58,69-73,96-98 **P** = 1964-77,96-98	**A** = 1950-82,96-98 **P** =1959-86,96-98	**A** = 1951-54,56-58,64-98 **P** =1950-58,64-98
South (Sb)	**A** = 1948,50-90,96-98 **P** = 1959-98	**A** = 1950-90,96-98 **P** = 1959-98	**A** = 1978-87,90,93-98 **P** = 1978-87,90,93-98
Southwest (SWb)	**A** = 1948,50-53,55-90,96-98 **P** = 1959-98	**A** = 1950-90,96-98 **P** = 1959-98	Not grown
West (W)	**A** = 1948,50-53,55-90,96-98 **P** = 1959-98	**A** = 1950-90,96-98 **P** = 1959-98	**A** = 1991,93-96 **P** = 1955-58,91,93-96
YEAR OF MISSING DATA			
Region	**Cocoa (A= 1948-98 P= 1959-98)**	**Coffee (A= 1950-98 P= 1959-98)**	**Cotton (A= 1951-98 P= 1950-98)**
Center (Cb)	**A** = 1949,83-95 **P** = No missing years	**A** = 1983-95 **P** = No missing years	**A** = 1951-63 **P** = 1950-63
Central-east (CEb)	**A** = 1949,91-95 **P** = No missing years	**A** = 1991-95 **P** = No missing years	**A** = 1951-90,92,97-98 **P** = 1950-90,92,97-98
Central-north (CNb)	**A** = 1949,1983-95 **P** = No missing years	**A** = 1983-95 **P** = 1989	**A** = 1952,55,59-63 **P** = 1959-63
Central-west (CWb)	**A** = 1949,91-95 **P** = No missing years	**A** = 1991-95 **P** = No missing years	**A** = 1951-63 **P** =1950-63
North (Nb)	Not grown	Not grown	**A** = 1955,59-63 **P** = 1959-63
Northeast (NE)	**A** = 1949,83-95 **P** = No missing years	**A** = 1983-95 **P** = No missing years	**A** = 1951-83 **P** = 1950-54,57-83
Northwest (NW)	**A** = 1948-54,59-68,74-95 **P** = 1959-63,78-95	**A** = 1983-95 **P** = 1987-95	**A** = 1955,59-63 **P** = 1959-63
South (Sb)	**A** = 1949,91-95 **P** = No missing years	**A** = 1991-95 **P** = No missing years	**A** = 1951-77,88-89,91-92 **P** = 1950-77,88-89,91-92
Southwest (SWb)	**A** = 1949,54,91-95 **P** = No missing years	**A** = 1991-95 **P** = No missing years	Not grown
West (W)	**A** = 1949,54,91-95 **P** = No missing years	**A** = 1991-95 **P** = No missing years	**A** = 1951-90,92,97-98 **P** = 1950-54,59-90,92, 97-98

Conversely, Tables 3.7*a-c* present the data availability for the staple crops of the study region. Here also, only the four major staple crops are treated for each country.

Table 3.7*a*: Data for individual staple crops in each of the seven agricultural regions of Mali. A = acreage, P = production, and years in parentheses indicate periods covered. See Figure 3.3 for locations of crop regions.

YEAR OF AVAILABLE DATA				
Region	**Maize (A, P = 1966-98)**	**Millet (A = 1984-98 P = 1967-98)**	**Rice (A, P = 1966-98)**	**Sorghum (A = 1984-98 P = 1967-98)**
Gao (G)	**A** = 1975,77-78 **P** = 1966,69,75	**A** = 1985-98 **P** = 1967-69,71-72, 74-78,85,88,90-98	**A** =1966-68,75-98 **P** = 1966-69,71-72, 74-98	**A** = 1984-98 **P** = 1967-69,71-72, 74,76-78,80,84-98
Kayes (Ky)	**A** = 1966-68,75-98 **P** = 1966-69,71-72, 74-98	**A** = 1984-98 **P** = 1967-69,71-72, 74-78,80-82,84-98	**A** = 1966-68,75-98 **P** =1966-69,71-72, 74-87,90-98	**A** = 1984-98 **P** =1967-69,71-72, 74,76-78,80-82,84-98
Koulikoro (Ko)	**A** = 1966-68,75-98 **P** = 1966-69,71-72, 74-98	**A** = 1984-98 **P** = 1967-69,71-72, 74-78,80-82,84-98	**A** =1966-68,76-98 **P** = 1966-69,71-72, 74-79,81-98	**A** = 1984-98 **P** =1967-69,71-72, 74,76-78,80-82,84-98
Mopti (Mb)	**A** = 1966-68,75-98 **P** = 1966-69,71-72, 74-77,79,81-83,86-87, 89-98	**A** = 1984-98 **P** = 1967-69,71-72, 74-78,80-82,84-98	**A** = 1966-68,75-98 **P** =1966-69,71-72, 74-98	**A** = 1984-98 **P** =1967-69,71-72, 74,76-78,80-82,84-98
Segou (Su)	**A** = 1966-68,75-98 **P** = 1966-69,71-72, 74-98	**A** = 1984-98 **P** = 1967-69,71-72, 74-78,80-82,84-98	**A** = 1966-68,75-98 **P** =1966-69,71-72, 74-98	**A** = 1984-98 **P** = 1967-69,71-72, 74,76-78,80-82,84-98
Sikasso (So)	**A** = 1966-68,75-98 **P** = 1966-69,71-72, 74-98	**A** = 1984-98 **P** = 1967-69,71-72, 74-78,80-82,84-98	**A** = 1966-68,75-98 **P** =1966-69,71-72, 74-98	**A** = 1984-98 **P** =1967-69,71-72, 74,76-78,80-82,84-98
Tombouctou (T)	**A** = 1983,94,96,98 **P** = 1998	**A** = 1984-98 **P** = 1980-82,84-98	**A** = 1979-98 **P** =1979-80,82-98	**A** = 1984-98 **P** =1980-82,84-98
YEAR OF MISSING DATA				
Region	**Maize (A, P = 1966-98)**	**Millet (A = 1984-98 P = 1967-98)**	**Rice (A, P = 1966-98)**	**Sorghum (A = 1984-98 P = 1967-98)**
Gao (G)	**A** = 1966-74,76,79-98 **P** = 1967-68,70-74, 76-98	**A** = 1984 **P** = 1970,73,79-84, 86-87,89	**A** = 1969-74 **P** = 1970,73	**A** = No missing years **P** = 1970,73,75,79, 81-83
Kayes (Ky)	**A** = 1969-74 **P** = 1970,73	**A** = No missing years **P** = 1970,73,79,83	**A** = 1969-74 **P** = 1970,73,88-89	**A** = No missing years **P** = 1970,73,75,79,83
Koulikoro (Ko)	**A** = 1969-74 **P** = 1970,73	**A** = No missing years **P** = 1970,73,79,83	**A** = 1969-75 **P** = 1970,73,80	**A** = No missing years **P** = 1970,73,75,79,83
Mopti (Mb)	**A** = 1969-74 **P** = 1970,73,78,80, 84-85,88	**A** = No missing years **P** = 1970,73,79,83	**A** = 1969-74 **P** = 1970,73	**A** = No missing years **P** = 1970,73,75,79,83
Segou (Su)	**A** = 1969-74 **P** = 1970,73	**A** = No missing years **P** = 1970,73,79,83	**A** = 1969-74 **P** = 1970,73	**A** = No missing years **P** = 1970,73,75,79, 83
Sikasso (So)	**A** = 1969-74 **P** = 1970,73	**A** = No missing years **P** = 1970,73,79,83	**A** = 1969-74 **P** = 1970,73	**A** = No missing years **P** = 1970,73,75,79,83
Tombouctou (T)	**A** = 1966-82,84-93, 95,97 **P** = 1966-97	**A** = No missing years **P** = 1967-79,83	**A** = 1966-78 **P** = 1966-78,81	**A** = No missing years **P** = 1967-79,83

Table 3.7*b*: Data for individual staple crops in each of the ten agricultural regions of Burkina Faso. A = acreage, P = production, and years in parentheses indicate periods covered. See Figure 3.3 for locations of crop regions.

YEAR OF AVAILABLE DATA				
Region	**Maize (A, P = 1970-98)**	**Millet (A, P = 1970-98)**	**Rice (A, P = 1970-98)**	**Sorghum (A, P = 1970-98)**
Center (Ca)	**A** = 1970-73,76-98 **P** = 1970-73,76-98	**A** = 1970-72,76-98 **P** = 1970-72,76-98	**A** = 1970-82,84-98 **P** = 1970-98	**A** = 1970-72,76-98 **P** = 1970-72,76-98
Central-east (CEa)	**A** = 1970-73,76-98 **P** = 1970-73,76-98	**A** = 1970-72,76-98 **P** = 1970-72,76-98	**A** = 1970-73,75-82, 84-98 **P** = 1970-98	**A** = 1970-72,76-98 **P** = 1970-72,76-98
Central-north (CNa)	**A** = 1970-73,76-98 **P** = 1970-73,76-98	**A** = 1970-72,76-98 **P** = 1970-72,76-98	**A** = 1970-82,84-98 **P** = 1970-82,84-98	**A** = 1970-72,76-98 **P** = 1970-72,76-98
Central-west (CWa)	**A** = 1970-73,76-98 **P** = 1970-73,76-98	**A** = 1970-72,76-98 **P** = 1970-72,76-98	**A** = 1970-82,84-98 **P** = 1970-82,84-98	**A** = 1970-72,76-98 **P** = 1970-72,76-98
East (E)	**A** = 1970-73,76-98 **P** = 1970-73,76,78-79, 81-98	**A** = 1970-72,76-98 **P** = 1970-72,76-98	**A** = 1970-82,84-98 **P** = 1970-98	**A** = 1970-72,76-98 **P** = 1970-72,76-98
Haut-Bassin (HB)	**A** = 1970-73,76-98 **P** = 1970-73,76-98	**A** = 1970-72,76-98 **P** = 1970-72,76-98	**A** = 1970-82,84-98 **P** = 1970-98	**A** = 1970-72,76-98 **P** = 1970-72,76-98
Mouhoun (Ma)	**A** = 1970-73,76-98 **P** = 1970-73,76-98	**A** = 1970-72,76-98 **P** = 1970-72,76-98	**A** = 1970-82,84-98 **P** = 1970-98	**A** = 1970-72,76-98 **P** = 1970-72,76-98
North (Na)	**A** = 1970,76-79,81-98 **P** = 1970,76-78,81-98	**A** = 1970-72,76-98 **P** = 1970-72,76-98	**A** = 1970,76-79, 81-82,84-98 **P** =1970-71,74-98	**A** = 1970-72,76-98 **P** = 1970-72,76-98
Sahel (Sa)	**A** = 1970,78-86,88-98 **A** = 1970,78-86,88-98	**A** = 1970-72,76-98 **P** = 1970-72,76-98	**A** = 1979,81,84-88, 93,95-98 **P** = 1979-80,83-88, 93,95-98	**A** = 1970-72,76-98 **P** = 1970-72,76-98
Southwest (SWa)	**A** = 1970-73,76-98 **P** = 1970-73,76-98	**A** = 1970-72,76-98 **P** = 1970-72,76-98	**A** = 1970-82,84-98 **P** = 1970-98	**A** = 1970-72,76-98 **P** = 1970-72,76-98
YEAR OF MISSING DATA				
Region	**Maize (A, P = 1970-98)**	**Millet (A, P = 1970-98)**	**Rice (A, P = 1970-98)**	**Sorghum (A, P = 1970-98)**
Center (Ca)	**A** = 1974-75 **P** = 1974-75	**A** = 1973-75 **P** = 1973-75	**A** = 1983 **P** = No missing years	**A** = 1973-75 **P** = 1973-75
Central-east (CEa)	**A** = 1974-75 **P** = 1974-75	**A** = 1973-75 **P** = 1973-75	**A** = 1974,83 **P** = No missing years	**A** = 1973-75 **P** = 1973-75
Central-north (CNa)	**A** = 1974-75 **P** = 1974-75	**A** = 1973-75 **P** = 1973-75	**A** = 1983 **P** = 1983	**A** = 1973-75 **P** = 1973-75
Central-west (CWa)	**A** = 1974-75 **P** = 1974-75	**A** = 1973-75 **P** = 1973-75	**A** = 1983 **P** = 1983	**A** = 1973-75 **P** = 1973-75
East (E)	**A** = 1974-75 **P** = 1974-75,77,80	**A** = 1973-75 **P** = 1973-75	**A** = 1983 **P** = No missing years	**A** = 1973-75 **P** = 1973-75
Haut-Bassin (HB)	**A** = 1974-75 **P** = 1974-75	**A** = 1973-75 **P** = 1973-75	**A** = 1983 **P** = No missing years	**A** = 1973-75 **P** = 1973-75
Mouhoun (Ma)	**A** = 1974-75 **P** = 1974-75	**A** = 1973-75 **P** = 1973-75	**A** = 1983 **P** = No missing years	**A** = 1973-75 **P** = 1973-75
North (Na)	**A** = 1971-75,80 **P** = 1971-75,79-80	**A** = 1973-75 **P** = 1973-75	**A** = 1971-75,80,83 **P** = 1972-73	**A** = 1973-75 **P** = 1973-75
Sahel (Sa)	**A** = 1971-77,87 **P** = 1971-77,87	**A** = 1973-75 **P** = 1973-75	**A** = 1970-78,80,82-83,89-92,94 **P** = 1970-78,81-82, 89-92,94	**A** = 1973-75 **P** = 1973-75
Southwest (SWa)	**A** = 1974-75 **P** = 1974-75	**A** = 1973-75 **P** = 1973-75	**A** = 1983 **P** = No missing years	**A** = 1973-75 **P** = 1973-75

Table 3.7*c*: Data for individual staple crops in each of the ten agricultural regions of Côte d'Ivoire. A = acreage, P = production, and years in parentheses indicate periods covered. See Figure 3.3 for locations of crop regions.

YEAR OF AVAILABLE DATA				
Region	**Maize (A, P = 1949-98)**	**Plantain (A, P = 1948-98)**	**Rice (A, P = 1947-98)**	**Yams (A, P = 1948-98)**
Center (Cb)	**A** = 1949-58,65-84, 96-98 **P** = 1949-83,96-98	**A** = 1948-58,75-84, 96-98 **P** = 1953-83,96-98	**A** = 1947-58,65-84, 96-98 **P** = 1947-84,96-98	**A** = 1948-58,65-84, 96-98 **P** = 1948-83,96-98
Central-east (CEb)	**A**=1949-58,65-84,96-98 **P**= 1949-52,54-83,96-98	**A**= 1948-58,75-84,96-98 **P** = 1948-83,96-98	**A**= 1947-58,65-84,96-98 **P** = 1947-84,96-98	**A**= 1948-58,65-84,96-98 **P** = 1948-83,96-98
Central-north (CNb)	**A**=1949-58,65-84,96-98 **P** = 1949-83,96-98	**A** = 1975-84,96-98 **P**= 1948-52,59-83,96-98	**A**=1947-58,65-84,96-98 **P** = 1947-84,96-98	**A**=1948-58,65-84,96-98 **P** = 1948-83,96-98
Central-west (CWb)	**A**=1949-58,65-84,96-98 **P** = 1949-83,96-98	**A**=1948-58,75-84,96-98 **P** = 1948-83,96-98	**A**=1947-58,65-84,96-98 **P** = 1947-84,96-98	**A**=1948-58,65-84,96-98 **P** = 1948-83,96-98
North (Nb)	**A** = 1949-56,58,65-84, 96-98 **P** = 1949-83,96-98	**A** = 1953-54,58 **P** =1953-54,58	**A** = 1947-58,65-84, 96-98 **P** = 1947-84,96-98	**A** = 1948-58,65-84, 96-98 **P** = 1948-83,96-98
Northeast (NE)	**A**= 1950-56,58,65-84, 96-98 **P** = 1950-56,58-83, 96-98	**A** = 1948-58,75-84, 96-98 **P** = 1948-83,96-98	**A** = 1947-58,65-84, 96-98 **P**= 1949-55,57-84,96-98	**A** = 1948-58,65-84, 96-98 **P** = 1948-83,96-98
Northwest (NW)	**A** = 1949-58,65-84, 96-98 **P** = 1949-83,96-98	**A** = 1996-98 **P** = 1959-77,96-98	**A** = 1947-58,65-84, 96-98 **P** = 1947-84,96-98	**A** = 1948-58,65-84, 96-98 **P** = 1948-83,96-98
South (Sb)	**A**=1949-58,65-84,96-98 **P** = 1949-83,96-98	**A**=1948-58,75-84,96-98 **P** = 1948-83,96-98	**A**=1947-58,65-84,96-98 **P** = 1947-84,96-98	**A**=1948-58,65-84,96-98 **P** = 1948-83,96-98
Southwest (SWb)	**A**=1949-58,65-84,96-98 **P** = 1949-83,96-98	**A**=1948-58,75-84,96-98 **P** = 1948-83,96-98	**A**=1947-58,65-84,96-98 **P** = 1947-84,96-98	**A**=1948-58,65-84,96-98 **P** = 1948-83,96-98
West (W)	**A** = 1949-58,65-84, 96-98 **P** = 1949-83,96-98	**A** = 1948-58,75-84, 96-98 **P** = 1948-83,96-98	**A** = 1947-58,65-84, 96-98 **P** = 1947-84,96-98	**A** = 1948-58,65-68, 71-73,75-84,96-98 **P** = 1948-58,60-68, 70-72,74-83,96-98
YEAR OF MISSING DATA				
Region	**Maize (A, P = 1949-98)**	**Plantain (A, P = 1948-98)**	**Rice (A, P = 1947-98)**	**Yams (A, P = 1948-98)**
Center (Cb)	**A** = 1959-64,85-95 **P** = 1984-95	**A** = 1959-74,85-95 **P** = 1948-52,84-95	**A** = 1959-64,85-95 **P** = 1985-95	**A** = 1959-64,85-95 **P** = 1984-95
Central-east (CEb)	**A** = 1959-64,85-95 **P** = 1953,84-95	**A** = 1959-74,85-95 **P** = 1984-95	**A** = 1959-64,85-95 **P** = 1985-95	**A** = 1959-64,85-95 **P** = 1984-95
Central-north (CNb)	**A** = 1959-64,85-95 **P** = 1984-95	**A** = 1948-74,85-95 **P** = 1953-58,84-95	**A** = 1959-64,85-95 **P** = 1985-95	**A** = 1959-64,85-95 **P** = 1984-95
Central-west (CWb)	**A** = 1959-64,85-95 **P** = 1984-95	**A** = 1959-74,85-95 **P** = 1984-95	**A** = 1959-64,85-95 **P** = 1985-95	**A** = 1959-64,85-95 **P** = 1984-95
North (Nb)	**A** = 1957,59-64,85-95 **P** = 1984-95	**A**=1948-52,55-57,59-98 **P**= 1948-52,55-57,59-98	**A** = 1959-64,85-95 **P** = 1985-95	**A** = 1959-64,85-95 **P** = 1984-95
Northeast (NE)	**A**=1949,57,59-64,85-95 **P** = 1949,57,84-95	**A** = 1959-74,85-95 **P** = 1984-95	**A** = 1959-64,85-95 **P** = 1947-48,56,85-95	**A** = 1959-64,85-95 **P** = 1984-95
Northwest (NW)	**A** = 1959-64,85-95 **P** = 1984-95	**A** = 1948-95 **P** = 1948-58,78-95	**A** = 1959-64,85-95 **P** = 1985-95	**A** = 1959-64,85-95 **P** = 1984-95
South (Sb)	**A** = 1959-64,85-95 **P** = 1984-95	**A** = 1959-74,85-95 **P** = 1984-95	**A** = 1959-64,85-95 **P** = 1985-95	**A** = 1959-64,85-95 **P** = 1984-95
Southwest (SWb)	**A** = 1959-64,85-95 **P** = 1984-95	**A** = 1959-74,85-95 **P** = 1984-95	**A** = 1959-64,85-95 **P** = 1985-95	**A** = 1959-64,85-95 **P** = 1984-95
West (W)	**A** = 1959-64,85-95 **P** = 1984-95	**A** = 1959-74,85-95 **P** = 1984-95	**A** = 1959-64,85-95 **P** = 1985-95	**A** = 1959-64,69-70, 74,85-95 **P** = 1959,69,73,84-95

Crop information in Tables 3.6*a-c* (cash) and Tables 3.7*a-c* (staple) are reviewed in Table 3.8 to emphasize the missing years. Table 3.8 shows that the crop data include missing years that vary from one crop to another across Central West African agricultural regions (e.g., from 0% for cocoa/coffee production in Côte d'Ivoire and peanuts/rice production in Burkina Faso to 100% for cotton acreage and sugar cane production in Mali and soybean acreage in Burkina Faso). Most of the missing data in Mali/Burkina Faso are during the Sahelian drought years (e.g., 1972-74, 1982-83) when difficult economic conditions, made worse by prolonged and sometimes severe famine, hampered crop data

Table 3.8: Summary of missing years for individual cash and staple crops in Central West Africa. Analyses draw upon the entire available data set collected for each crop; years for individual crops are listed in Tables 3.6*a-c* and 3.7*a-c*. Ranges of missing data across regions within each country are also converted into percentages. A = acreage, P = production.

Crop	Mali	Burkina Faso	Côte d'Ivoire
Cocoa	Not grown	Not grown	**A** = 6-39 years (≈ 12-76%) **P** = 0-23 years (≈ 0-58%)
Coffee	Not grown	Not grown	**A** = 5-13 years (≈ 10-27%) **P** = 0-9 years (≈ 0-23%)
Cotton	**A** = 15-32 years (≈ 47-100%) **P** = 7-30 years (≈ 22-94%)	**A** = 5-27 years (≈ 17-93%) **P** = 1-27 years (≈ 3-93%)	**A** = 6-43 years (≈ 13-90%) **P** = 5-44 years (≈ 10-90%)
Peanuts	**A** = 15-30 years (≈ 47-94%) **P** = 5-29 years (≈ 16-91%)	**A** = 0-4 years (≈ 0-14%) **P** = 0-4 years (≈ 0-14%)	Not selected
Sugarcane	**A** = 0-12 years (≈ 0-86%) **P** = 0-14 years (≈ 0-100%)	Not selected	Not selected
Soybeans	Not selected	**A** = 1-14 years (≈ 7-100%) **P** = 3-13 years (≈ 21-93%)	Not selected
Maize	**A** = 6-30 years (≈ 18-91%) **P** = 2-32 years (≈ 6-97%)	**A** = 2-8 years (≈ 7-28%) **P** = 2-8 years (≈ 7-28%)	**A** = 17-19 years (≈ 34-38%) **P** = 12-14 years (≈ 24-28%)
Millet	**A** = 0-1 years (≈ 0-7%) **P** = 4-14 years (≈ 13-44%)	**A** = 3 years (≈ 10%) **P** = 3 years (≈ 10%)	Not selected
Plantain	Not grown	Not grown	**A** = 27-48 years (≈ 53-94%) **P** = 12-48 years (≈ 24-94%)
Rice	**A** = 6-13 years (≈ 18-39%) **P** = 2-14 years (≈ 6-42%)	**A** = 1-17years (≈ 3-59%) **P** = 0-16 years (≈ 0-55%)	**A** = 17 years (≈ 33%) **P** = 11-14 years (≈ 21-27%)
Sorghum	**A** = 0 years (≈ 0%) **P** = 5-14 years (≈ 16-44%)	**A** = 3 years (≈ 10%) **P** = 3 years (≈ 10%)	Not selected
Yams	Not selected	Not selected	**A** = 17-20 years (≈ 33-39%) **P** = 12-15 years (≈ 24-29%)
Remarks	Missing years coincide with the most severe Sahelian drought years (e.g., 1973-75, 1982-84)	Missing years coincide with the most severe Sahelian drought years (e.g., 1973-75, 1982-84)	Missing years occur during 1st years of independence (1960s); international cash crops price crisis from mid-80s to mid-90s

estimation programs. Missing data in Côte d'Ivoire on the other hand, are from the transitional period from colony to independence, as well as from the mid-1980s to the mid-1990s in association with the intense crop failures and bush fires of 1983-84 and the international cash crop (coffee, cocoa) price crisis of 1986. However, the missing crop data did not limit the pursuit of the crop analysis, but provided the basis for the unique results obtained that were then compared to rainfall trends (especially for overlapping periods of rainfall/crop yields). The fundamental component of analysis performed here involves assessment of agricultural change. Thus, crop data are analyzed spatially and temporally to document the variations in acreage/production/yields with the goals of drawing conclusions about agricultural patterns and changes in the study area.

3.2.2 Applied Methodology: Spatial Distribution and Time Series of Crops

Maps showing the spatial distribution of crops are drawn. Time series of acreage, production, and yields are also computed and compared to determine which crop parameters display similar trends. This part of the study conveys information that contributes to:

- Defining dominant/lowest growth region(s) for crop(s) within each country and comparing the area of each crop planted to the whole area of a region;
- Evaluating the total cultivated area and the segments occupied by each of the selected individual crops;
- Analyzing the trends and relationships of major crop acreage/production/yields in order to reveal dominant parameter association in both cash and staple crops;

- Observing extremes (i.e., highs/lows) in crop acreage/production/yield time series in order to document agricultural change (interannual/decadal variability); and
- Establishing where and when acreage has been added, ascertaining if the areas added are associated with higher or lower yields and assessing the productivity of the marginal lands.

3.3 Rainfall Variability and Crop Yield Relationships

Research Objective III: To evaluate rainfall variability/agricultural change from the standpoint of crop yield variations. This includes analyzing inter-country comparisons among common crops of cotton, maize, and rice as they relate to rainfall variability. This third objective requires investigation of the following two components:

- Verify whether spatial and temporal rainfall variations have impacts on crop productivity (i.e., how strong are the impacts of rainfall variability; when there is a change in rainfall from one year to another, what happens to crop data?); and
- Analyze how adaptive strategies, such as the replacement of long vegetative cycles by short ones, promotion of drought-resistant crops (e.g., sorghum), as well as nomadic and transhumance movements, help coping with rainfall variability consequences in Central West Africa.

Tools traditionally used to evaluate crop response to rainfall change vary in complexity from statistical (e.g., correlation analysis and regression estimates) and survey methods (e.g., questionnaire surveys) to complex mechanistic models that employ several meteorological variables to simulate key physiological processes of crops. Since this study considers only rainfall variability, direct statistical methods (rather than mechanistic models) were used to study the crop/rainfall relationships. First, time series of rainfall and crop yields were prepared and presented. Then, correlation analyses were performed to quantify the influence of rainfall on crop acreage, production, and yields (Chapter 4).

3.3.1 Time Series of Rainfall/Crop Relationships

This general statistical approach is used to document and relate the variations in both rainfall and crops over time. Time series provides graphical insight into rainfall/crop yield relationship processes through: (1) assessing the degree of coherent crop/rainfall temporal behavior; and (2) providing guidance for future relationships based on the past. Effort is made to examine and compare the influence of annual rainfall totals, especially for years characterized by particular rainfall patterns, such as wet or dry, on crop output (increase or decline).

3.3.2 Correlation Analyses of Rainfall/Crop Relationships

The correlation analyses measure the strength of associations between crop yields and rainfall variability. The purpose is to identify the nature and strength of rainfall/crop yield associations. In other words, correlation analyses investigate the potential impacts of rainfall variability.

3.4 Socioeconomic Impact, Agroclimatologic History, and Environmental Policy Analyses

Research Objective IV: To review the socioeconomic impacts of rainfall variability/crop yield relationships and evaluate/compare agroclimatologic histories and environmental policies in Central West Africa; then to use these results as bases for making recommendations for the future. This fourth objective investigates these five components:

- Verify whether rainfall variability/crop yield relationships have strong socioeconomic impacts in Mali, Burkina Faso, and Côte d'Ivoire;
- Examine the extent to which agroclimatologic histories in Central West Africa reflect the use of rainfall information and acknowledge rainfall variability as a significant factor for crop growth and development in the study region;
- Identify the relationships between resource use and environmental preservation in the study region;
- Evaluate the effectiveness of relevant environmental policies and the perceptions of local populations; and
- Provide recommendations for more effective agricultural policies to sustain agriculture and promote socioeconomic development.

3.4.1 Comparisons of Agroclimatologic Histories in Central West Africa

This section discusses the agroclimatologic histories in Mali, Burkina Faso, and Côte d'Ivoire. It assesses how the three countries acknowledge and cope with rainfall variability. The presentation of these agroclimatologic strategies seeks to provide understanding of the role and importance of climate information within the general environmental policy guidelines of Central West Africa that are developed in Chapter 5.

3.4.2 Comparisons of Environmental Policies in Central West Africa

Like the previous section's discussion of agroclimatologic histories, the colonial-to-recent decades environmental policies of Central West Africa are reviewed. Environmental policies are also compared to discrepancy years between rainfall and crops in order to determine their influences on crop productivity. In other words, the objective here is to determine when and how environmental policies have affected crop yields (Chapter 5).

Thus, this part of the study (Chapter 5) evaluates the socioeconomic development, agroclimatologic histories, and the colonial-to-recent decades environmental policies of Central West Africa in order to make recommendations for sustainable agriculture and sound socioeconomic development. Indeed, the equilibrium of human societies and their economies are particularly fragile in areas that suffer severe and frequent alternations in rainfall patterns. Crop data is the socioeconomic variable that has been considered by this Dissertation. Rainfall data sets are analyzed in combination with crop records to derive indicators for the impacts on the societies and economies of Central West Africa.

Chapter 3 has presented the four research objectives addressed in this study, the data to be analyzed, and the methodology to be used. Each of these objectives was associated with several specific components that orient and frame the investigation. The results and discussions that follow in Chapters 4 and 5 are therefore derived from four main areas: (1) rainfall analyses; (2) agricultural change documentations; (3) rainfall variability/crop yield relationship evaluations; and (4) socioeconomic impact of these relations as well as assessments of agroclimatologic histories/environmental policies in Central West Africa.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents and discusses the results of the rainfall analyses, agricultural documentations, and rainfall variability/crop yield relationship assessments in Mali, Burkina Faso, and Côte d'Ivoire during recent decades. First, the study uses Principal Component Analysis (PCA) to group rainfall stations into coherent regions and select representative stations, for which several analyses are performed including annual rainfall index/totals, multidecadal isohyetal trends, monthly rainfall patterns, number of rain days per year/season/month, and the onset/cessation dates of the rainy seasons. Secondly, Central West African crop assessments are derived from their spatial and temporal trends and agricultural change analyses. Finally, Chapter 4 examines rainfall and crop relationships to establish a basis for the evaluation in Chapter 5 of the socioeconomic impacts of these relations for Mali, Burkina Faso, and Côte d'Ivoire.

4.1 Results of Rainfall Analyses

4.1.1 Classification and Selection of Rainfall Stations

This section summarizes the use of S-mode Varimax-rotated PCA to cluster stations into climatic regions where rainfall varies similarly. As explained in Section 3.1.2.2, the purpose of this process was to arrive at regionalizations that grouped stations into climatic regions, within each country and for the complete study area, from which representative stations with the most complete records were selected for analysis in Section 4.2. PCA was applied to seasonal and annual rainfall totals, where the combinations of months into seasons were suggested by individual month analyses that also were supported by preliminary studies such as CNRS/IGN (1978), Lamb (1978b), Aligbe et al. (1997), and Ward (1998). Table 4.1 summarizes results from the experimental application of four tests that commonly are used to determine the number of PCs to retain and rotate. Transfer of results of these tests onto maps helped identify the spatial modes of rainfall variation and justify the choice of representative rainfall stations from each climatic region.

Table 4.1: Number of principal components (PCs) suggested to be retained by applying each of the four tests for seasonal/annual rainfall within Mali (M), Burkina Faso (BF), Côte d'Ivoire (CI), and entire study region (ALL). See Section 3.1.2.2 for explanation of the tests. The extreme right-hand column indicates the final decision concerning the number of PCs to retain and rotate.

Seasonal/Annual Rainfall	Test Applied				
	Eigenvalue (≥ 1.0)	Scree Plot Test	North et al. Test	Cumulative Unrotated Variance (≥ 50%)	Final number of PCs retained/rotated
M (Mar-Sep)	8	2	1	3	2
M (May-Oct)	7	2	1	3	2
M (Jul-Sep)	7	2	1	3	2
M (Annual)	8	2	2	3	2
BF (Mar-Sep)	4	2	1	2	2
BF (May-Oct)	6	2	2	3	2
BF (Jul-Sep)	7	2	1	3	2
BF (Annual)	6	2	2	2	2
CI (Mar-Jun)	8	3	2	5	2
CI (Mar-Sep)	8	2	2	4	2
CI (May-Oct)	7	2	1	3	2
CI (Mar-Nov)	7	2	2	3	2
CI (Jul-Sep)	7	2	2	3	3
CI (Oct-Nov)	5	2	3	2	2
CI (Annual)	8	2	1	3	2
M/BF (Mar-Sep)	14	2	2	4	2
M/BF (May-Oct)	14	2	1	4	2
M/BF (Jul-Sep)	15	2	2	4	2
M/BF (Annual)	14	2	2	4	2
ALL (Mar-Sep)	20	3	2	5	2
ALL (May-Oct)	20	3	2	5	2
ALL (Jul-Sep)	21	3	2	5	3
ALL (Annual)	20	3	2	5	2

Table 4.1 reveals that based on the eigenvalue ≥1 criterion, the scree plot method, the eigenvalue sampling error test (or eigenvalue separations), and use of the first PCs

that cumulatively account for at least 50% of the total variance explained, the number of PCs to be retained varied from one test to another. In order to determine the best set of PCs to be retained, Varimax rotation was applied to different sets of PCs suggested by each test. This involved experiments to rotate two, three, four, or more PCs separately. Mapping of preliminary results displayed fragmented regions when using more than three or four PCs, depending on the cases. Consequently, the final selection of PCs (Table 4.1) took into account these experimental results. In addition, inter-station correlation analyses among time series of stations were used to classify stations that were between two or more PCA-based rainfall regions or appeared not to belong to any of the regions (see Figs. 4.1*a*-*d*, white areas). The July-September-centered rainy season was most appropriate for the PCA-based rainfall regionalizations of Mali, Burkina Faso, and Côte d'Ivoire separately, as well as when the countries were combined (Folland et al., 1991); thus these data are used for display. Tables 4.2*a*-*d* and Figures 4.1*a*-*e* present the Varimax-rotated PCA results for the July-September-centered rainy season, and identify the 42 stations chosen for further use.

Tables 4.2*a*-*d* and Figures 4.1*a*-*e* show that Mali and Burkina Faso seasonal rainfall can be represented by two Varimax-rotated PCs each, while Côte d'Ivoire is best represented by three PCs. These PCs account for cumulative variance fractions of 48.20% (Mali), 46.87% (Burkina Faso), and 51.66% (Côte d'Ivoire). However, the climatic region 3 for Côte d'Ivoire only had one station due to the limited number of rainfall stations. Further, Côte d'Ivoire had three stations that did not fall in any region and, as stated in the previous paragraph, inter-station correlation analyses (among time series of stations) were used to classify these stations as part of region 2. When dealing with the entire study area, three PCs with a cumulative variance of 43.70% were retained.

Table 4.2*a*: Varimax-rotated PCA-based rainfall regions for Mali (July-September-centered rainy season). Stations are listed by numbers given in Table 3.1*a* (see Chapter 3). Stations in bold are considered representative of their regions and are used henceforth because they also possess the most reliable data.

PC	Eigenvalue	Unrotated Variance (%)	Varimax Variance (%)	Number of Stations in PCA-based Rainfall Region	Stations per Rainfall Region
1	13.10	40.94	26.03	15	**1**, **2**, 3, **7**, **8**, **10**, 11, **13**, 14, **15**, **23**, **24**, 28, 33, 34
2	2.32	7.26	22.16	17	4, 5, 6, 9, 12, 16, 17, **18**, **19**, **20**, 21, 25, 27, 29, 30, **31**, 32
Sum 1+2		48.20	48.19	32	

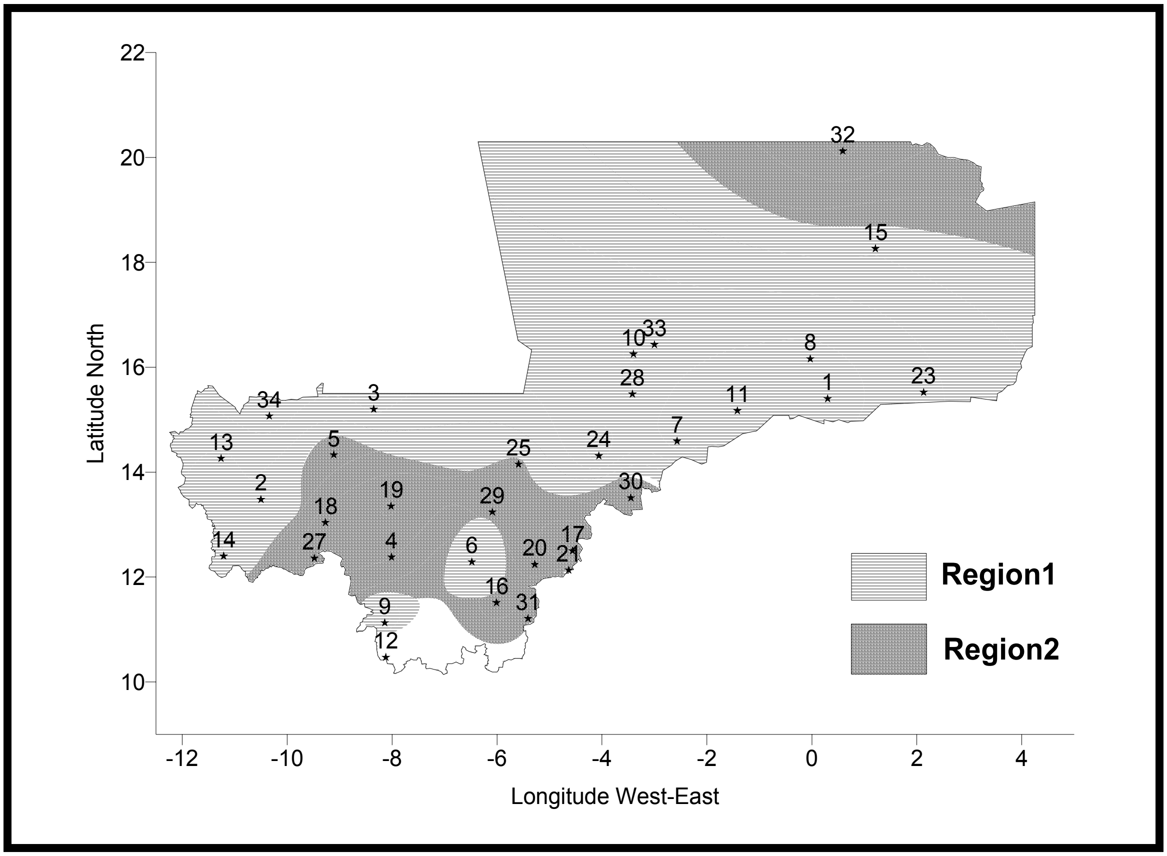


Figure 4.1*a*: Varimax-rotated PCA-based rainfall regions for Mali (July-September-centered rainy season). Stations are listed by numbers given in Table 3.1*a* (see Chapter 3). Regionalization is based on 0.4 PC loading isopleths.

Table 4.2*b*: Varimax-rotated PCA-based rainfall regions for Burkina Faso (July-September-centered rainy season). Stations are listed by numbers given in Table 3.1*b* (see Chapter 3). Stations in bold are considered representative of their regions and are used henceforth because they also possess the most reliable data.

PC	Eigenvalue	Unrotated Variance (%)	Varimax Variance (%)	Number of Stations in PCA-based Rainfall Region	Stations per Rainfall Region
1	10.01	37.08	25.86	16	35, 41, **44**, **45**, **46**, 49, 50, 52, **53**, **54**, 56, **60**, **61**, 66, **68**, 69
2	2.64	9.79	21.01	11	**37**, **40**, **43**, **48**, **51**, **55**, 58, 59, 63, 64, 70
Sum 1+2		46.87	46.87	27	

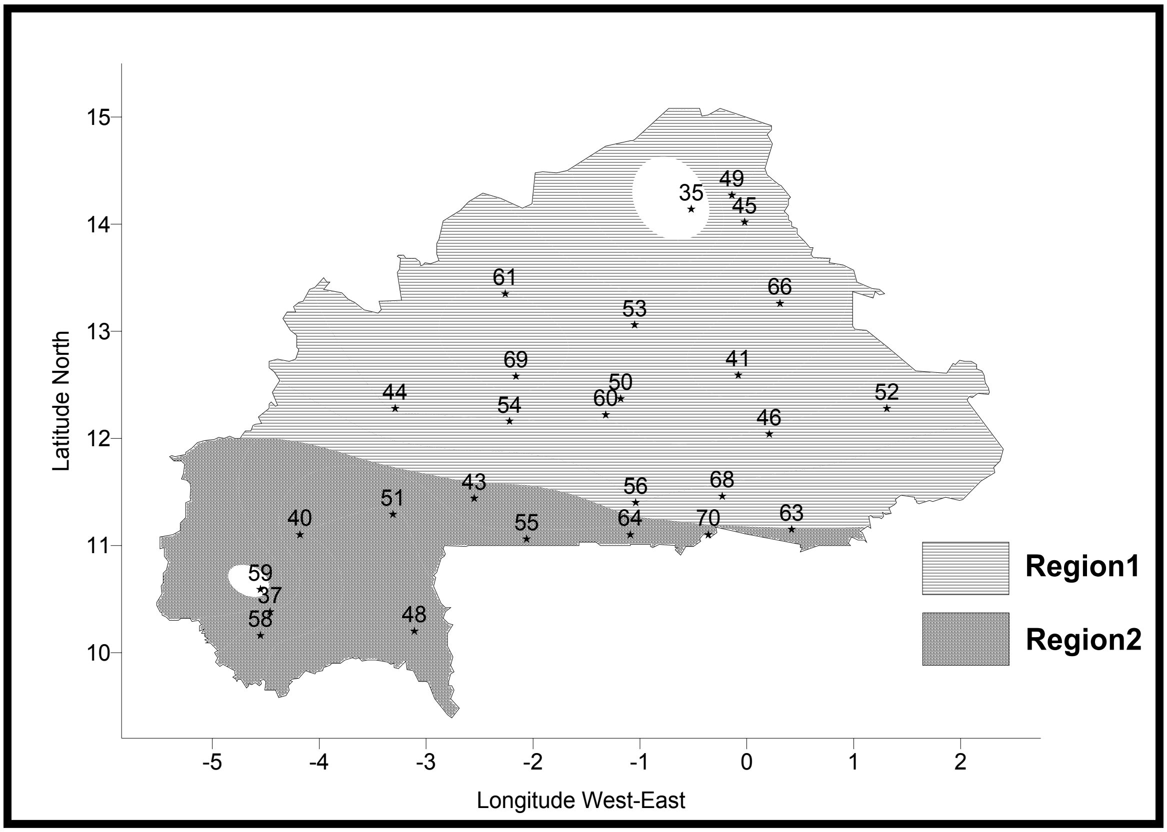


Figure 4.1*b*: Varimax-rotated PCA-based rainfall regions for Burkina Faso (July-September-centered rainy season). Stations are listed by numbers given in Table 3.1*b* (see Chapter 3). Regionalization is based on 0.4 PC loading isopleths.

Table 4.2*c*: Varimax-rotated PCA-based rainfall regions for Côte d'Ivoire (July-September-centered rainy season). Stations are listed by numbers given in Table 3.1*c* (see Chapter 3). Stations in bold are considered representative of their regions and are used henceforth because they also possess the most reliable data.

PC	Eigenvalue	Unrotated Variance (%)	Varimax Variance (%)	Number of Stations in PCA-based Rainfall Region	Stations per Rainfall Region
1	8.29	33.14	26.53	13	**71**, 72, **73**, **74**, 75, 76, **80**, **84**, **85**, 90, **94**, 96, **97**
2	2.85	11.39	16.76	11	**78**, **79**, **86**, 87, **89**, 92, **95**, 98, 99, 100, **101**
3	1.78	7.13	8.37	1	**91**
Sum 1+2+3		51.66	51.66	25	

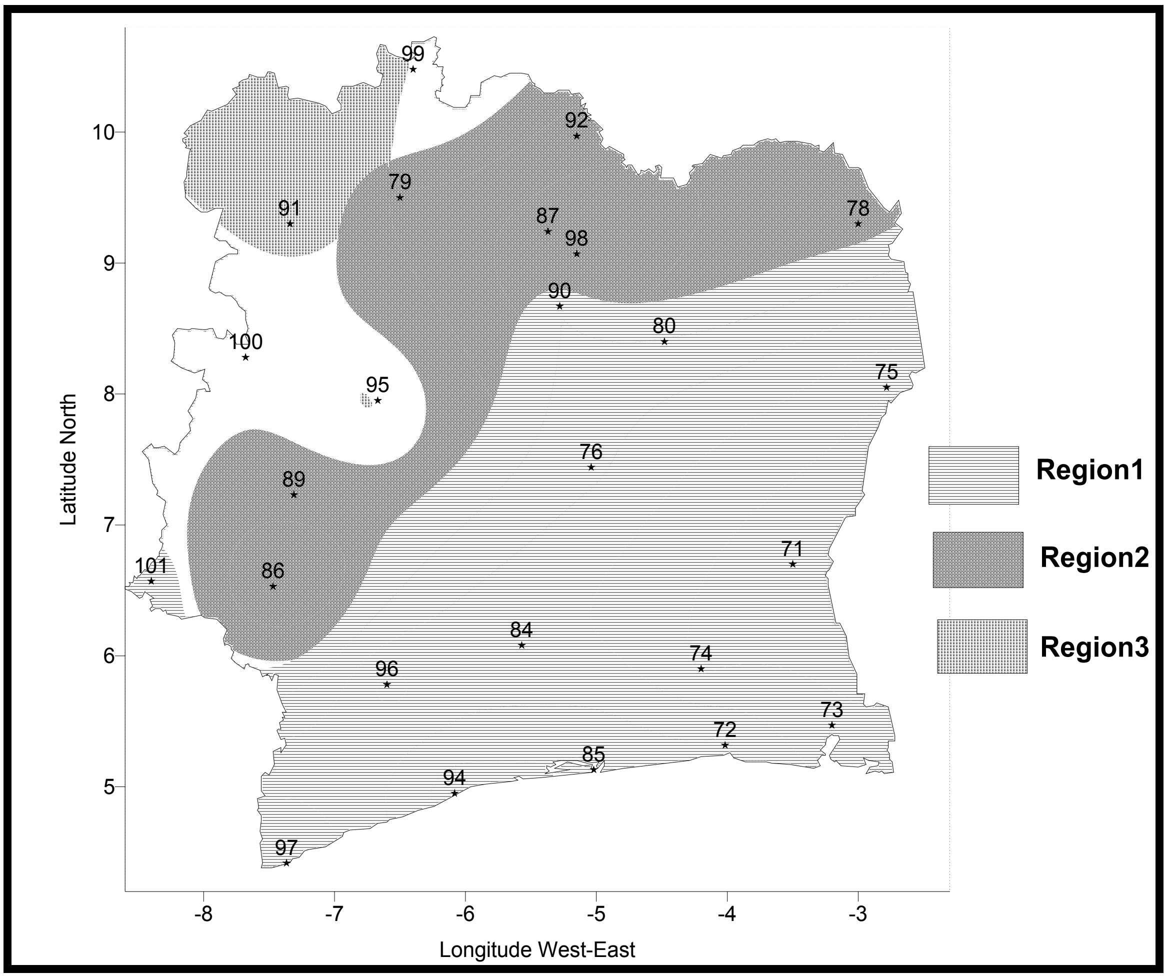


Figure 4.1*c*: Varimax-rotated PCA-based rainfall regions for Côte d'Ivoire (July-September-centered rainy season). Stations are listed by numbers given in Table 3.1*c* (see Chapter 3). Regionalization is based on 0.4 PC loading isopleths.

Table 4.2*d*: Varimax-rotated PCA-based rainfall regions for entire study region (July-September-centered rainy season). Stations are listed by numbers given in Table 3.1*a-c* (see Chapter 3). Stations in bold are considered representative of their regions and are used henceforth because they also possess the most reliable data.

PC	Eigenvalue	Unrotated Variance (%)	Varimax Variance (%)	Number of Stations in PCA-based Rainfall Region	Stations per Rainfall Region
1	22.96	27.33	26.94	64	Mali (**1**, **2**, 3, 4, 5, 6, **7**, **8**, 9, **10**, 11, 12, **13**, 14, **15**, 16, 17, **18**, **19**, **20**, 21, **23**, **24**, 25, 27, 28, 29, 30, **31**, 32, 33, 34) -- Burkina Faso (35, **37**, **40**, 41, **43**, **44**, **45**, **46**, 49, 50, **51**, 52, **53**, **54**, **55**, 56, 58, 59, **60**, **61**, 63, 64, 66, **68**, 69, 70) -- Côte d'Ivoire (**79**, **91**, 92, **95**, 99, 100)
2	10.03	11.94	11.18	11	Mali (none) -- Burkina Faso (**48**) -- Côte d'Ivoire (75, 76, **78**, **80**, **86**, 87, **89**, 90, 98, **101**)
3	3.72	4.43	5.58	9	Mali/Burkina Faso (none) -- Côte d'Ivoire (**71**, 72, **73**, **74**, **84**, **85**, **94**, 96, **97**)
Sum 1+2+3		43.70	43.70	84	

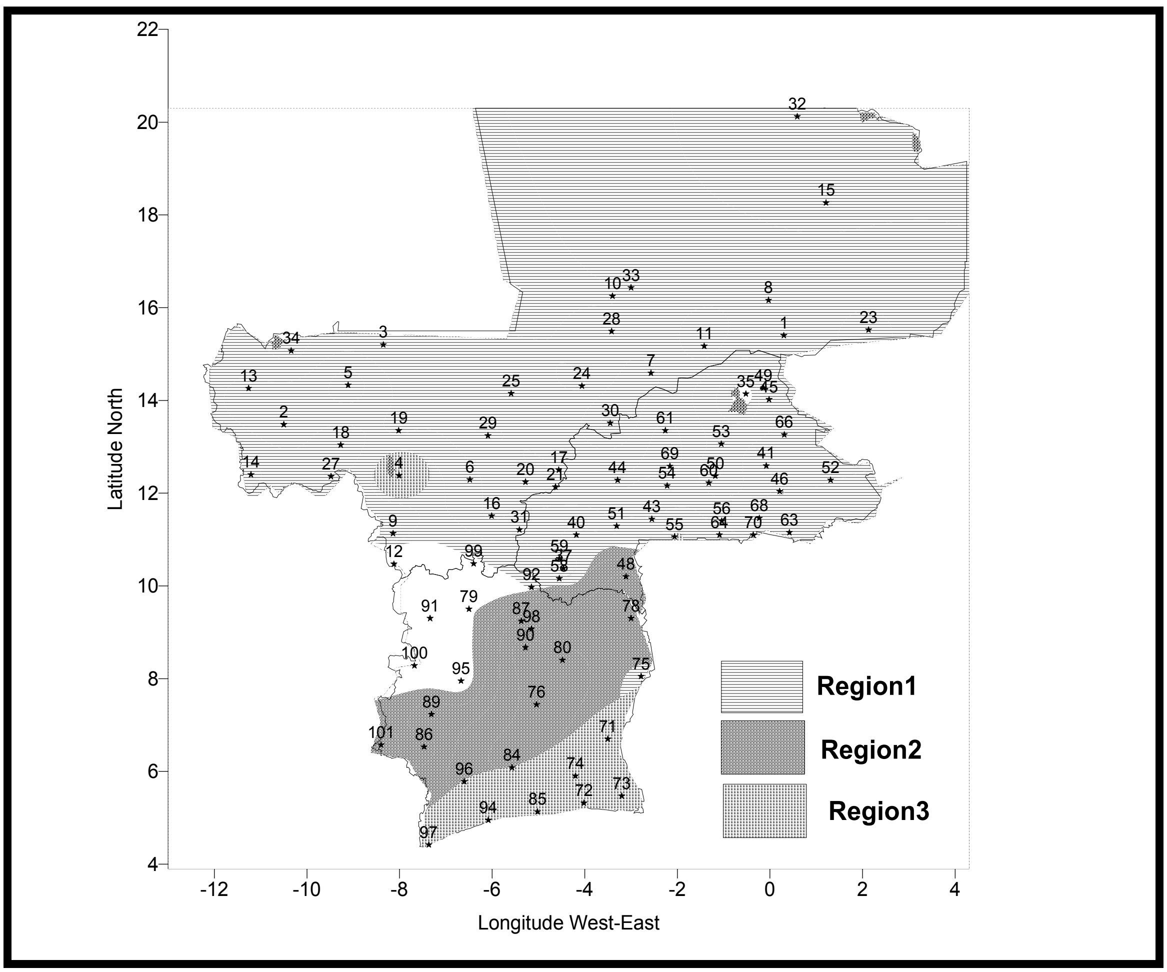


Figure 4.1*d*: Varimax-rotated PCA-based rainfall regions for entire study region (July-September-centered rainy season). Stations are listed by numbers given in Table 3.1*a-c* (see Chapter 3). Regionalization is based on 0.4 PC loading isopleths.

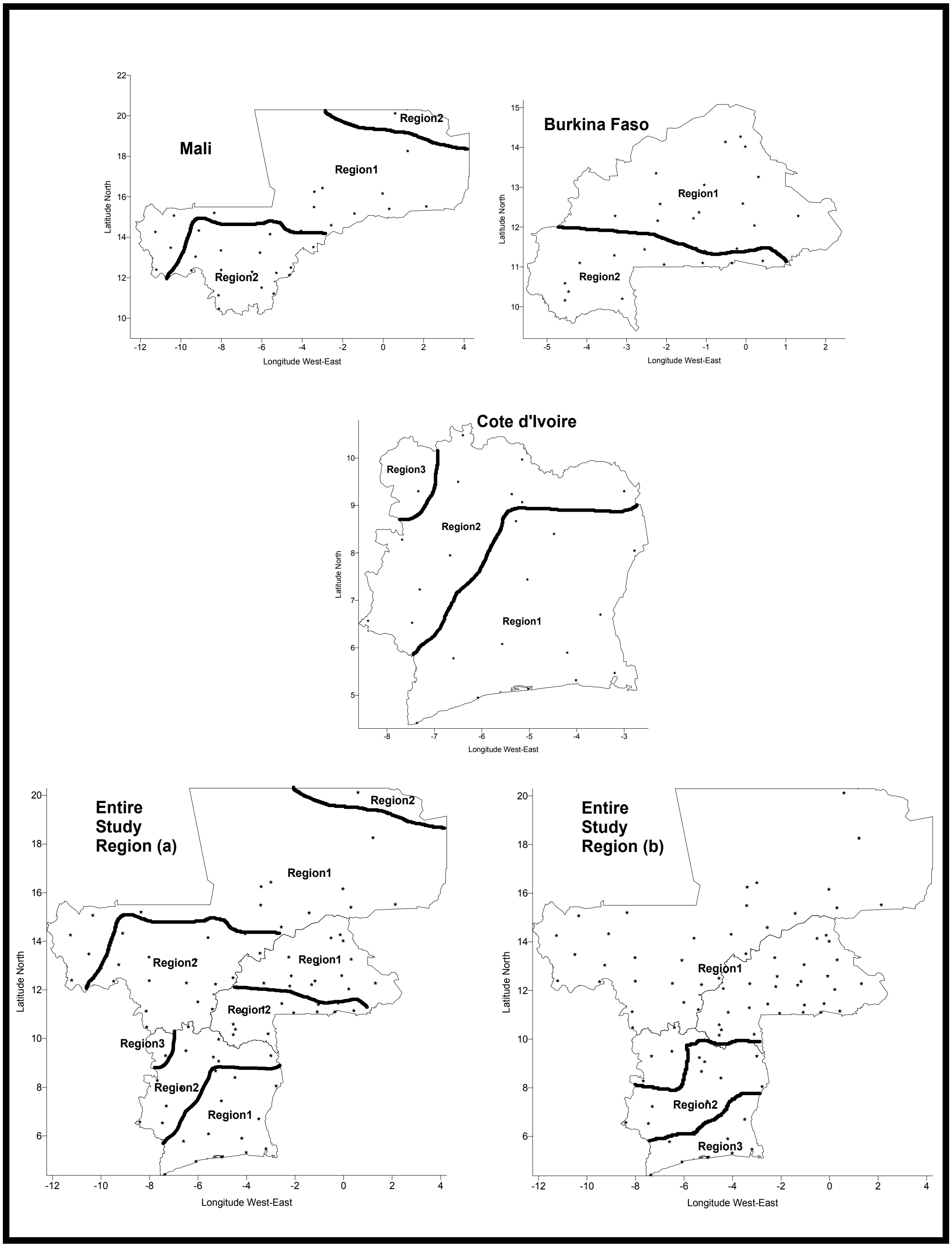


Figure 4.1*e*: Summary of Varimax-rotated PCA-based rainfall regions for each country (top/center) and for entire study region (bottom). Bottom left panel (a) includes all of the regional boundaries obtained in each of the separate country analyses. Bottom right panel (b) contains the regional boundaries obtained when the study area stations are analyzed together. Dots locate rainfall stations used in the PCA.

The regionalization for the entire study region (Fig. 4.1*e*, bottom right) reflects some of the regions obtained when each country was analyzed separately (Fig. 4.1*e*, top, center, bottom left). For instance, regions 1 and 2 of Côte d'Ivoire can be reconciled with regions 2 and 3 for the entire study area, while region 3 of Côte d'Ivoire falls into region 1 for the overall study area. Regions 1 and 2 for Burkina Faso and Mali together form most of region 1 for the entire study area. Region 2 of the overall study area is formed by a small part of region 2 in Burkina Faso and all of region 2 in Côte d'Ivoire. The regionalization for each separate country thus gives more detailed information than when the countries are combined.

Representative rainfall stations were then selected from the PCA rainfall regions, based on the completeness, length, and reliability of each station's records. In other words, stations are considered representative of their regions when they possess the most complete and reliable data. Further, PCA-based rainfall regions for the entire study area (Fig. 4.1*e*, bottom right) largely support the 9.3º N boundary (separating areas to the north and south) used in the analyses reported in later sections of this chapter. Tables 4.3 and 4.4 present summary information from Tables 4.2*a-d* concerning the number of selected stations from each PCA-based rainfall region. 42 representative rainfall stations (13 for Mali, 14 for Burkina Faso, 15 for Côte d'Ivoire) were selected for use in the rainfall analyses in the rest of this chapter. Figure 4.2 shows that these representative stations have an even distribution across Burkina Faso (except in extreme east), while for southern Mali and central Côte d'Ivoire the coverage includes some "holes" that are due to the lack of reliable rainfall stations. Furthermore, the above PCA-based rainfall regionalizations will be used to interpret some of the results (rainfall variability/crop yield relationships) in Section 4.3. Note that the records for the selected 42 stations were extended back to include 1930-1949 where possible, in order to be consistent with rainfall analyses in the rest of this chapter that emphasize the entire study period spanning from 1930 to 1998.

Table 4.3: Stations selected for use in rest of study as fractions of total number of rainfall stations in each Varimax-rotated PCA-based rainfall region within Mali (M), Burkina Faso (BF), Côte d'Ivoire (CI), and entire Central West African (CWA) study region.

PCA-based Rainfall Region	Selected Stations as Fraction of Total Rainfall Station per PCA-based Rainfall Region			
	M (Jul-Sep)	BF (Jul-Sep)	CI (Jul-Sep)	CWA (Jul-Sep)
1	9/15	8/16	8/13	29/64
2	4/17	6/11	6/11	6/11
3			1/1	7/9
Total	13/32	14/27	15/25	42/84

4.1.2 Rainfall Variability from the Guinea Coast to the Sahel

4.1.2.1 Annual Average Rainfall Patterns

Figure 4.3 reveals a striking contrast between the dry (low rainfall amount) and wet (high rainfall amount) regions of Central West Africa, showing strong latitudinal rainfall differences which might have implications for changes in agricultural potential across the study area (Sivakumar et al., 1993; AGHRYMET, 1997). In Côte d'Ivoire, the annual average rainfall declines gradually from Tabou in the southwest (2,235 mm) to Bouna in the northeast (1,062 mm), with a mean (for stations in Fig. 4.2) close to 1,500 mm. Côte d'Ivoire rainfall shows a non-zonal pattern because of the country's topography, which is interrupted by mountain ranges in the West and hills in the center, causing distinctive spatial rainfall variability (windward vs. leeward phenomena). Furthermore, the orientation of the Ivorian coast affects the penetration of the southwest monsoon airstream (perpendicular vs. parallel to coast), which brings more rainfall to the southwest coast than the central (especially) and southeast coasts (CNRS/IGN, 1978; Brou, 1992).

Table 4.4: Rainfall stations that were selected out of Varimax-rotated PCA-based rainfall regions for use in the rest of study. Numbers for stations are given in Tables 3.1*a-c* (see Chapter 3).

Mali	Station Number	Burkina Faso	Station Number	Côte d'Ivoire	Station Number
Ansongo	1	Boromo	43	Boundiali	79
Douentza	7	Dedougou	44	Odienne	91
Gao	8	Hounde	51	Seguela	95
Goundam	10	Koudougou	54	Aboisso	73
Kidal	15	Leo	55	Agboville	74
Menaka	23	Banfora	37	Grand Lahou	85
Mopti	24	Bobo Dioulasso	40	Sassandra	94
Kita	18	Gaoua	48	Tabou	97
Kolokani	19	Ouahigouya	61	Abengourou	71
Koutiala	20	Fada N'gourma	46	Gagnoa	84
Sikasso	31	Kaya	53	Bouna	78
Bafoulabe	2	Ouagadougou	60	Dabakala	80
Kayes	13	Tenkodogo	68	Guiglo	86
		Dori	45	Man	89
				Toulepleu	101

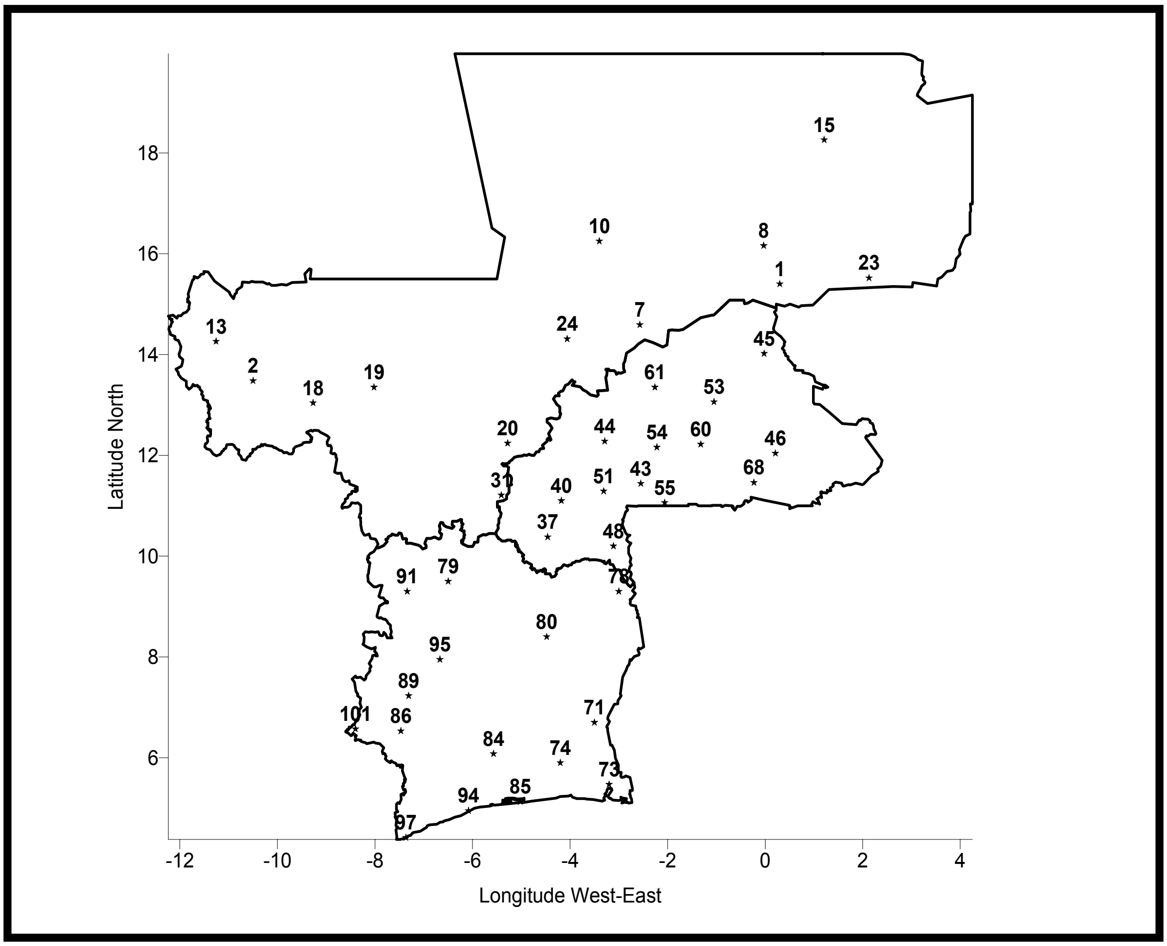


Figure 4.2: Location of the rainfall stations selected from Varimax-rotated PCA-based rainfall regions and used in the remainder of the study. Numbers locate rainfall stations. Numbers and corresponding names for stations are given in Table 4.4.

For Burkina Faso, the isohyets are approximately zonal. The annual average rainfall decreases gradually from Gaoua and Bobodioulasso in the south/southwest (1100 mm) to Dori in the northeast (517 mm). Most of the stations located in southwest Burkina Faso register more than 1,000 mm, while those in the center record from 800 to 900 mm, and those in the northeast have less than 700 mm. Overall, the Burkina Faso stations in Figure 4.2 have an annual mean of about 880 mm.

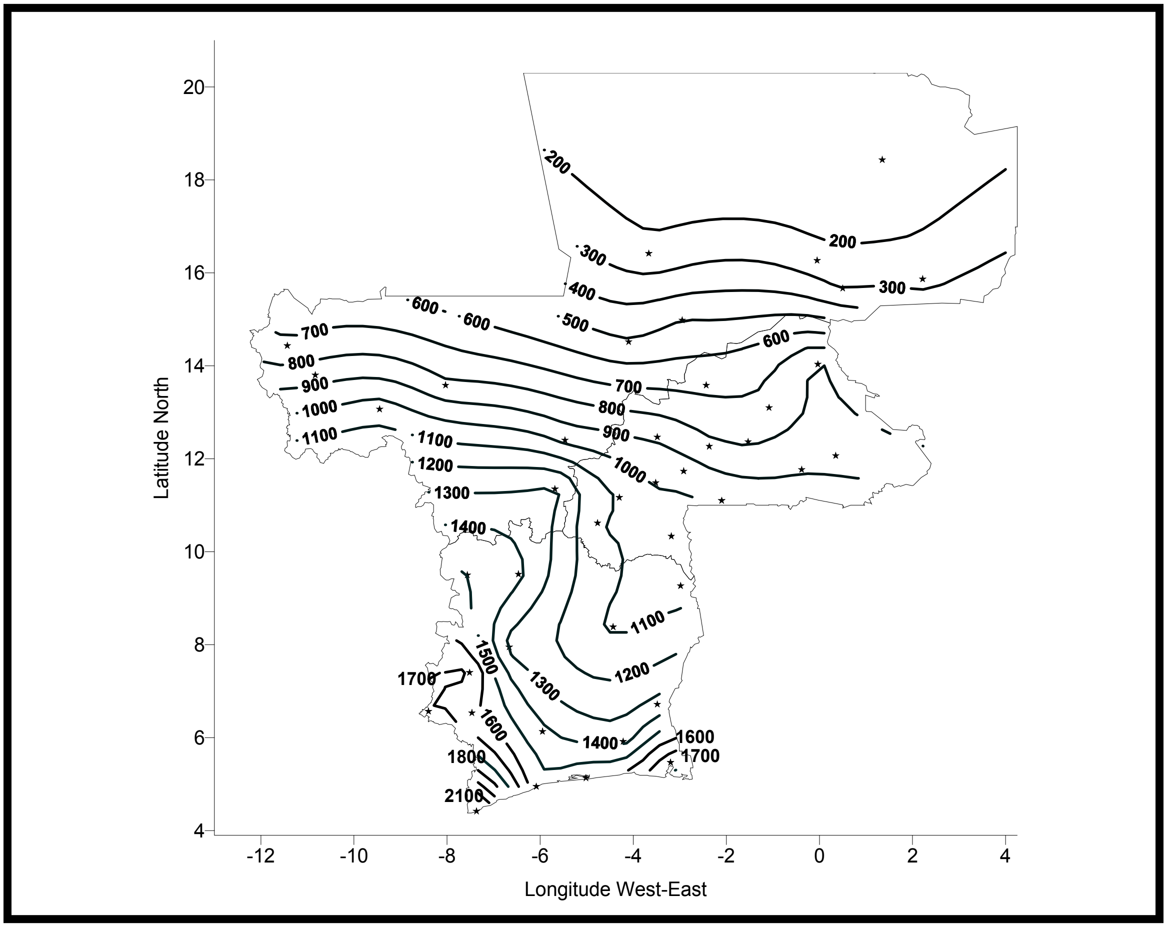


Figure 4.3: Average annual rainfall totals (mm) across the study area. Asterisks locate the 42 representative stations used in the analysis.

The Malian rainfall isohyets also are approximately zonal and the annual average rainfall shows a strong gradient from Sikasso in the south (1,360 mm) to Kidal in the northeast (136 mm). The mean annual rainfall for the Mali stations in Figure 4.2 is only around 600 mm as a result of the huge rainfall variation. North of the 20°N parallel, there is very little to no rain and Sivakumar et al. (1993, p. 5) concluded, "near 20°N, where the ITCZ disappears, the zone of continual dryness or desert begins," which means that the extreme north is a zone of continental hot and dry winds where rainfall hardly occurs (Section 2.1.1).

Note that for Mali south of 16° N and the southern half of Burkina Faso, the isohyets have a pronounced west-northwest to east-southeast orientation (Nicholson, 1980; Le Barbé et al., 2002). This reflects the isohyetal pattern across the entire Sahel, which Nicholson (1980, p. 473) described as "a strong coherence of variation [that] occurs throughout the region from ~20-10°N, a latitude which frequently marks a climatic discontinuity…in both the north-south and east-west directions." Tables 4.5*a*,*b* provide further information on Central West African rainfall characteristics and emphasize the strong latitudinal rainfall differences in the study area between the humid south and arid north, especially during wet Sahel years.

Table 4.5*a*: Selected statistics of annual average rainfall (mm) from 1930 to 1998. Ranges are for the selected stations within each country (13 for Mali, 14 for Burkina Faso, and 15 for Côte d'Ivoire) and the entire study region (42 rainfall stations).

Rainfall Values	Mali	Burkina Faso	Côte d'Ivoire	Entire Study Region
Minimum	3-662	146-778	331-1219	3-1219
Maximum	385-2122	979-1887	1742-3985	385-3985
Mean	147-1327	673-1102	1062-2296	147-2296
Standard Deviation	67-293	149-248	238-473	67-473
Coefficient of Variation (%)	0.20-0.46	0.17-0.26	0.17-0.29	0.17-0.46

Table 4.5*b*: Latitudinal variation of Central West Africa annual average rainfall (mm) for entire study period and for selected wet (1943, 1950, 1975, 1994) and dry (1968, 1972, 1983, 1990) years as explained in Section 3.1.2.4.

Station	Lat.	Long.	Average	Wet Years				Dry Years			
				1943	1950	1975	1994	1968	1972	1983	1990
Kidal	18.26'N	01.21'E	136	194	293	112	148	126	105	78	66
Goundam	16.25'N	03.40'W	223	294	474	291	267	268	185	129	70
Gao	16.16'N	00.03'W	232	219	340	310	229	261	178	103	138
Menaka	15.52'N	02.13'E	253	456	296	216	276	254	168	220	165
Ansongo	15.40'N	00.30'E	284	391	387	375	319	252	165	129	292
Douentza	14.59'N	02.57'W	491	475	980	525	594	532	248	506	364
Mopti	14.31'N	04.06'W	502	702	717	560	635	476	401	445	457
Kayes	14.26'N	11.26'W	724	966	837	900	605	481	486	428	461
Dori	14.02'N	00.02'W	517	924	1212	671	743	1045	729	617	648
Bafoulabe	13.48'N	10.50'W	857	904	1221	700	662	695	466	661	862
Kolokani	13.35'N	08.02'W	805	1008	1114	714	844	599	746	549	644
Ouahigouya	13.35'N	02.26'W	670	784	769	493	965	702	502	358	403
Kaya	13.06'N	01.05'W	723	919	829	889	1225	522	582	574	620
Kita	13.04'N	09.27'W	1047	1228	1318	980	1115	1073	832	677	754
Dedougou	12.28'N	03.29'W	878	859	1206	512	1131	981	670	648	720
Koutiala	12.24'N	05.28'W	964	1220	1204	850	1358	906	860	755	1058
Ouagadougou	12.22'N	01.32'W	784	1013	739	756	728	774	1060	675	676
Koudougou	12.16'N	02.22'W	822	924	1212	671	743	1045	729	617	648
Fada N'gourma	12.04'N	00.21'E	862	1011	888	996	991	987	840	668	568
Tenkodogo	11.46'N	00.23'W	889	1202	946	813	893	1005	912	790	683
Boromo	11.44'N	02.55'W	943	776	970	934	987	1009	876	635	584
Hounde	11.29'N	03.31'W	980	997	980	933	1070	983	1034	773	633
Sikasso	11.21'N	05.41'W	1360	1140	1622	1283	1968	1751	1137	662	1679
Bobo Dioulasso	11.10'N	04.18'W	1100	1179	861	888	897	1413	894	778	995
Leo	11.06'N	02.06'W	980	1029	1196	906	1119	1185	827	369	683
Banfora	10.38'N	04.46'W	1093	1109	1257	1077	1092	1390	1048	544	595
Gaoua	10.20'N	03.11'W	1100	1369	849	954	1004	1585	874	714	1007
Boundiali	09.50'N	06.50'W	1430	1228	1581	1508	1431	1253	2058	837	1221
Odienne*	09.30'N	07.34'W	1521	1640	1203	1451	1510	1559	1709	1038	1169
Bouna*	09.30'N	03.00'W	1062	983	1025	1103	769	1434	934	722	1204
Dabakala	08.40'N	04.48'W	1081	1160	782	827	929	1639	835	331	908
Seguela	07.95'N	06.67'W	1258	1428	1162	1007	1258	1592	1030	503	1256
Man	07.23'N	07.31'W	1722	2072	1313	1813	1901	1763	1576	1250	1393
Abengourou	06.70'N	03.50'W	1326	1524	1102	1322	1332	1977	1441	1095	1252
Toulepleu	06.57'N	08.40'W	1702	1017	1365	1703	1875	1605	1853	1069	1027
Guiglo	06.53'N	07.47'W	1623	2133	1288	1585	1354	915	1830	1305	1425
Gagnoa	06.08'N	05.57'W	1421	1796	1318	1162	1293	1563	1265	1319	1364
Agboville	05.90'N	04.20'W	1356	1217	1502	1247	1357	1968	1063	773	1357
Aboisso	05.47'N	03.20'W	1796	2177	1377	1910	1956	2429	1484	1318	1401
Grand Lahou	05.13'N	05.02'W	1595	1851	1606	1763	2119	1634	900	897	1033
Sassandra	04.95'N	06.08'W	1525	1731	1616	1344	1085	1736	1360	1083	705
Tabou	04.42'N	07.37'W	2235	2760	2044	1779	2042	2945	2138	2128	2500

*** Odienne and Bouna have the same latitudes but have different longitudes.**

In summary, there is a strong latitudinal rainfall variation within Mali and Burkina Faso, while Côte d'Ivoire shows a non-zonal pattern with rainfall decreasing northward and northeastward (Fig. 4.3). The zonal component of the northward rainfall decline parallels the decrease in depth of the southwest monsoon flow inland from the Guinea Coast (Landsberg, 1972; Lamb, 1978b, 1983; Ballo, 1996). In other words, rainfall declines northward with increasing distance from the Gulf of Guinea moisture source. The Central West African rainfall gradient is influenced by the movement of the ITCZ, "a zone of rising turbulences" (Sivakumar et al., 1993, p. 4) discussed in Section 2.1, which suggests that convergence and rainfall often follow the passage of the ITD, but remain several hundred kilometers to the south. The strong rainfall gradient (latitudinal variability) explains the diversity of cropping and the geographic locations of different crop types.

With the purpose of documenting temporal rainfall variations to complement the above spatial analysis, a normalized rainfall index time series also was calculated for annual rainfall (Lamb, 1978b; Servat et al., 1997; Lamb et al., 1998). This standardized index quantifies the rainfall departure from the long-term average in terms of standard deviations. Station means ($\bar{x}$) and standard deviations (σ) were computed for the entire 69-year study period. The use of the whole period quantifies the rainfall deviations optimally with less bias toward dry or wet periods. In contrast, when $\bar{x}$ and σ were calculated using a standard WMO 30-year normal period (e.g., 1931-60 or 1961-90), the means were either significantly larger or smaller than the 1930-98 average, neither of which depicted realistic patterns for the whole 69-year study period (see Section 3.1.2.3 for details of methodology).

Figure 4.4 gives a comprehensive picture of the standardized annual rainfall departures for 1930-98, based on the 42 selected rainfall stations, and depicts a very interesting pattern of large multidecadal- and interannual-scale rainfall variability for Mali, Burkina Faso, and Côte d'Ivoire, as well as for all three countries combined. On the multidecadal-scale, there are two contrasting trends that show more wet years before the mid-1960s (upward trend) and more dry years (downward trend) thereafter in all cases. Furthermore, there is a substantial interannual variability superimposed on these trends. Prominent periods of especially strong interannual variability are as follows:

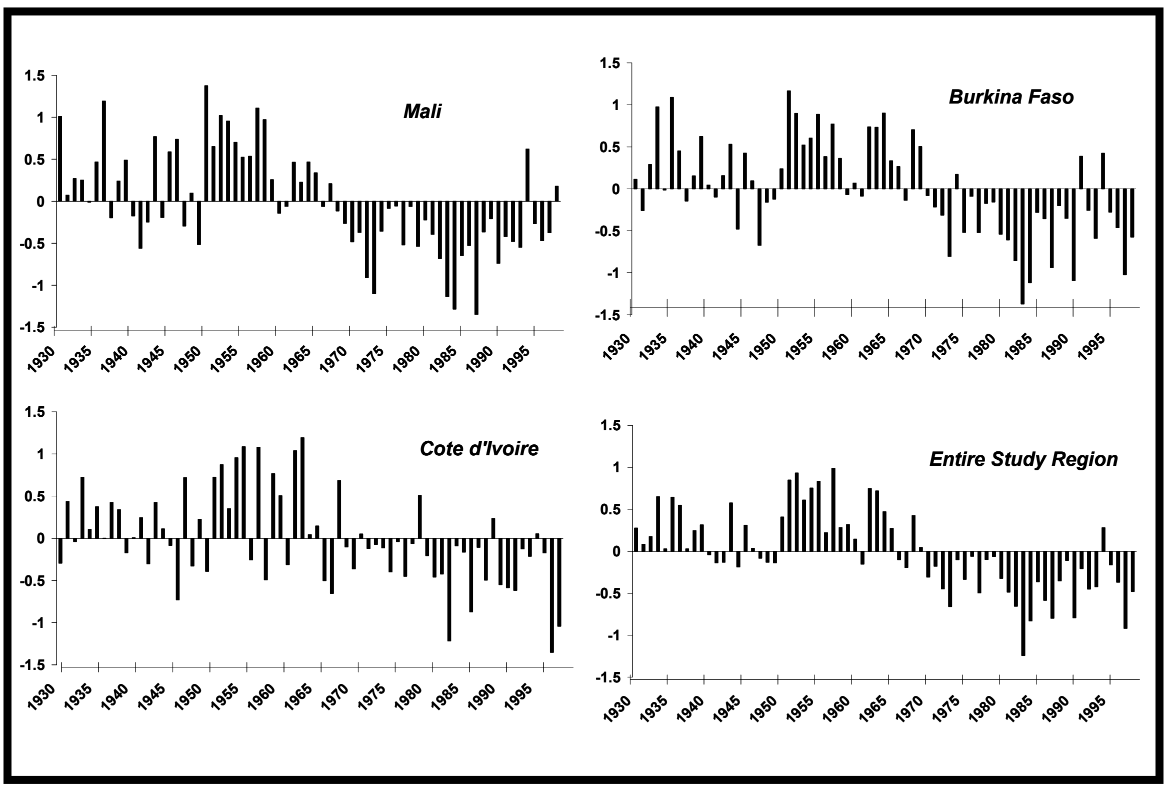


Figure 4.4: Central West Africa annual normalized rainfall index time series (σ). The plots are derived from 42 long-term stations for the entire study region (13 for Mali, 14 for Burkina Faso, 15 for Côte d'Ivoire) using means and standard deviations calculated over 1930-1998. See text for further explanation.

1936-38, 1942-50, 1965-67, 1993-95 for Mali; 1930-32, 1936-38, 1943-45, 1959-61, 1966-68, 1973-75, 1990-95 for Burkina Faso; 1930-33, 1939-50, 1955-62, 1978-80, 1988-90 for Côte d'Ivoire; and 1942-45, 1960-62, 1993-95 for the entire study region. A further key point is the clear regime change around the 1950s. From 1930 to 1950, the monsoon system functioned differently concerning Mali/Burkina Faso versus Côte d'Ivoire. But, since the 1950s the monsoon system has had the same effect on the three countries as quantified in Table 4.6.

Table 4.6: Correlation coefficients between Mali (M), Burkina Faso (BF), and Côte d'Ivoire (CI) rainfall indices in Figure 4.4 for indicated periods. Levels of significance derived from two-tailed t test are 95% (*), 98% (**) and 99%(***).

Period	M vs. BF	M vs. CI	BF vs. CI	M vs. BF+CI	BF vs. M+CI	CI vs. BF+M
1930-98	+0.75***	+0.33***	+0.58***	+0.61***	+0.82***	+0.48***
1930-50	+0.51**	-0.42*	+0.01	+0.11	+0.54***	-0.27
1951-98	+0.81***	+0.50***	+0.68***	+0.71***	+0.86***	+0.62***

Figure 4.4 shows that the time series for Mali (based on 13 stations) and Burkina Faso (14 stations) are very similar, while that of Côte d'Ivoire (15 stations) is slightly different because of its larger interannual variability superimposed on the multidecadal trends. Therefore, the time series for the entire study region resembles more closely those of Mali and Burkina Faso, because of their similarity and their dominant contribution to the input (27 rainfall stations out of the total of 42). However, Côte d'Ivoire retains the basic multidecadal variability despite more interannual variability. To verify the similarity of the time series of Mali/Burkina Faso, detect the differences with Côte d'Ivoire, and establish the meaningfulness of the entire study region's time series, correlation coefficients are presented in Table 4.6. As discussed above, the clear regime change (in terms of Mali/Burkina Faso versus Côte d'Ivoire) that occurred around 1950 is the reason for Table 4.6's breakpoint at 1950/1951.

Table 4.6 reveals that Mali and Burkina Faso have very similar indices for the three periods of analysis with correlation coefficients increasing from r = +0.51, 98% significance level (1930-1950) to r = +0.81, 99% significance level (1951-98). Each of these two countries also is quite strongly correlated to the other two study nations combined for 1930-98 (≥ +0.61) and 1951-98 (≥ +0.71). On the other hand, the Côte d'Ivoire index has near zero to moderate correlation with Mali and Burkina Faso separately, and with the two countries combined. The moderate correlations occur for 1930-98 (+0.33 to +0.58) and 1951-98 (+0.50 to +0.68), while 1930-1950 registers negative to extremely weak correlations (-0.42 to +0.01). The prevailing moderate-to-strong positive correlations between each country and the other two nations combined for the overall period, and especially 1951-98, support the present focus on the entire study region as a whole. The contrasting behavior during 1930-50, especially between Côte d'Ivoire and the other two countries (singly as well as combined) could be a reflection of the distinctiveness of the Côte d'Ivoire climate and the shorter period involved (21 years versus 48 and 69 years).

4.1.2.2 Multidecadal Isohyetal Trend Determination

The focus here is on rainfall variability between the study's seven decades (i.e., 1930s, 1940s, 1950s, 1960s, 1970s, 1980s, and 1990s). As explained in Section 3.1.2.4, these decades happen to coincide with study area decadal rainfall regime changes that are characterized by abundant rainfall in the 1930s, 1950s, and early-to-mid-1960s as well as low rainfall and sometimes drought in the 1940s, late 1960s, 1970s, 1980s, and 1990s (Fig. 4.4). Furthermore, Table 4.7*a* presents the rainfall index summarized into decades, while Table 4.7*b* shows the rainfall mean per decade and the role of each decade in the long-term rainfall variability. Here, the wet and dry years within each decade are positive or negative deviations from the decades' mean, respectively.

Table 4.7*a*: Sign of average standardized departure for each decade. Number of wet (W; above mean) and dry (D; below mean) years determines the dominant characteristic for each decade.

Decade	Mali	Burkina Faso	Côte d'Ivoire	Entire Study Region	Characteristic
1930-39	W = 8 and D = 2	W = 7 and D = 3	W = 7 and D = 3	W = 10 and D = 0	Wet
1940-49	W = 4 and D = 6	W = 5 and D = 5	W = 6 and D = 4	W = 3 and D = 7	Dry
1950-59	W = 10 and D = 0	W = 9 and D = 1	W = 7 and D = 3	W = 10 and D = 0	Wet
1960-69	W = 5 and D = 5	W = 8 and D = 2	W = 6 and D = 4	W = 7 and D = 3	Wet
1970-79	W = 0 and D = 10	W = 1 and D = 9	W = 2 and D = 8	W = 0 and D = 10	Dry
1980-89	W = 0 and D = 10	W = 0 and D = 10	W = 1 and D = 9	W = 0 and D = 10	Dry
1990-98	W = 2 and D = 7	W = 2 and D = 7	W = 1 and D = 8	W = 1 and D = 8	Dry

Table 4.7*b*: Average rainfall ($\bar{x}$) for each decade (mm) and the decadal contribution (percent) to the sum of the decadal average values for 1930-1998. Rainfall stations used for calculations are located in Figure 4.2 (13 for Mali, 14 for Burkina Faso, 15 for Côte d'Ivoire, and 42 for entire region).

Country ($\bar{x}$, %)	1930-39	1940-49	1950-59	1960-69	1970-79	1980-89	1990-98
Mali ($\bar{x}$)	676	618	722	624	545	503	572
Mali (%)	15.9	14.5	16.9	14.6	12.8	11.8	13.4
Burkina Faso ($\bar{x}$)	973	886	1000	946	822	746	812
Burkina Faso (%)	15.7	14.3	16.2	15.3	13.3	12.1	13.1
Côte d'Ivoire ($\bar{x}$)	1577	1513	1672	1578	1488	1366	1391
Côte d'Ivoire (%)	14.9	14.3	15.8	14.9	14.1	12.9	13.1
Entire Region ($\bar{x}$)	1075	1006	1131	1049	952	872	925
Entire Region (%)	15.3	14.3	16.1	15.0	13.6	12.4	13.2

Tables 4.7*a*,*b* provide clear evidence of considerable multidecadal variations in rainfall for the study area. The decade of 1930-39 was wet and followed by the drier decade of 1940-49, two wet decades (1950-59 especially, and 1960-69), and dry decades afterwards (especially 1970-89) coinciding with the highly publicized Sahelian drought (extending to Soudan zone and Guinea Coast) since the late 1960s. The decadal contributions to the sum of the decadal average values for 1930-1998 recovered slightly in the 1990s, though remaining dry. This large multidecadal rainfall variability characterizes each country to varying degrees, as well as the three countries combined.

These variations further confirm that Central West Africa has a long history of rainfall fluctuations of varying time-scales and intensities (see Section 2.1). However, the rainfall from 1970 onwards has been consistently below the long-term average, while the years from 1950 to 1969 (especially 1950-58) were among the wettest of the period (Lamb, 1982; Lamb et al., 1998; Ward et al., 1999). The low rainfall values since 1970, which often are representative of severe drought, adversely impacted traditional agricultural production in much of Central West Africa, especially in the low rainfall areas (Sivakumar et al., 1993; Servat et al., 1997). These impacts are explored in depth in Section 4.3.

In addition, special attention is paid to the locations of the 250 mm, 500 mm, 750 mm, 1,000 mm, 1,250 mm, and 1,500 mm annual isohyets, which are important for the study region's crops (see Chapter 2, Table 2.1). These isohyets were chosen to document the decadal trends that have affected crops and their water requirements and needs (Figs. 4.5 and 4.6). Furthermore, Table 4.8*a* summarizes information on average isohyetal positions during each decade, while Table 4.8*b* displays the decadal number of rainfall stations (out of 42) in each selected isohyet range.

The isohyets in Figures 4.5 and 4.6 display a definite trend, showing consistent evidence of a southward shift, which is summarized in Tables 4.8*a*,*b*. During the 1930s, the 250 mm isohyet was confined to north Mali, while the 500 mm isohyet crossed central Mali and northern Burkina Faso, but did not appear south of 14^{o} N, which contained the 750 mm isohyet extending between 12.4^{o} N and 15.4^{o} N. The 1,000 mm isohyet occupied the latitudes between 11^{o} and 14^{o} N, while the 1,250 mm isohyet covered the latitudes between 7.8^{o} N and 13.2^{o} N, and the 1,500 mm isohyet ran south of 10^{o} N.

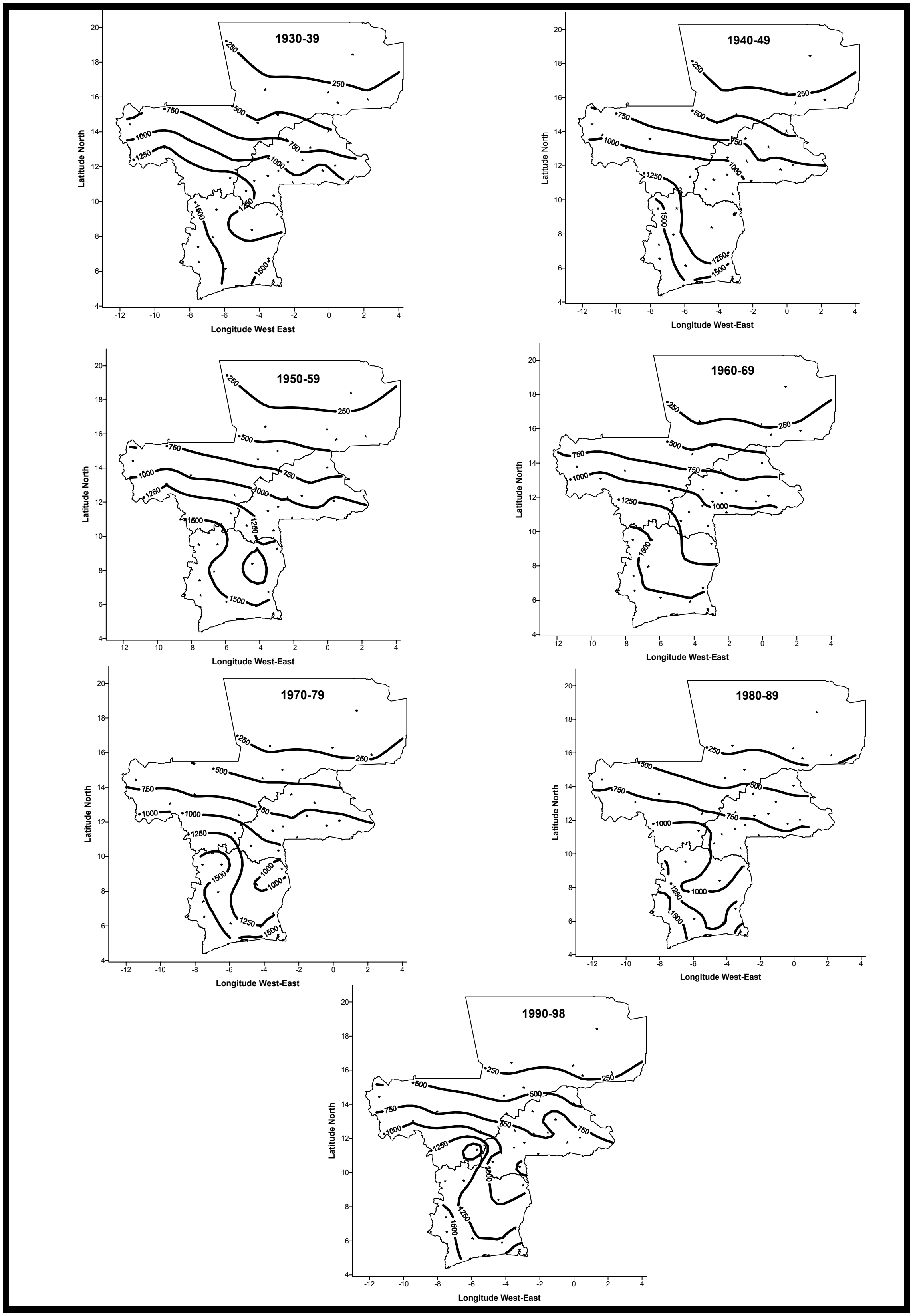


Figure 4.5: Selected average annual isohyets (mm) for the 1930s, 1940s, 1950s, 1960s, 1970s, 1980s, and 1990s. Dots locate the 42 rainfall stations used in the analysis.

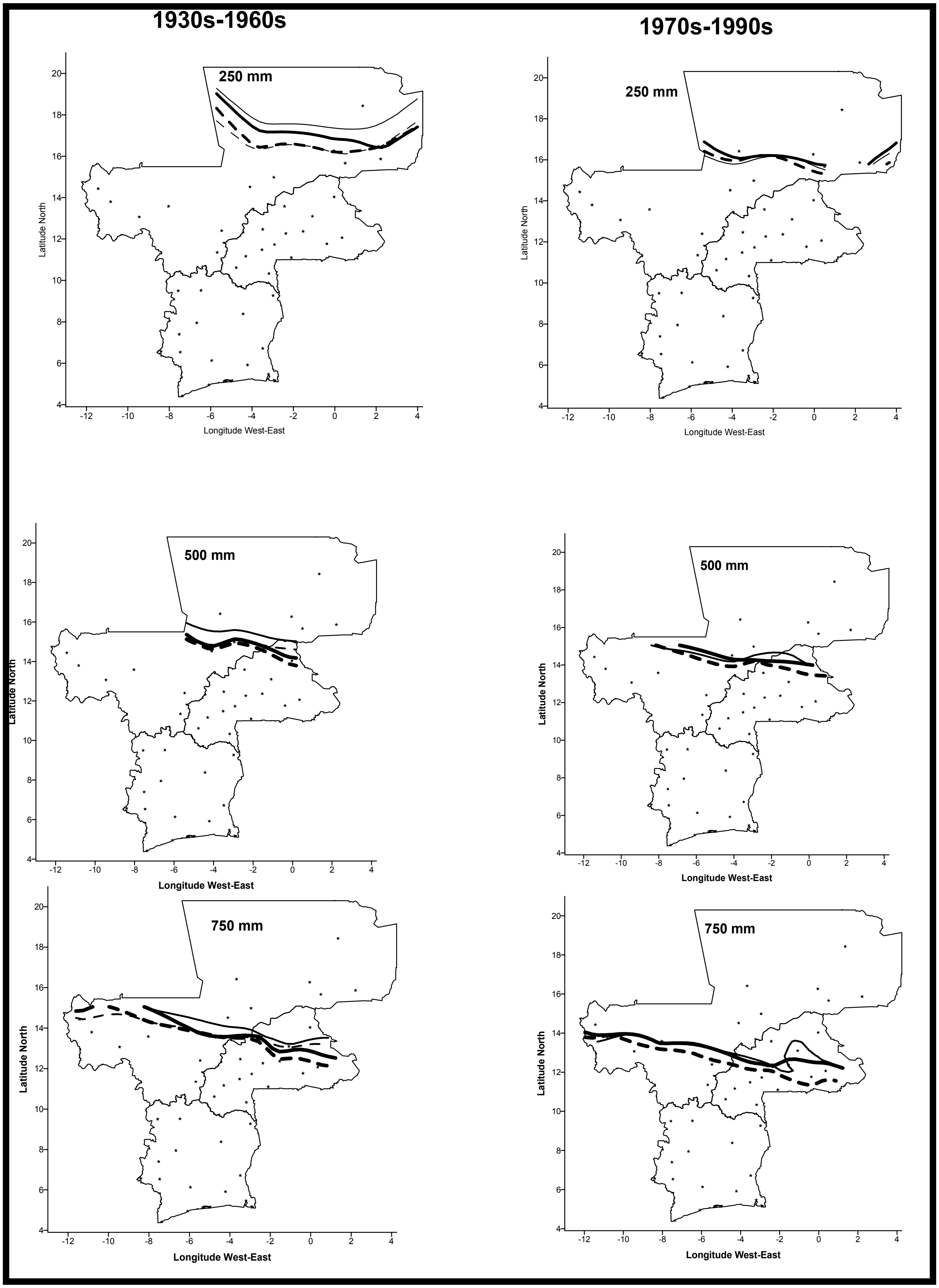


Figure 4.6: Comparisons of the positions of 250, 500, and 750 mm isohyets during the seven decades. Left panels include 1930s = solid thick line, 1940s = broken thick line, 1950s = solid thin line, and 1960s = broken thin line. Right panels contain 1970s = solid thick line, 1980s = broken thick line, and 1990s = solid thin line. Dots locate the 42 rainfall stations used in the analysis.

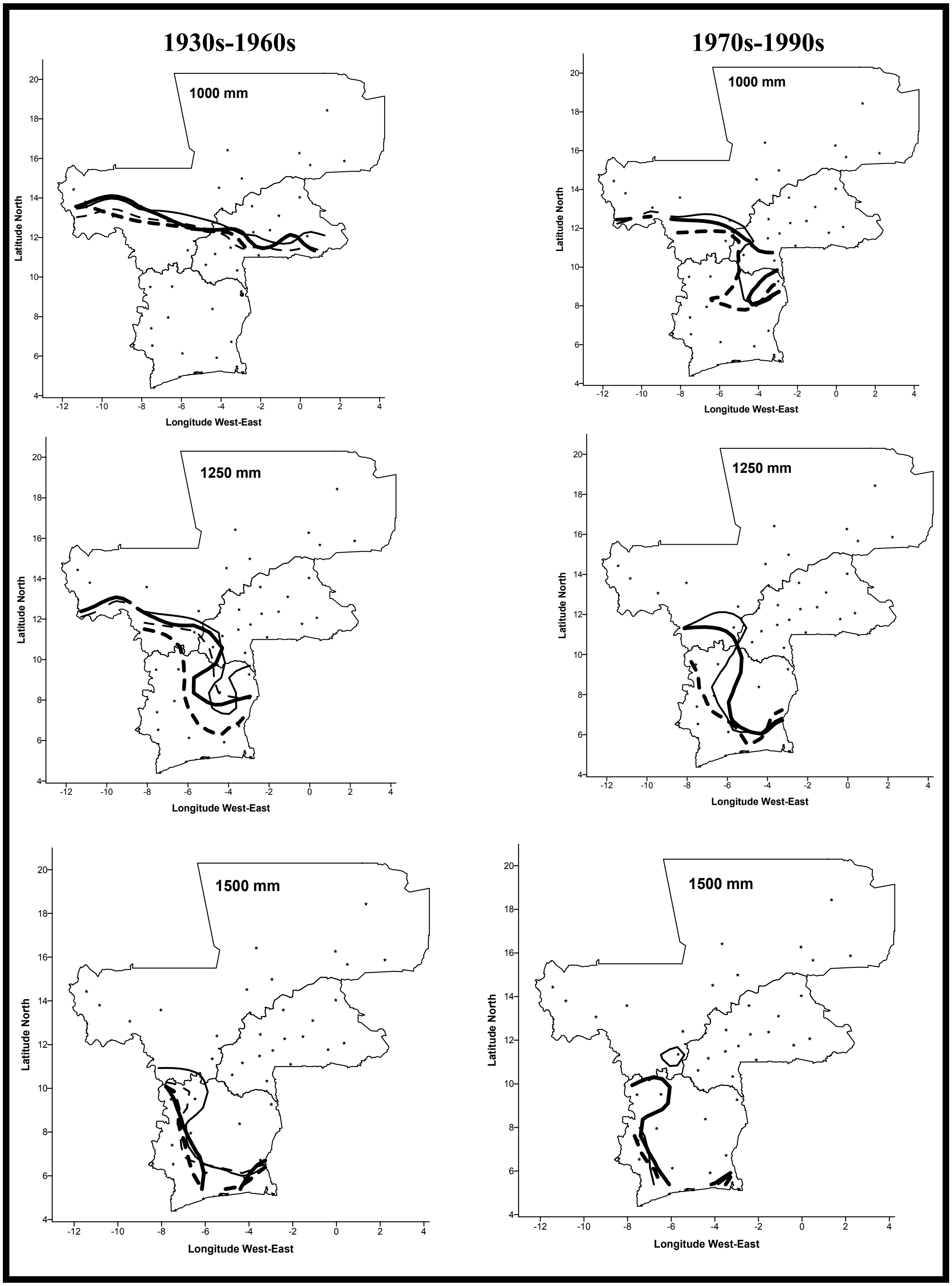


Figure 4.6 (continued): Comparisons of the positions of 1000, 1250, and 1500 mm isohyets during the seven decades. Left panels include 1930s = solid thick line, 1940s = broken thick line, 1950s = solid thin line, and 1960s = broken thin line. Right panels contain 1970s = solid thick line, 1980s = broken thick line, and 1990s = solid thin line. Dots locate the 42 rainfall stations used in the analysis.

Table 4.8*a*: Summary information on average latitudinal positions of the selected isohyets (mm). L = latitude, a = 250 mm, x = 500 mm, r = 750 mm, y = 1000 mm, s = 1250 mm, z = 1500 mm, M = Mali, BF = Burkina Faso, and CI = Côte d'Ivoire.

Decade	250 mm	500 mm	750 mm	1000 mm	1250 mm	1500 mm
1930-39	$16.2^o \leq a \leq 19.2^o$ L (north M)	$14^o \leq x \leq 15.4^o$ L (central M to north BF)	$12.4^o \leq r \leq 15.4^o$ L (south-central M to north-central BF)	$11.2^o \leq y \leq 14^o$ L (southwest M to central and southeast BF)	$7.8^o \leq s \leq 13.2^o$ L (south M and southwest BF to northeast CI)	$4.9^o \leq z \leq 10.1^o$ L (northwest to south and central-east CI)
1940-49	$16^o \leq a \leq 18.1^o$ L (north to central M)	$13.7^o \leq x \leq 15.3^o$ L (central M to north BF)	$12^o \leq r \leq 15.2^o$ L (central M/BF)	$11^o \leq y \leq 13.5^o$ L (southwest M to central-south BF)	$6.4^o \leq s \leq 11.5^o$ L (south M to north-central and central-east CI)	$5.1^o \leq z \leq 10^o$ L (northwest to south and central-east CI)
1950-59	$17.4^o \leq a \leq 19.6^o$ L (north M)	$15^o \leq x \leq 16^o$ L (central-north M to northern border BF)	$13.1^o \leq r \leq 15.4^o$ L (central M to north BF)	$11.6^o \leq y \leq 13.9^o$ L (southwest M to central BF)	$9.5^o \leq s \leq 13^o$ L (southwest M to southwest BF and extreme northeast CI)	$5.9^o \leq z \leq 11^o$ L (extreme south M to northwest and central to central-east CI)
1960-69	$16.4^o \leq a \leq 20^o$ L (north M)	$14.6^o \leq x \leq 15.3^o$ L (central M to extreme north BF)	$13.1^o \leq r \leq 14.7^o$ L (central M to north BF)	$11.2^o \leq y \leq 13.5^o$ L (southwest M to central and south-southeast BF)	$8.1^o \leq s \leq 11.7^o$ L (southwest M and extreme southwest BF to northeast CI)	$6.1^o \leq z \leq 10.3^o$ L (northwest to central and central-east CI)
1970-79	$15.5^o \leq a \leq 16.8^o$ L (north-central M)	$14^o \leq x \leq 15.3^o$ L (central M to north BF)	$11.9^o \leq r \leq 14^o$ L (central M and central BF)	$8^o \leq y \leq 12.6^o$ L (southwest M/BF and northeast CI)	$6^o \leq s \leq 11.3^o$ L (south M to central-east CI)	$5.2^o \leq z \leq 10.3^o$ L (northwest to south and southeast CI)
1980-89	$15^o \leq a \leq 16^o$ L (north-central M)	$13.4^o \leq x \leq 15.2^o$ L (central M to north BF)	$11.4^o \leq r \leq 14^o$ L (south M to central and south BF)	$7.7^o \leq y \leq 11.9^o$ L (south M to southwest BF and central to northeast CI)	$5.5^o \leq s \leq 9.6^o$ L (northwest to central, south, and southeast CI)	$5^o \leq z \leq 7.7^o$ L (west to southwest and southeast CI)
1990-98	$15.4^o \leq a \leq 16.3^o$ L (north-central M)	$14^o \leq x \leq 15.3^o$ L (central M to extreme north BF)	$11.7^o \leq r \leq 14^o$ L (south-central M to central and central-north BF)	$8.1^o \leq y \leq 13^o$ L (southwest M/BF to northeast CI)	$6.1^o \leq s \leq 12.1^o$ L (south M and extreme southwest BF to north-central and central-east CI)	$5^o \leq z \leq 8.2^o$ L (west to southwest and southeast CI)

Table 4.8*b*: Decadal number of rainfall stations out of 42 in each isohyet range (mm).

Decade	≤ 250	251-500	501-750	751-1000	1001-1250	1251-1500	≥ 1501
1930-39	1	4	5	8	8	10	6
1940-49	2	6	3	9	9	5	8
1950-59	1	4	4	7	9	7	10
1960-69	1	4	6	8	9	3	11
1970-79	4	4	6	11	6	2	9
1980-89	5	3	9	11	4	5	5
1990-98	5	3	7	11	4	5	7

During the relatively drier 1940s, when more rainfall stations (8 vs. 5 in the 1930s) recorded less than 500 mm (only 2 had less than 250 mm), all of these six isohyets moved slightly southward from their location in the 1930s. In the 1950s, the isohyets reversed their trend and shifted northward. The stations with less than 500 mm again were reduced to five (only 1 recorded ≤ 250 mm) and were confined to central Mali and northern Burkina Faso. However, the number of stations with more than 1,500 mm increased to 10 (vs. 8 in the 1940s). The situation again was slightly reversed during the 1960s, with southward isohyetal shifts that gradually continued to move further equatorward during the 1970s. In the 1980s, all of the six isohyets shifted toward the south, with an increased number of rainfall stations recording less than 1,000 mm (28 vs. 16 in the 1950s). The 1990s brought about a very slight northward shift of the six isohyets, with a noticeable rainfall increase occurring only in central Côte d'Ivoire for the ≥ 1,501 mm category (7 vs. 5 in the 1980s).

The conclusions from these decadal rainfall patterns are that rainfall has declined since the late 1960s, continued and intensified this decline from the 1970s to the 1980s, and made only slight improvement towards the end of the 1990s, with the last three decadal average rainfalls well below the long-term mean. These observations reinforce the downward trends detected from the rainfall index in earlier paragraphs (see Section 4.1.2.1). These conclusions have also been well-recognized and documented by numerous authors (e.g., Lamb, 1978a,b, 1982; Servat et al., 1997; Nicholson, 1998). However, this Dissertation also had the opportunity to look in detail at the spatial coherence of the decadal patterns of this multi-country area, which stretches from the Sahelo-Sahara south to the Guinea Coast. Furthermore, this study has started earlier (1930) and ended later (1998) than some of these other studies (See Chapter 2).

4.1.2.3 Monthly Rainfall Patterns

Mean monthly rainfall totals were computed from daily records. These computations permitted identification of the three driest and three rainiest calendar months for each Central West African rainfall station, as shown in Table 4.9*a* and Figure 4.7. With this information and especially the PCA-based rainfall regionalization (see Figs. 4.1*d*,*e*) as a basis, Central West Africa was divided into two unequal zones composed of rainfall stations with similar annual cycle characteristics: north and south of 9.3° N latitude (Table 4.9*b* and Fig. 4.8). Using three-month periods was appropriate since the prevailing July-September-centered rainy season (for 29 out of 42 rainfall stations; all of which are north of 9.3° N) consists of three months. This three-month focus also is applied to the remaining 13 rainfall stations south of 9.3° N to harmonize the monthly rainfall study throughout Central West Africa, thus making data comparisons more uniform.

In Figure 4.8, each zone has an average annual rainfall cycle that is either mono-modal (north of 9.3° N) or bimodal (south of 9.3° N). The north zone (29 stations), in which rainfall increases rapidly from May to August and then decreases more abruptly by October, is from 9.3° to 18.5° N. Rainfall in the north zone is distinctly mono-modal and is concentrated in July-September, with these three rainiest months contributing more than 60% of the total annual rainfall. The south zone (13 stations) is smaller and extends from 9.3° N south to the coast. Rainfall here is bimodal and increases from April to June, decreases during July-August, and increases again through October. The rain is heaviest in May, June, and September, but these three months together contribute only from 30% to 50% of the annual rainfall because the other months still receive some amounts of rain.

Table 4.9*a*: Mean monthly rainfall totals (mm) for the 42 stations used. The three driest (underlined) and rainiest (bold) months for each station are highlighted; Tot. = annual totals. Rainfall stations are ordered by latitude, as in Table 4.5*b*. See Table 4.9*b* for station latitudes.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tot.
Kidal	1.1	0.7	0.5	2.3	10.0	10.6	**34.9**	**46.5**	**24.1**	3.8	0.5	0.5	135.5
Goundam	1.7	0.3	0.2	0.8	6.7	16.3	**60.5**	**85.5**	**39.3**	10.9	0.6	0.3	223.1
Gao	0.4	0.2	1.2	3.2	10.1	23.1	**64.7**	**86.9**	**35.1**	6.3	0.0	0.3	231.5
Menaka	0.1	0.2	1.7	2.2	11.4	23.3	**71.1**	**98.1**	**36.9**	7.9	0.2	0.1	253.2
Ansongo	0.0	1.2	1.3	2.0	21.5	26.9	**68.5**	**111.6**	**41.1**	9.5	0.0	0.0	283.6
Douentza	0.3	1.3	3.9	8.1	19.7	60.5	**125.2**	**156.2**	**86.6**	26.2	1.1	1.4	490.5
Mopti	2.4	0.1	1.3	5.1	22.4	50.8	**137.8**	**169.0**	**90.2**	20.6	0.8	1.0	501.5
Kayes	0.8	1.0	0.3	3.4	19.6	92.9	**162.6**	**244.4**	**150.5**	41.2	4.8	2.0	723.5
Dori	0.0	6.5	2.8	5.8	24.0	63.2	**140.5**	**177.4**	**81.4**	14.3	0.4	0.3	516.6
Bafoulabe	0.1	1.7	0.5	4.4	25.9	115.8	**195.1**	**281.9**	**178.6**	47.1	5.1	0.7	856.9
Kolokani	0.9	0.7	5.2	12.2	34.8	103.6	**196.6**	**246.1**	**156.5**	40.0	7.2	1.3	805.1
Ouahigouya	0.0	0.2	3.1	11.8	37.5	89.9	**169.1**	**210.0**	**117.3**	28.7	2.1	0.5	670.2
Kaya	0.0	0.7	5.1	21.2	47.6	112.0	**156.4**	**223.6**	**129.8**	25.4	1.3	0.3	723.4
Kita	1.5	0.7	2.2	12.7	44.9	147.3	**239.3**	**312.8**	**204.2**	69.5	10.4	1.8	1047.3
Dedougou	1.5	1.9	8.3	24.3	67.3	111.2	**197.4**	**260.1**	**153.6**	47.8	4.5	0.5	878.4
Koutiala	1.5	3.2	6.4	26.4	67.8	128.5	**214.0**	**274.2**	**176.5**	53.2	8.5	4.1	964.3
Ouagadougou	0.0	2.0	8.1	22.1	73.7	105.2	**172.0**	**233.6**	**132.1**	32.8	2.1	0.6	784.3
Koudougou	0.2	1.4	10.1	22.3	65.6	104.1	**171.5**	**247.2**	**154.4**	40.9	3.2	1.3	822.2
FadaN'gourma	0.3	1.7	10.7	25.1	82.8	122.5	**182.3**	**244.4**	**154.9**	33.2	1.8	2.0	861.7
Tenkodogo	1.0	3.9	12.9	30.9	89.5	117.6	**175.2**	**252.9**	**166.1**	36.3	2.5	0.6	889.4
Boromo	0.8	2.4	9.4	35.6	84.5	108.9	**196.2**	**269.3**	**178.1**	45.5	9.7	2.5	942.9
Hounde	0.9	4.9	10.8	40.4	90.4	127.2	**193.2**	**260.2**	**184.2**	53.6	11.3	2.6	979.7
Sikasso	2.6	88.4	19.2	60.0	115.9	172.1	**240.4**	**305.7**	**233.4**	86.2	31.7	4.5	1360.1
BoboDioulasso	1.5	4.8	20.9	45.9	106.9	130.8	**214.2**	**307.5**	**190.4**	63.7	10.8	2.9	1100.3
Leo	2.5	3.8	18.4	51.2	97.4	126.2	**183.9**	**256.5**	**179.0**	48.7	8.6	3.6	979.8
Banfora	1.8	7.1	23.0	57.5	107.0	133.9	**195.8**	**283.8**	**190.7**	68.1	20.0	3.9	1092.6
Gaoua	4.4	6.0	30.2	71.3	128.2	138.3	**184.7**	**231.4**	**198.5**	81.7	17.6	8.0	1100.3
Boundiali	5.9	14.0	53.9	83.8	115.1	165.9	**254.1**	**336.9**	**241.7**	119.4	31.9	7.4	1430.0
Odienne	4.1	12.7	35.4	77.7	120.7	158.0	**283.2**	**351.8**	**275.5**	148.5	42.8	10.3	1520.7
Bouna	4.5	14.0	45.8	92.4	132.9	**138.8**	**138.9**	136.3	**219.4**	98.4	30.8	9.4	1061.6
Dabakala	8.4	29.4	62.3	118.2	124.2	**134.1**	103.4	**142.5**	**201.6**	115.5	28.7	13.1	1081.4
Seguela	13.0	40.3	76.2	101.4	141.1	129.2	118.8	**185.0**	**230.5**	**152.9**	45.5	23.9	1257.8
Man	14.0	54.0	110.9	158.1	153.3	192.0	**204.3**	**275.8**	**312.0**	172.6	52.6	22.6	1722.2
Abengourou	10.1	45.1	123.4	147.6	**193.2**	**216.1**	132.5	63.3	138.0	**175.3**	60.4	21.1	1326.1
Toulepleu	15.6	49.4	124.8	142.0	**191.9**	**227.0**	151.4	181.0	**321.2**	191.8	73.2	33.1	1702.4
Guiglo	18.4	52.1	110.1	149.4	169.5	**232.6**	138.2	181.7	**286.6**	**202.1**	54.0	28.6	1623.3
Gagnoa	25.0	64.3	136.7	161.4	**183.1**	**212.9**	88.7	79.0	**166.3**	161.0	100.1	42.2	1420.7
Agboville	17.5	44.2	106.7	141.5	**190.3**	**250.7**	115.5	65.1	114.4	**165.9**	111.9	32.5	1356.2
Aboisso	30.9	61.0	115.2	157.0	**227.5**	**359.1**	197.1	94.1	135.2	**214.9**	142.1	61.7	1795.8
Grand Lahou	16.6	39.2	80.5	121.9	**267.6**	**495.0**	**162.1**	28.7	45.9	126.7	140.2	70.5	1594.9
Sassandra	22.5	29.5	61.4	109.3	**276.0**	**483.9**	**146.6**	29.5	44.5	99.3	139.3	83.1	1524.9
Tabou	49.5	48.9	83.5	138.1	**410.3**	**521.6**	177.3	128.3	**231.9**	192.1	118.5	134.9	2234.9

Table 4.9*b*: Average classifications of the driest and rainiest months. Rainfall stations are ordered by latitude, as in Table 4.5*b*. Months are ordered from wettest to least wet for rainiest months and from driest to least dry for driest months. Parentheses contain peak(s) of the annual cycle.

Zone	Station	Latitude (^oN)	Driest Months	Rainiest Months	Annual Cycle Characteristic
NORTH OF 9.3° N	Kidal	18.26	Nov, Dec, Mar	Aug, Jul, Sep	Mono-modal (Aug)
	Goundam	16.25	Mar, Dec, Feb	Aug, Jul, Sep	Mono-modal (Aug)
	Gao	16.16	Nov, Feb, Dec	Aug, Jul, Sep	Mono-modal (Aug)
	Menaka	15.52	Dec, Jan, Nov	Aug, Jul, Sep	Mono-modal (Aug)
	Ansongo	15.40	Nov, Dec, Jan	Aug, Jul, Sep	Mono-modal (Aug)
	Douentza	14.59	Jan, Nov, Feb	Aug, Jul, Sep	Mono-modal (Aug)
	Mopti	14.31	Feb, Nov, Dec	Aug, Jul, Sep	Mono-modal (Aug)
	Kayes	14.26	Mar, Jan, Feb	Aug, Jul, Sep	Mono-modal (Aug)
	Dori	14.02	Jan, Dec, Nov	Aug, Jul, Sep	Mono-modal (Aug)
	Bafoulabe	13.48	Jan, Mar, Dec	Aug, Jul, Sep	Mono-modal (Aug)
	Kolokani	13.35	Feb, Jan, Dec	Aug, Jul, Sep	Mono-modal (Aug)
	Ouahigouya	13.35	Jan, Feb, Dec	Aug, Jul, Sep	Mono-modal (Aug)
	Kaya	13.06	Jan, Dec, Feb	Aug, Jul, Sep	Mono-modal (Aug)
	Kita	13.04	Feb, Jan, Dec	Aug, Jul, Sep	Mono-modal (Aug)
	Dedougou	12.28	Dec, Jan, Feb	Aug, Jul, Sep	Mono-modal (Aug)
	Koutiala	12.24	Jan, Feb, Dec	Aug, Jul, Sep	Mono-modal (Aug)
	Ouagadougou	12.22	Jan, Dec, Feb	Aug, Jul, Sep	Mono-modal (Aug)
	Koudougou	12.16	Jan, Dec, Feb	Aug, Jul, Sep	Mono-modal (Aug)
	Fada N'gourma	12.04	Jan, Feb, Nov	Aug, Jul, Sep	Mono-modal (Aug)
	Tenkodogo	11.46	Dec, Jan, Nov	Aug, Jul, Sep	Mono-modal (Aug)
	Boromo	11.44	Jan, Feb, Dec	Aug, Jul, Sep	Mono-modal (Aug)
	Hounde	11.29	Jan, Dec, Feb	Aug, Jul, Sep	Mono-modal (Aug)
	Sikasso	11.21	Jan, Dec, Mar	Aug, Jul, Sep	Mono-modal (Aug)
	Bobo Dioulasso	11.10	Jan, Dec, Feb	Aug, Jul, Sep	Mono-modal (Aug)
	Leo	11.06	Jan, Dec, Feb	Aug, Jul, Sep	Mono-modal (Aug)
	Banfora	10.38	Jan, Dec, Feb	Aug, Jul, Sep	Mono-modal (Aug)
	Gaoua	10.20	Jan, Feb, Dec	Aug, Sep, Jul	Mono-modal (Aug)
	Boundiali	9.50	Jan, Dec, Feb	Aug, Jul, Sep	Mono-modal (Aug)
	Odienne*	9.30	Jan, Dec, Feb	Aug, Jul, Sep	Mono-modal (Aug)
SOUTH OF 9.3° N	Bouna*	9.30	Jan, Dec, Feb	Sep, Jul, Jun	Bimodal (Jul, Sep)
	Dabakala	8.40	Jan, Dec, Nov	Sep, Aug, Jun	Bimodal (Jun, Sep)
	Seguela	7.95	Jan, Dec, Feb	Sep, Aug, Oct	Bimodal (May, Sep)
	Man	7.23	Jan, Dec, Nov	Sep, Aug, Jul	Bimodal (Apr, Sep)
	Abengourou	6.70	Jan, Dec, Feb	Jun, May, Oct	Bimodal (Jun, Oct)
	Toulepleu	6.57	Jan, Dec, Feb	Sep, Jun, May	Bimodal (Jun, Sep)
	Guiglo	6.53	Jan, Dec, Feb	Sep, Jun, Oct	Bimodal (Jun, Sep)
	Gagnoa	6.08	Jan, Dec, Feb	Jun, May, Sep	Bimodal (Jun, Sep)
	Agboville	5.90	Jan, Dec, Feb	Jun, May, Oct	Bimodal (Jun, Oct)
	Aboisso	5.47	Jan, Feb, Dec	Jun, May, Oct	Bimodal (Jun, Oct)
	Grand Lahou	5.13	Jan, Aug, Feb	Jun, May, Jul	Bimodal (Jun, Nov)
	Sassandra	4.95	Jan, Feb, Aug	Jun, May, Jul	Bimodal (Jun, Nov)
	Tabou	4.42	Feb, Jan, Mar	Jun, May, Sep	Bimodal (Jun, Sep)

*** Odienne and Bouna have the same latitudes but have different longitudes (see Table 4.5*b*).**

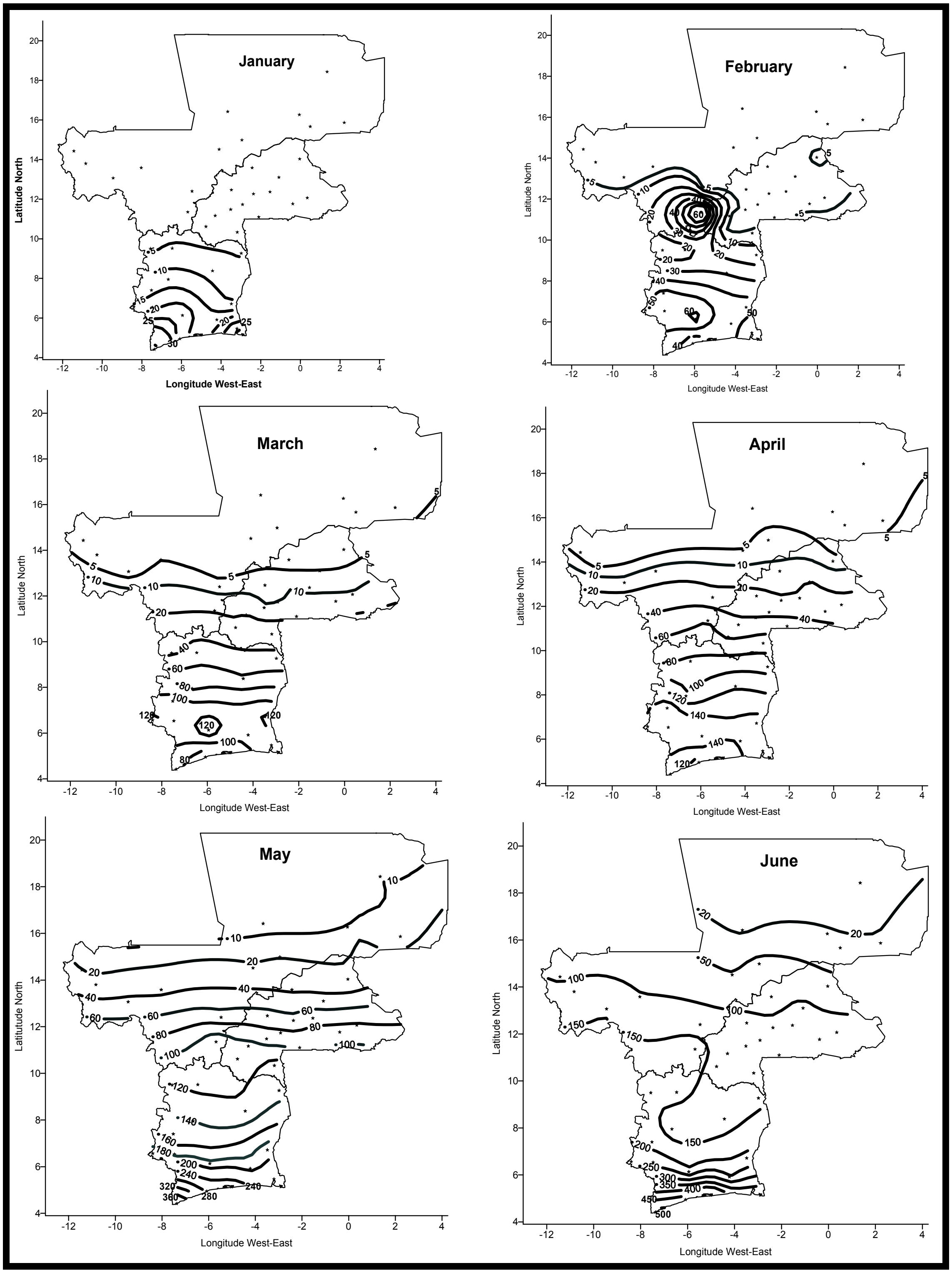


Figure 4.7: Average monthly rainfall (mm) across Central West Africa. Dots locate the 42 rainfall stations used in the analysis.

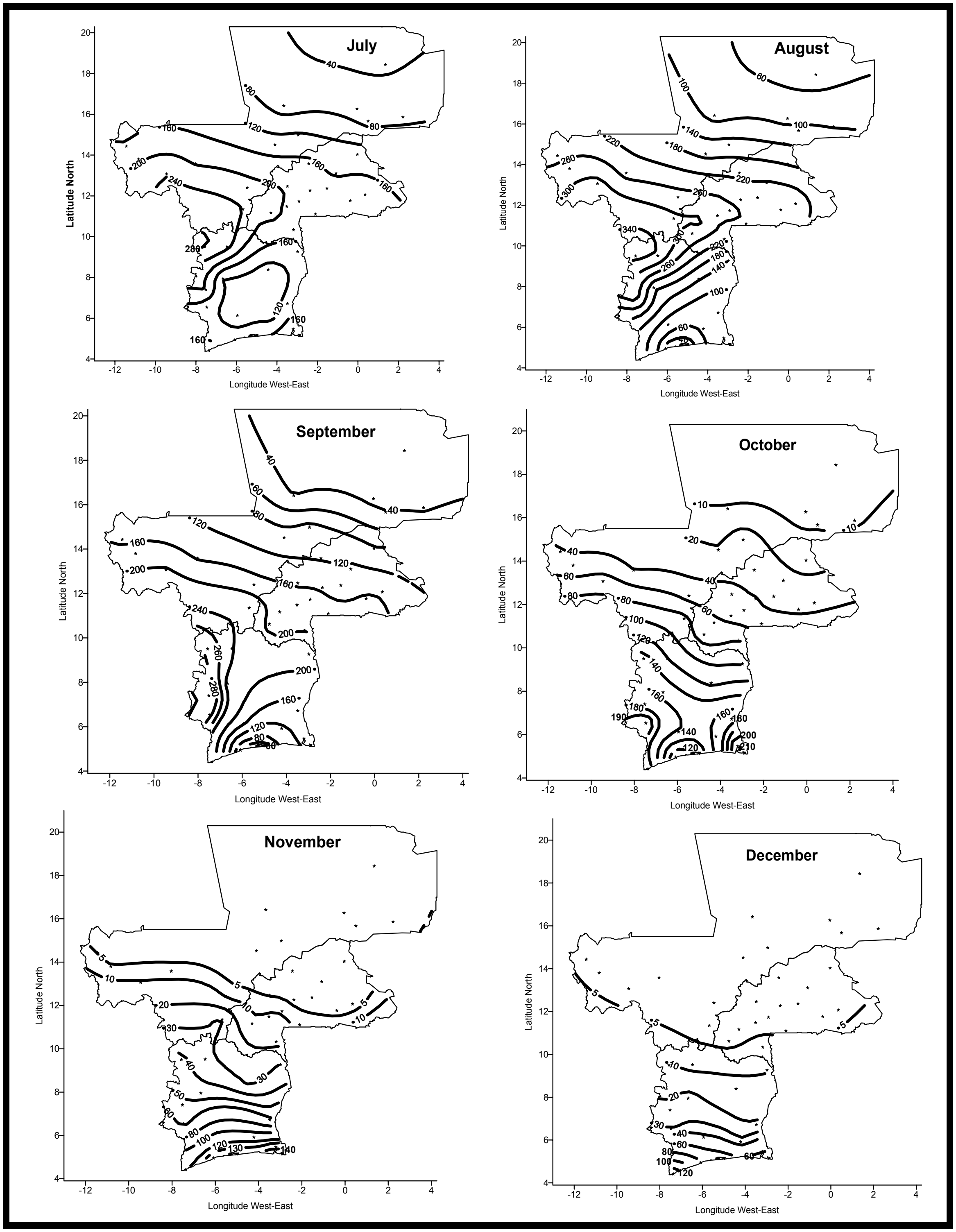


Figure 4.7 (continued): Average monthly rainfall (mm) across Central West Africa. Dots locate the 42 rainfall stations used in the analysis.

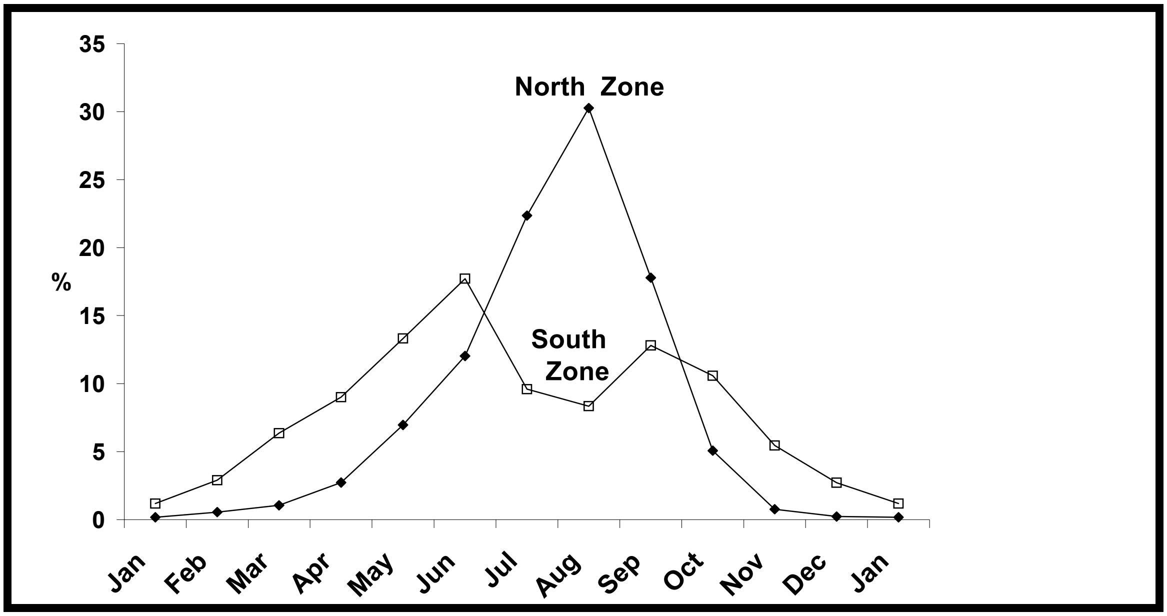


Figure 4.8: Average monthly contributions (percent) to the annual rainfall in the zones north and south of 9.3° N. Percentages are obtained by first calculating the average percent for each month and for each station, and then averaging those percents across the stations in each zone.

Table 4.10*a* indicates the number of stations (out of 42) for which each three-month contribution was driest or rainiest, while Table 4.10*b* displays the contributions of each month to the annual rainfall totals. Note that Tables 4.10*a*,*b* follow the monthly calendar order for ease of formatting.

Tables 4.10*a*,*b* confirm that December, January, and February are the three driest months (24 stations), while July, August, and September are the three rainiest months (30 stations). Each month's contribution to the annual average station rainfall varies from none to little in January (0-2%) to a maximum in August (39%), when the seasonal northward movement of the ITCZ has its full effect in northern Central West Africa (Section 2.1.1). However, the coastal stations of Grand Lahou and Sassandra register their lowest percentages (2%) in August, when they experience their short dry season associated with Gulf of Guinea upwelling that generally occurs in that month. In summary, individual months during November-February contribute the least (0-9%), while individual months between May-October supply the most (2-39%), to Central West African station annual average rainfall. These monthly contributions vary greatly from one zone to another. For instance, in the zone north of 9.3° N, individual months during November-April register 0% of annual average rain for 19 of the 29 stations. The fewest stations (1 of 29) report 0% for April, while the most stations (15 of 29) report 0% for January. In the zone south of 9.3° N, on the other hand, out of 13 rainfall stations only Bouna contributes 0% rain in January. Table 4.10*b* illustrates these differences in monthly contributions.

Table 4.10*a*: Number of stations (out of 42) for which each three-month contribution was driest or rainiest. Months follow the calendar order (unlike in Table 4.9*b*).

Driest Months	Nov Dec Mar	Dec Feb Mar	Nov Dec Feb	Nov Dec Jan	Nov Jan Feb	Jan Feb Mar	Dec Jan Mar	Dec Jan Feb	Jan Feb Aug
Number of Stations	1	1	2	6	2	2	2	24	2
Rainiest Months	Jul Aug Sep	Jun Jul Sep	Jun Aug Sep	Aug Sep Oct	May Jun Oct	May Jun Sep	Jun Sep Oct	May Jun Jul	
Number of Stations	30	1	1	1	3	3	1	2	

Table 4.10*b*: Range of monthly contributions (%) to the annual average rainfall at 42 individual stations. Months follow the calendar order.

Month	North of 9.3° N	South of 9.3° N	Entire Study Region
January	0 - 1	0 - 2	0 - 2
February	0 - 6	1 - 5	0 - 6
March	0 - 4	4 - 10	0 - 10
April	0 - 6	6 - 11	0 - 11
May	3 - 12	9 - 18	3 - 18
June	7 - 15	10 - 32	7 - 32
July	17 - 28	6 - 13	6 - 28
August	21 - 39	2 - 16	2 - 39
September	14 - 21	3 - 21	3- 21
October	3 - 10	7 - 13	3 - 13
November	0 - 3	3 - 9	0 - 9
December	0 - 1	1 - 6	0 - 6
Months that contribute the least	Nov, Dec, Jan	Dec, Jan, Feb	Dec, Jan, Feb
Months that contribute the most	Jul, Aug, Sep	May, Jun, Sep	Jun, Jul, Aug

In addition, for the entire study area, each of the six months during May-October receives a monthly station total ranging from 3.8 mm (October for Kidal) to 521.6 mm (June for Tabou), while the other months between November-April register from 0 mm (November for Gao and Ansongo; December for Ansongo; January for Ansongo, Dori, Ouahigouya, Kaya, and Ouagadougou), to 161.4 mm (April for Gagnoa), which is less than one third of the above May-October range (from 3.8 mm to 521.6 mm). Admittedly, during November-April, there are enough rain occurrences for the zone south of 9.3^{o} N to permit the growth and development of most plants in this (southern) part of the study area. However, it is clear that most of the rainfall in Central West Africa when viewed as a whole is normally received over a 6-month period (during May-October), and water availability for most plant growth is therefore concentrated on those months.

4.1.2.4 Monthly, Seasonal, and Annual Number of Rain Days

This portion of the study determines the average number of rain days over different time-scales (i.e., months, seasons, annual) and emphasizes the latitudinal rainfall differences and distributions within the study area based on the 0.1 mm day^{-1} threshold (definition of rain day) as suggested by the National Meteorological Services across Central West Africa (see Section 3.1.2.5 for discussion of threshold issues). The results are presented in Tables 4.11*a*,*b*, describing the geographical variation of rain days across the study region.

Table 4.11*a* reveals that the average number of rain days per month in Central West Africa increases from no rain day (January) to 12 days (August) for the zone north of 9.3^{o} N, and from 2 days (January) to 14 days (June) then 13 days (September) for the zone south of 9.3^{o} N. January registers the least rain days for all stations, while August has the most rain days for both the zone north of 9.3° N and entire study area, and June and September record the most rain days for the zone south of 9.3° N. For the whole of Central West Africa as well as for the zone north of 9.3° N, there is a distinct increase from April to August and an abrupt decrease after September. For the zone south of 9.3° N, there is an increase from March to June, a decrease in July-August, another increase in September-October, and a decrease thereafter.

Table 4.11*a*: Average number of rain days per month across stations that are located in the zones north (29 stations) and south (13 stations) of 9.3° N. Extreme values are in bold, including two maxima south of 9.3° N.

Month	North of 9.3° N	South of 9.3° N	Entire Study Region
January	**0**	**2**	**1**
February	**0**	3	1
March	1	6	2
April	2	8	4
May	4	11	6
June	7	**14**	9
July	9	10	10
August	**12**	10	**12**
September	11	**13**	11
October	5	12	7
November	1	8	3
December	0	4	1

Complementing the above zonally and regionally averaged information, Table 4.11*b* displays for each station the average seasonal and annual number of rain days, as well as the contribution of each season to the annual total. During the March-June-centered rainy season, the average number of rain days in the zone south of 9.3° N varies greatly from 25 days at Dabakala to 57 days at Tabou. For the July-September- centered rainy season north of 9.3° N, this seasonal average number of rain days fluctuates from 15 days at Goundam to 57 days at Odienne, while for the October-November-centered rainy season south of 9.3° N, the range is from 12 days at Bouna and Dabakala to 34 days at Tabou. Also, there is a large variation in the annual average total rain days, which ranges from 20 days at Goundam to more than 164 days at Tabou (Table 4.11*b*).

Table 4.11*b*: Seasonal and annual average number (#) of rain days and the contribution (%) of each rainy season to the annual average number of rain days. Extreme values are in bold; MAMJ = March-June; JAS = July-September; ON = October-November.

Zone	Station	Lat. (^{o}N)	MAMJ#	MAMJ%	JAS#	JAS%	ON#	ON%	Annual#
NORTH OF 9.3^o N	Kidal	18.26	NOT APPICABLE	NOT APPICABLE	17	**81**	NOT APPICABLE	NOT APPICABLE	21
	Goundam	16.25			**15**	75			**20**
	Gao	16.16			23	77			30
	Menaka	15.52			22	76			29
	Ansongo	15.40			21	75			28
	Douentza	14.59			27	71			38
	Mopti	14.31			35	70			50
	Kayes	14.26			40	69			58
	Dori	14.02			34	71			48
	Bafoulabe	13.48			39	71			55
	Kolokani	13.35			38	68			56
	Ouahigouya	13.35			36	67			54
	Kaya	13.06			33	66			50
	Kita	13.04			49	64			77
	Dedougou	12.28			38	63			60
	Koutiala	12.24			46	61			75
	Ouagadougou	12.22			41	62			66
	Koudougou	12.16			36	62			58
	Fada N'gourma	12.04			43	61			70
	Tenkodogo	11.46			36	59			61
	Boromo	11.44			45	59			76
	Hounde	11.29			37	59			63
	Sikasso	11.21			28	74			38
	Bobo Dioulasso	11.10			49	57			86
	Leo	11.06			37	59			63
	Banfora	10.38			36	55			66
	Gaoua	10.20			44	51			87
	Boundiali	9.50			39	**50**			78
	Odienne*	9.30			**57**	**50**			115
SOUTH OF 9.3^o N	Bouna*	9.30	26	38	NOT APPICABLE	NOT APPICABLE	**12**	18	68
	Dabakala	8.40	**25**	38			**12**	18	65
	Seguela	7.95	26	36			15	21	73
	Man	7.23	44	**33**			22	**16**	134
	Abengourou	6.70	44	40			22	20	109
	Toulepleu	6.57	39	36			21	19	109
	Guiglo	6.53	37	36			19	19	102
	Gagnoa	6.08	52	40			27	21	129
	Agboville	5.90	45	41			24	**22**	111
	Aboisso	5.47	42	39			23	21	107
	Grand Lahou	5.13	35	**45**			17	**22**	77
	Sassandra	4.95	47	42			22	20	111
	Tabou	4.42	**57**	35			**34**	21	**164**

*** Odienne and Bouna have the same latitudes but have different longitudes (see Table 4.5*b*).**

Additionally, Figure 4.9 portrays the geographical distribution of the average number of rain days for the seasonal and annual time-scales. Note that Figure 4.9 provides original continuous three-country maps of these vital climatological parameters. The average contributions of Central West African rainy seasons to the annual average number of rain days for individual stations range from 50 to 81% (July-September) to 33 to 45% (March-June) and 16 to 22% (October-November) (see Table 4.11*b* for breakdown by station and season). These fractions reveal that in spite of there being two principal rainy seasons (March-June and October-November) in the zone south of 9.3^{o} N, the other months (during July-September and between December-February) still have a considerable number of rain days in that zone that vary between 33 and 51% from one station to another (percentages left after subtracting the contributions of the rainy seasons centered on March-June and October-November). This situation indicates that rainfall occurs in every month in the zone south of 9.3^{o} N. On the other hand, in the zone north of 9.3^{o} N, only very few rainfall events occur outside of the July-September-centered rainy season, totaling less than 35% of the contributions of the other months for most stations. As can be expected, these rain day differences also contribute to the geographical variation of crop type in the study area (Section 4.3).

4.1.2.5 Onset and Cessation of the Rainy Seasons

The onset and cessation dates of the rainy seasons are important in planning farming activities such as plowing, planting, weeding, and harvesting (Sivakumar, 1988; Camberlain and Diop, 1999). Various methods have been used to determine the onset and cessation of tropical rainy seasons at a given station. The estimation of the beginning and ending of the rainy seasons was discussed in Section 3.1.2.6 and, as mentioned earlier, the

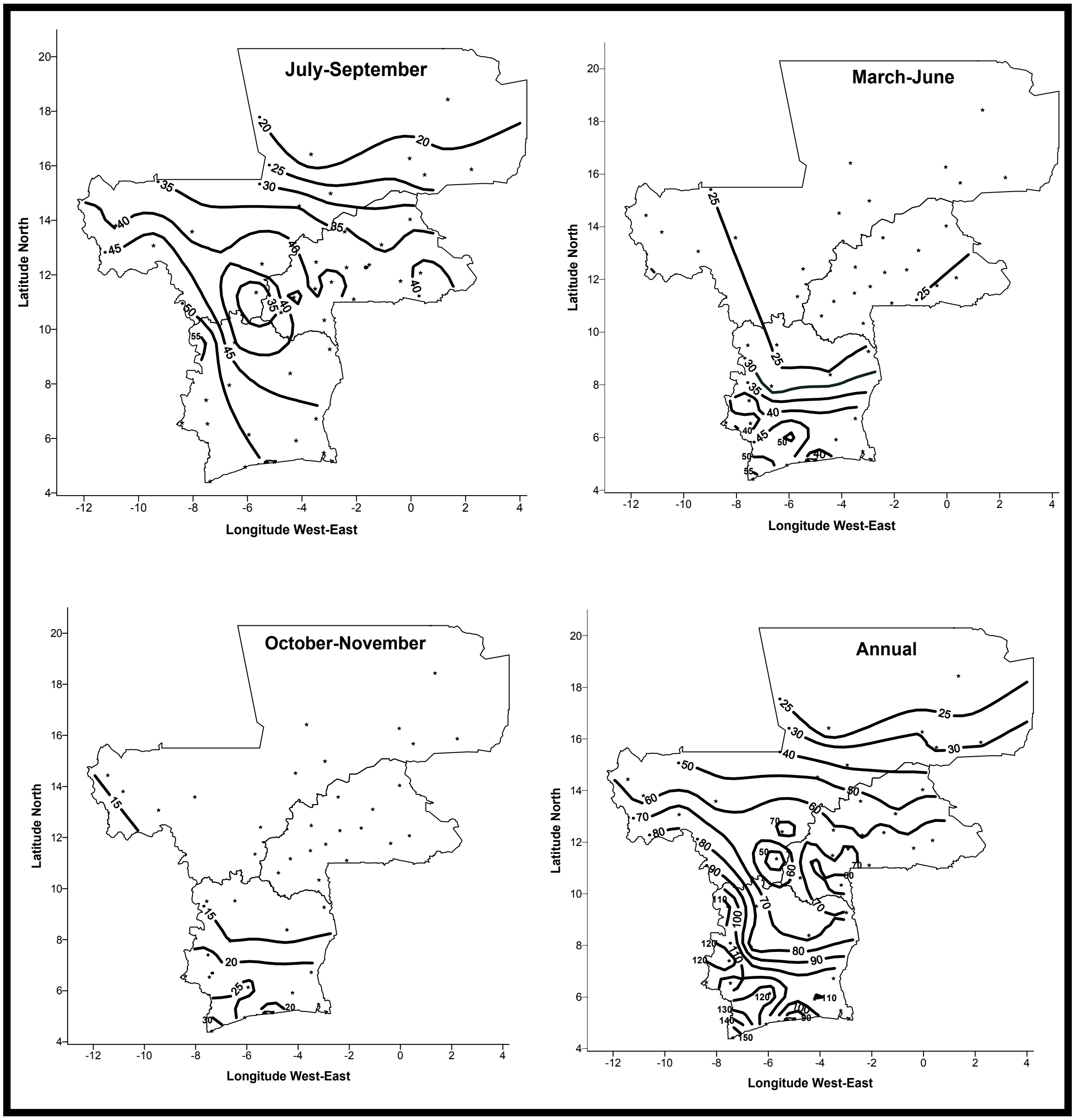


Figure 4.9: Average number of rain days for seasonal and annual time-scales. July-September-centered rainy season occurs in the zone north of 9.3° N, while both March-June- and October-November-centered rainy seasons occur in the zone south of 9.3° N. Dots locate the 42 rainfall stations used in the analysis.

Stern et al. (1982) and the Sivakumar (1988) techniques are employed in this study. Further, preliminary analyses suggested that the Sivakumar (1988) criteria work better for the rainy season centered on July-September (zone north of 9.3° N), while the Stern et al. (1982) technique is more appropriate for the rainy seasons centered on March-June and

October-November (zone south of 9.3^o N). However, due to the large northward rainfall gradient in Central West African, the application of these criteria produced some inconsistencies in the onset/cessation dates, high standard deviations, and unreasonably early beginnings and endings of rains.

To have more realistic results for the rainy season onset dates, the standard Stern et al. (1982) and Sivakumar (1988) criteria therefore were modified slightly for use in this study. Specifically, the "false start" assessment part of the onset component in the Sivakumar (1988) criterion was adjusted to correct inconsistencies (e.g., high standard deviations and unreasonably early beginnings/endings of rains) in onset dates for the zone north of 9.3^o N (July-September). As recommended by the AGRHYMET Center (2000) for modification of the Sivakumar criterion, the onset of the rainy season is defined as that date from January 1 onward, when rainfall P accumulated over a maximum of three consecutive days is at least 20 mm and when no dry spell within the next 30 days exceeds n days, where n is defined as follows:

$$n = \min[0, round(\frac{P}{1.8} + 1)]$$

Thus, a "false start" is considered to have occurred when the dry spell period in the next 30 days exceeds 20 days. The above formula was used to compute n for each station north of 9.3^o N. The results varied from one station to another, but all were ≤ 20 days. As a result, instead of the acceptable dry spell period not exceeding 7 days in the next 30 days, as stipulated in the original Sivakumar (1988) criterion, the modified one implies an extended acceptable dry spell period of ≤ 20 days (depending on the rainfall station) in the next 30 days, which would indicate that the rainy season has truly began.

Likewise, using the original Stern et al. (1982) criterion proved inadequate for determining the onset dates for the rainy season centered on October-November for bimodal rainfall stations in the zone south of 9.3^o N. Indeed, the onset dates for these bimodal stations produce October-November start date results that intermingle with the end of the rainy season centered on March-June, showing no break between the two seasons (March-June and October-November). To overcome this problem, after some experimentation the original Sivakumar (1988) criterion for "false start" here was substituted for the Stern et al. (1982) criterion for "false start" when applying the Stern onset criteria (see Chapter 3, Table 3.4). Hence, the Stern et al. (1982) criterion for onset and the Sivakumar (1988) criterion for "false start" are combined and used to determine the onset dates for the rainy season centered on October-November for bimodal stations in the zone south of 9.3^o N. Note that no modifications were needed for the rainy season cessation criteria of both Stern et al. (1982) and Sivakumar (1988).

Table 4.12 summarizes these standard, modified, and combined criteria, while Tables 4.13*a*,*b* and Figures 4.10*a*,*b* present the mean/earliest/latest onset/cessation dates at individual rainfall stations for the rainy seasons centered on March-June (south of 9.3^o N), July-September (north of 9.3^o N), and October-November (south of 9.3^o N, bimodal rainfall stations). Further, Table 4.14 reviews the dominant months of onset/cessation dates for these major Central West African rainy seasons centered on March-June, July-September, and October-November.

Table 4.12: Adoption and modification of Stern et al. (1982) and Sivakumar (1988) criteria for estimation of rainy season onset/cessation dates in the study area (see Chapter 3, Table 3.4).

RAINY SEASON	CRITERIA
ONSET	Earliest possible starting date is January 1 for March-June- and July-September-centered rainy seasons, and July 1 for October-November-centered rainy season
	Maximum number of consecutive days to record the cumulative rainfall amount is 2 (Stern) and 3 (Sivakumar) consecutive days
	Cumulative rainfall amount for specified period is 20 mm for both Stern and Sivakumar criteria
	Significant daily rainfall threshold is 0.1 mm
FALSE START	Dry spell period in the next 30 days should not exceed 7 (Sivakumar) or 10 (Stern) days [based on the AGRHYMET Center formula, the Sivakumar criterion was modified for the zone north of 9.3^{o} N]
CESSATION	Earliest possible ending date is June 1 for March-June season, July 1 for July-September season, and October 1 for October-November season
	Cumulative dry days for end of rainy season are 15 (Stern) and 20 (Sivakumar) days

Using the long-term (1930-98) daily rainfall for the 42 selected rainfall stations across Central West Africa, the mean/earliest/latest dates of onset and cessation of rains and their standard deviations were computed and plotted (Tables 4.13*a*,*b* and Figs. 4.10*a*,*b*). The results reveal that the onset/cessation dates of the rainy seasons centered on March-June (south of 9.3^{o} N), July-September (north of 9.3^{o} N), and October-November (south of 9.3^{o} N) vary greatly across the study region, showing a latitudinal progression of rainfall occurrence and retreat that are explained in detail in subsequent paragraphs. The average lengths and standard deviations of the growing season (Table 4.14 and Fig. 4.10*c*) indicate the magnitude and extent of interannual rainfall variability and contribute to the wide latitudinal variation in crops and farming strategies across the study area (Section 4.3).

Table 4.13*a* and Figure 4.10*a* (top) show variations in Central West African seasonal rainfall occurrence dates with a smooth northward progression of rains to produce both March-June- and July-September-centered rainy seasons. For the zone south of 9.3^{o} N, the March-June-centered rainy season starts on average by early to mid-March across the areas below 7.23^{o} N and the extreme southwest coast, and from early to mid-April across the remaining coastal regions and areas above 7.23^{o} N. Within this zone south of 9.3^{o} N, the

Table 4.13*a*: Mean/earliest/latest March-June- and July-September-centered rainy season onset/cessation dates in Central West Africa. March-June-centered rainy season results (south of 9.3^{o} N) are based on the unmodified Stern et al. (1982) criteria, while July-September-centered season results (north of 9.3^{o} N) are based on the Sivakumar (1988) criteria but with the onset modification described in the text and Table 4.12. Parentheses contain year(s) of earliest and latest date occurrence(s). σ = standard deviations (days) of mean onset and cessation dates.

Station	Lat. (^{o}N)	Mean				Earliest		Latest	
		Onset	σ	Cessation	σ	Onset	Cessation	Onset	Cessation
Kidal	18.26	19 Jul	25	16 Sep	12	27 May (57)	21 Aug (49)	26 Aug (44)	19 Oct (86)
Goundam	16.25	20 Jul	21	24 Sep	12	29 May (57)	29 Aug (41)	24 Aug (68)	22 Oct (30)
Gao	16.16	13 Jul	22	22 Sep	12	15 May (92)	30 Aug (91)	20 Aug (75)	27 Oct (76)
Menaka	15.52	14 Jul	21	22 Sep	13	9 May (84)	28 Aug (91)	18 Aug (74)	24 Oct (76)
Ansongo	15.40	6 Jul	24	27 Sep	13	12 May (98)	26 Aug (30)	10 Aug (95)	27 Oct (76)
Douentza	14.59	20 Jun	19	4 Oct	13	11 May (64)	3 Sep (35)	5 Aug (79)	28 Oct (76)
Mopti	14.31	19 Jun	23	5 Oct	14	28 Apr (63)	4 Sep (93)	3 Aug (42)	31 Oct (76)
Kayes	14.26	16 Jun	15	15 Oct	9	5 May (60)	25 Sep (64)	14 Jul (78)	28 Oct (55)
Dori	14.02	12 Jun	23	3 Oct	12	25 Apr (78)	30 Aug (48)	24 Jul (96)	28 Oct (30)
Bafoulabe	13.48	8 Jun	13	14 Oct	13	5 May (36)	31 Aug (95)	5 Jul (77)	12 Nov (51)
Kolokani	13.35	4 Jun	19	15 Oct	12	24 Apr (82)	15 Sep (42)	18 Jul (75)	8 Nov (51)
Ouahigouya	13.35	9 Jun	19	11 Oct	12	25 Apr (78)	7 Sep (53)	12 Jul (47)	2 Nov (51)
Kaya	13.06	30 May	17	8 Oct	12	28 Apr (41)	14 Sep (34)	6 Jul (35)	2 Nov (51)
Kita	13.04	27 May	15	22 Oct	9	15 Apr (68)	5 Oct (83)	27 Jun (70)	14 Nov (79)
Dedougou	12.28	24 May	20	18 Oct	13	9 Apr (36)	6 Sep (53)	6 Jul (44)	20 Nov (36)
Koutiala	12.24	19 May	18	23 Oct	10	3 Apr (31)	4 Oct (86)	24 Jun (93)	25 Nov (54)
Ouagadougou	12.22	22 May	20	15 Oct	12	8 Apr (88)	20 Sep (48)	4 Jul (63)	5 Nov (33)
Koudougou	12.16	28 May	22	17 Oct	12	30 Mar (68)	23 Sep (75)	6 Jul (34)	16 Nov (54)
Fada N'gourma	12.04	17 May	19	12 Oct	12	21 Mar (78)	21 Sep (37)	6 Jul (84)	6 Nov (92)
Tenkodogo	11.46	17 May	20	15 Oct	13	4 Apr (72)	23 Sep (48)	3 Jul (74)	5 Nov (53)
Boromo	11.44	16 May	23	19 Oct	14	18 Mar (71)	24 Sep (59)	15 Jul (43)	20 Nov (49)
Hounde	11.29	13 May	22	21 Oct	14	25 Mar (68)	24 Sep (59)	11 Jul (36)	18 Nov (41)
Sikasso	11.21	3 May	18	4 Nov	11	19 Mar (82)	30 Sep (86)	12 Jun (34)	26 Nov (58)
BoboDioulasso	11.10	27 Apr	20	26 Oct	13	10 Mar (82)	29 Sep (38)	11 Jun (47)	20 Nov (49)
Leo	11.06	10 May	23	21 Oct	16	7 Mar (55)	9 Sep (47)	8 Jul (85)	26 Nov (54)
Banfora	10.38	2 May	22	27 Oct	15	23 Mar (68)	17 Sep (83)	8 Jul (94)	9 Dec (42)
Gaoua	10.20	19 Apr	21	30 Oct	13	2 Mar (51)	3 Oct (88)	9 Jun (87)	10 Dec (47)
Boundiali	9.50	27 Apr	29	11 Nov	17	27 Feb (86)	1 Oct (59)	28 Jul (75)	9 Dec (56)
Odienne	9.30	21 Apr	22	20 Nov	16	22 Feb (93)	4 Sep (96)	22 Jun (34)	11 Dec (33)
Bouna	9.30	19 Apr	23	5 Aug	22	5 Mar (49)	23 Jun (80)	11 Jun (53)	4 Dec (49)
Dabakala	8.40	6 Apr	24	26 Jul	30	12 Feb (42)	24 Jun (35)	9 Jun (51)	3 Dec (38)
Seguela	7.95	3 Apr	28	18 Jul	37	5 Feb (51)	25 Jun (57)	10 Jun (47)	12 Dec (54)
Man	7.23	9 Mar	23	20 Oct	15	16 Jan (58)	25 Sep (38)	28 Apr (90)	16 Dec (75)
Abengourou	6.70	16 Mar	20	31Aug	27	27 Jan (55)	24 Jun (58)	8 May (95)	12 Dec (75)
Toulepleu	6.57	13 Mar	27	2 Sep	25	14 Jan (51)	27 Jun (64)	5 Jun (89)	15 Dec (81)
Guiglo	6.53	15 Mar	27	24 Aug	24	18 Jan (63)	3 Jul (68)	29 May (44)	15 Dec (55)
Gagnoa	6.08	4 Mar	21	29 Aug	36	24 Jan (70)	10 Jul (38)	23 Apr (37)	16 Dec (91)
Agboville	5.90	17 Mar	26	17 Aug	35	2 Feb (33)	20 Jul (38)	23 Jun (51)	16 Dec (48)
Aboisso	5.47	12 Mar	28	20 Aug	29	7 Jan (31)	20 Jul (86)	6 Jun (71)	13 Dec (79)
Grand Lahou	5.13	3 Apr	30	22 Jul	19	20 Jan (91)	26 Jun (61)	10 Jun (47)	15 Dec (84)
Sassandra	4.95	4 Apr	24	31 Jul	30	7 Feb (78)	29 Jun (80)	28 May (91)	16 Dec (75)
Tabou	4.42	8 Mar	37	24 Aug	44	5 Jan (80)	11 Jul (38)	13 May (35)	15 Dec (59)

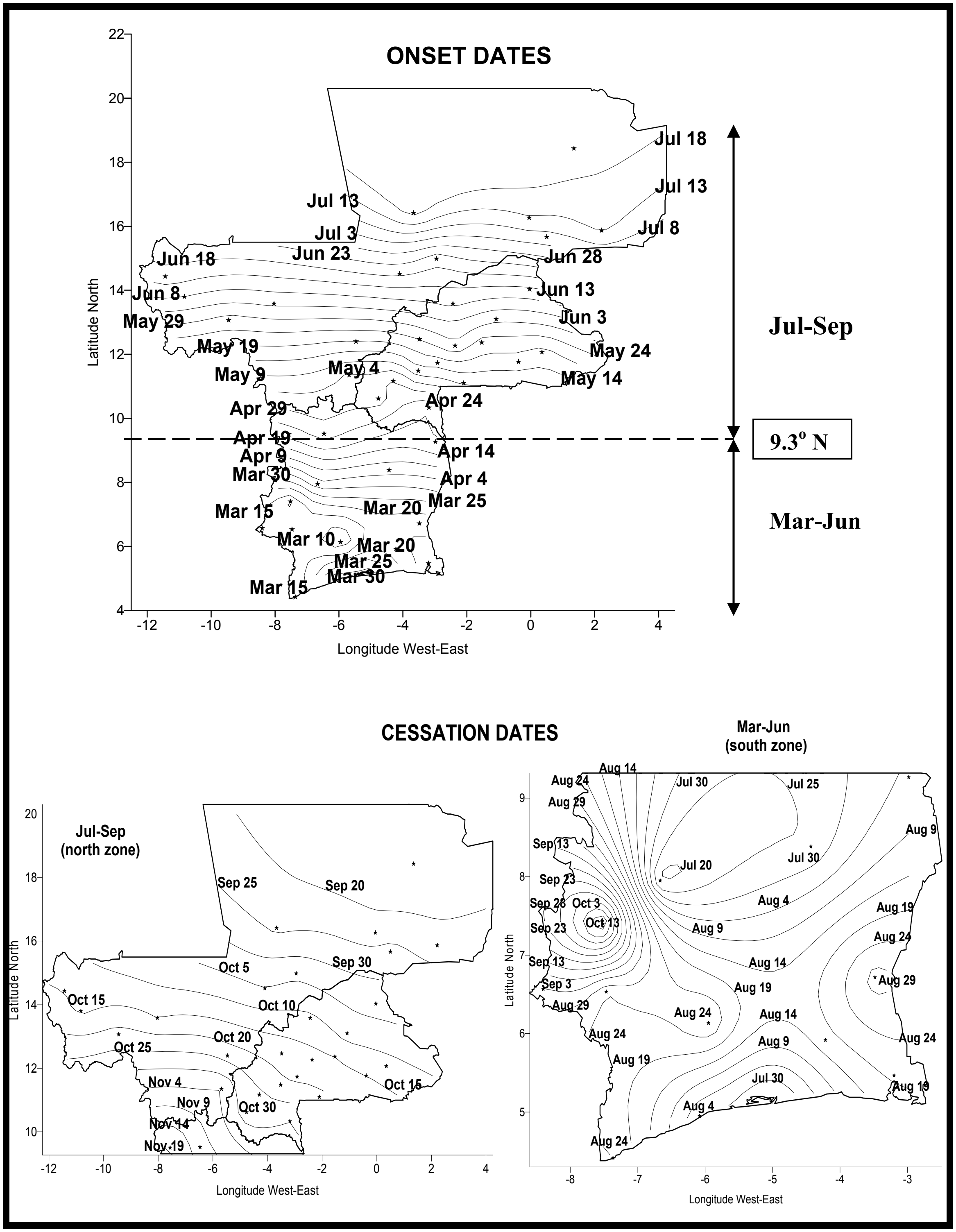


Figure 4.10*a*: Mean onset (top) and cessation (bottom left and right) dates of principal rainy seasons across Central West Africa. March-June-centered rainy season (south of 9.3° N) is based on the unmodified Stern et al. (1982) criteria, while July-September-centered rainy season (north of 9.3° N) is based on the Sivakumar (1988) criteria but with the onset modification described in the text and Table 4.12. Dots locate the 42 rainfall stations used in the analysis.

Table 4.13*b*: Mean/earliest/latest October-November-centered rainy season onset/cessation dates for bimodal rainfall stations in the zone south of 9.3^o N, based on combined Stern et al. (1982) and Sivakumar (1988) criteria as described in the text and Table 4.12. Parentheses contain year(s) of earliest/latest date occurrence(s). σ = standard deviations (days) of mean onset and cessation dates.

Station	Lat. (^{o}N)	Mean				Earliest		Latest	
		Onset	σ	Cessation	σ	Onset	Cessation	Onset	Cessation
Bouna	9.30	21 Aug	12	19 Nov	10	6 Aug (49)	20 Oct (35)	12 Oct (66)	4 Dec (49)
Dabakala	8.40	19 Aug	15	21 Nov	8	27 Jul (53)	20 Oct (44)	27 Sep (58)	3 Dec (38)
Seguela	7.95	10 Aug	16	24 Nov	10	19 Jul (39)	22 Oct (33)	17 Sep (81)	12 Dec (54)
Man	7.23	25 Oct	7	29 Nov	10	21 Oct (32)	26 Oct (71)	21 Nov (31)	16 Dec (75)
Abengourou	6.70	15 Sep	12	29 Nov	11	1 Sep (64)	19 Oct (84)	23 Oct (91)	12 Dec (75)
Toulepleu	6.57	9 Sep	10	29 Nov	15	3 Sep (30)	19 Oct (36)	26 Oct (63)	15 Dec (81)
Guiglo	6.53	2 Sep	9	27 Nov	12	25 Aug (31)	21 Oct (31)	14 Oct (78)	15 Dec (55)
Gagnoa	6.08	13 Sep	15	3 Dec	12	30 Aug (51)	27 Oct (37)	1 Nov (83)	16 Dec (91)
Agboville	5.90	15 Sep	18	4 Dec	12	18 Aug (66)	5 Nov (68)	25 Oct (82)	16 Dec (48)
Aboisso	5.47	10 Sep	17	1 Dec	14	21 Aug (33)	3 Nov (39)	17 Oct (72)	13 Dec (79)
Grand Lahou	5.13	3 Oct	23	24 Nov	18	7 Aug (96)	22 Oct (34)	5 Nov (76)	15 Dec (84)
Sassandra	4.95	4 Oct	29	15 Nov	19	16 Aug (70)	18 Oct (71)	23 Nov (71)	16 Dec (75)
Tabou	4.42	6 Sep	10	26 Nov	21	25 Aug (94)	28 Oct (68)	5 Oct (42)	15 Dec (59)

mean onset dates for the rainy season centered on March-June occur progressively later from the south-central and western regions to the coastal and northern areas and differ by a month and half (from March 4 at Gagnoa to April 19 at Bouna). Here, also, Table 4.13*a* shows there have been years when the onset of rains began as early as January 5-24 for south-central to western and coastal regions (1931 for Aboisso, 1951 for Toulepleu, 1955 for Abengourou, 1958 for Man, 1963 for Guiglo, 1970 for Gagnoa, 1980 for Tabou, 1991 for Grand Lahou) and as late as June 5-11, like in 1947 for Grand Lahou and Seguela, 1951 for Agboville and Dabakala, 1953 for Bouna, 1971 for Aboisso, and 1989 for Toulepleu.

For the zone north of 9.3^o N, the July-September-centered rainy season starts on average in late April-May across the areas below 13.06^o N, and from early June to mid-July across the regions above 13.06^o N (Table 4.13*a* and Fig. 4.10*a*, top). Still, there have been years when the rainy season began as early as February 22-27 in the extreme south of

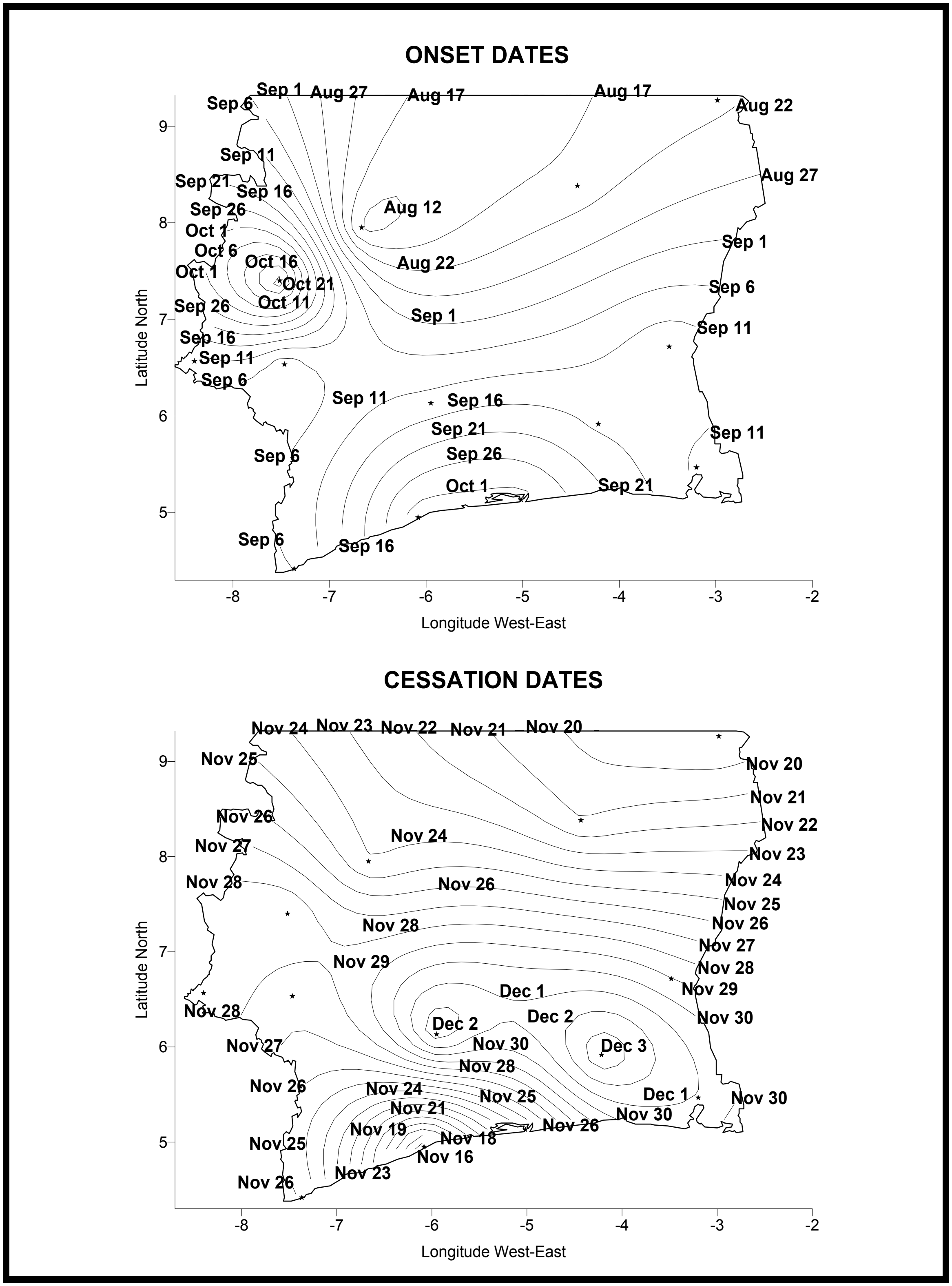


Figure 4.10*b*: Mean October-November-centered rainy season onset (top) and cessation (bottom) dates across bimodal rainfall stations in the zone south of 9.3° N, based on combined Stern et al. (1982) and Sivakumar (1988) criteria as described in text and Table 4.12. Dots locate the 13 bimodal stations used in the analysis.

Table 4.14: Calendar month percentage of occurrence (parentheses) of mean/earliest/ latest rainy season onset/cessation dates in Central West Africa. March-June-centered rainy season (south of 9.3° N) is based on the unmodified Stern et al. (1982) criteria; July-September-centered rainy season (north of 9.3° N) is based on the Sivakumar (1988) criteria but modified for onset as explained in text; October-November-centered rainy season (south of 9.3° N) is based on the combined Stern et al. (1982) and Sivakumar (1988) criteria as explained in text and Table 4.12. Length of the growing season in days indicates the spatial extent of seasonal rainfall variability in the study area.

ONSET (%)			
Season	**Mean**	**Earliest**	**Latest**
March-June	Mar (62), Apr (38)	Jan (61), Feb (31) Mar (8)	Apr (15), May (31) Jun (54)
Dominant Month	March	January	June
July-September	Apr (14), May (45) Jun (24), Jul (17)	Feb (7), Mar (31) Apr (34), May (28)	Jun (21), Jul (55) Aug (24)
Dominant Month	May	April	July
October-November	Aug (23), Sep (54) Oct (23)	Jul (15), Aug (62) Sep (15), Oct (8)	Sep (15), Oct (54) Nov (31)
Dominant Month	September	August	October
CESSATION (%)			
Season	**Mean**	**Earliest**	**Latest**
March-June	Jul (31), Aug (53) Sep (8), Oct (8)	Jun (54), Jul (38) Sep (8)	Dec (100)
Dominant Month	August	June	December
July-September	Sep (17), Oct (73) Nov (10)	Aug (24), Sep (62) Oct (14)	Oct (31), Nov (55) Dec (14)
Dominant Month	October	September	November
October-November	Nov (77), Dec (23)	Oct (85), Nov (15)	Dec (100)
Dominant Month	November	October	December
LENGTH OF THE GROWING SEASON (number of days)*			
Season	**Range of Rain Duration**	**Longest**	**Shortest**
March-June	From 106 to 225	225 (Man)	106 (Seguela)
Average	149		
July-September	From 59 to 213	213 (Odienne)	59 (Kidal)
Average	137		
October-November	From 35 to 106	106 (Seguela)	35 (Man)**
Average	76		

*** Duration of rainy season is the difference between mean onset and mean cessation (Tables 4.13*a*,*b*).**
**** There is nearly no perceptible break in Man's growing seasons.**

this zone (1986 for Boundiali, 1993 for Odienne), or as late as August 3-26 for the most northern stations such as Mopti (1942), Kidal (1944), Goundam (1968), Menaka (1974), Gao (1975), Douentza (1979), and Ansongo (1995). The average dates of rain onset advance progressively from the south-southwest to the north-northeast and differ by three months (from April 19 at Gaoua to July 20 at Goundam) within this zone north of 9.3° N.

Even though the onset dates of both seasons are related because of the northward advance of rains (Fig. 4.10*a*, bottom), the cessation dates of the March-June-centered rainy season south of 9.3° N (Fig. 4.10*a*, bottom right) are discontinuous from those of the July-September-centered rainy season north of 9.3° N (Fig. 4.10*a*, bottom left), as also illustrated in Table 4.13*a*. For the zone south of 9.3° N, the March-June-centered rains end on average by late July-early August (along the coast and northwestern regions) and early August (south-central regions) to mid-October (western mountainous regions). Here, also, there have been years when the rains ceased as early as June 23-July 20 for all regions (except in 1938 at Man in the mountain areas, which ended two months later, September 25) and as late as December 3-16 for all regions (see Table 4.13*a* for specific cessation years in this zone). Within this zone south of 9.3° N the mean cessation dates for the March-June-centered rains differ by less than two months (from Jul 18 for Seguela to Sep 2 for Toulepleu).

In the zone north of 9.3° N, the July-September-centered rains gradually end on average from mid-September (Kidal) to mid-November (Odienne). Still, there have been years when the rainy season ceased as early as August 21-30 for northernmost stations (1930 for Ansongo, 1941 for Goundam, 1949 for Kidal, 1991 for Gao and Menaka) or as late as December 9-11 for the most extreme southern areas (1933 and 1954 for Odienne, 1938 and 1956 for Boundiali, 1942 for Banfora, 1947 for Gaoua). The mean cessation has a west-north-west to east-south-east orientation and its dates differ by approximately two months (from September 15 at Kidal to November 19 at Odienne) within this zone north of 9.3° N. Note that the retreat of the July-September-centered season north of 9.3° N is associated with onset of the October-November-centered season south of 9.3° N because of the retreat of rains to Gulf of Guinea coast by end of the year.

Furthermore, there is another rainy season centered on October-November for bimodal rainfall stations in the zone south of 9.3^{o} N (Table 4.13*b* and Fig. 4.10*b*, top). However, the “little dry season” (see Chapter 2, Section 2.1.1) that separates the two seasons (March-June and October-November) sometimes barely occurs, causing almost no break between seasons in years such as 1932 and 1952 at Man (see Table 4.13*b* for specific early onset years). The combination of the standard Stern et al. (1982) and Sivakumar (1988) criteria (Table 4.12) was used to determine the onset dates for the October-November-centered rainy season. Table 4.13*b* and Figure 4.10*b* (top) show that this rainy season starts on average between early August for Seguela (northern part of the zone south of 9.3^{o} N) and early-to-late October for the coastal (Grand Lahou, Sassandra) and mountainous (Man) regions where the non-zonal onset pattern is quite striking. This pattern in the western mountainous regions and the coastal areas is due to the situation of having almost no break between the two rainy seasons (March-June and October-November), as mentioned earlier in this section. Still, there have been years when the rains began as early as July 19 for Seguela (1939, 1953) and as late as October 21 for Man (1932, 1952).

The October-November-centered season for bimodal rainfall stations in the zone south of 9.3^{o} N ends on average between mid-to-late November (for most stations) and during early December for Gagnoa, Agboville, and Aboisso in a belt stretching from the central-west to southeast coast, where the cessation pattern also is non-zonal. This early December feature can be explained by the presence of the conspicuous 250 km long Baoulé range of hills oriented from east to west in the central part of the country (see Section 1.3.1). Indeed, the orientation of the eastern and central Ivorian coasts and the topography (even small elevation) cause an upward motion (convergence/convection) within the unstable monsoon air, giving the long-lasting rainy season in Gagnoa, Agboville, and Aboisso. Still, there have been years when the rains ceased as early as October 18 in 1971 for Sassandra on the central coast, and as late as December 3-16 for all regions (see Table 4.13*b* for specific cessation years). Here, also, the mean cessation dates differ by about two months. Table 4.13*b* and Figure 4.10*b* (bottom) present the cessation date variations for the October-November-centered season.

In addition, the mean onset and cessation standard deviations in Tables 4.13*a*,*b* show some key variations in the advance and retreat of the three rainy seasons. First, the cessation variability for all three seasons generally is relatively smaller than the onset variability. The major exceptions are in the zone south of 9.3^{o} N -- a few bimodal stations (i.e., Dabakala, Seguela, Abengourou, Gagnoa, Agbovile, Aboisso) that stretch from northwest to central-east and central-west to southeast for the March-June-centered season, and Man, Toulepleu, Guiglo, Tabou from west to southwestern coast for the October-November-centered season. This situation implies that the withdrawal of the monsoon systems is better defined and organized and more rapid (than their onset) in the study area. Second, the standard deviations for the onset (especially) and cessation dates for the rainy seasons centered on July-September (north of 9.3^{o} N) and October-November (south of 9.3^{o} N) are smaller than those of the March-June-centered rainy season south of 9.3^{o} N. Indeed, the standard deviations vary from 13-29 days (onset) to 9-17 days (cessation) for the July-September-centered season, from 7-29 days (onset) to 8-21 days (cessation) for the October-November-centered season, and from 20-37 days (onset) to 15-44 days (cessation) for the March-June-centered season. These ranges of variation produce the difficulties sometimes encountered in finding a break between the two rainy seasons for bimodal rainfall stations in the zone south of 9.3^{o} N.

Overall, there is a gradual rain occurrence and retreat across the study area, especially for the rainy seasons centered on March-June and July-September. The gradients in these rainy season onset and cessation dates are related to the latitudinal migrations of the ITCZ (as discussed in Section 2.1.1). Thus, the high variability in the onset/cessation dates (i.e., rainy season length or growing season, Fig. 4.10*c*) of the rains contributes to wide variations in crop types, as shown in Section 4.3.2.

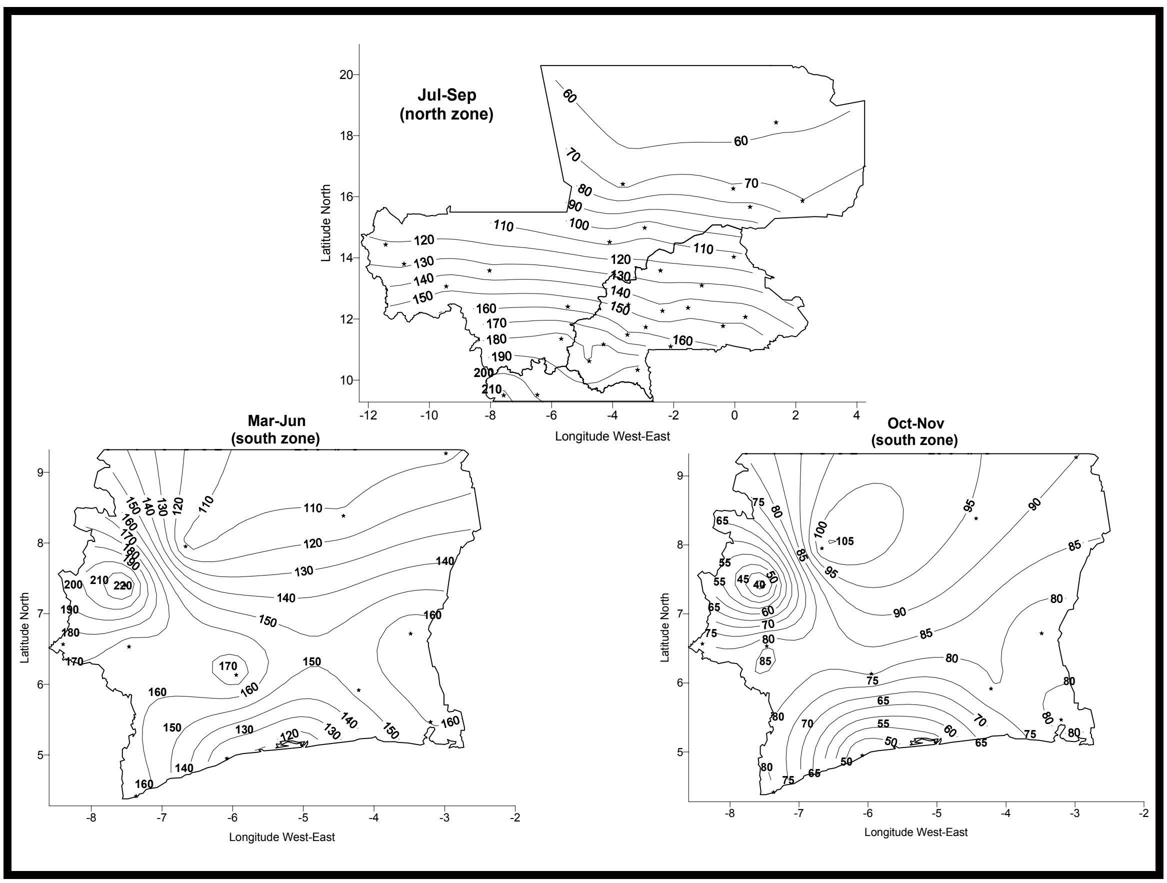


Figure 4.10*c*: Mean rainy season lengths across Central West Africa. Top panel shows the durations of the rainy seasons centered on July-September (north of 9.3^{o} N), while bottom panels focus on the duration of the rainy seasons centered on March-June (south of 9.3^{o} N, left) and October-November (south of 9.3^{o} N, right). Dots locate the representative rainfall stations used in the analysis.

4.1.2.6 Concluding Remarks

The preceding rainfall analyses provide the foundation for subsequent agricultural pattern (Section 4.2) and rainfall/agriculture relationship (Section 4.3) analyses extending from the Sahel to the Gulf of Guinea coast. Therefore, it is important to emphasize that rainfall in the study area is highly variable regardless of time-scale (days, months, years, decades). Low rainfall has led the region to experience large-scale (i.e., region-wide) drought years, such as in 1972, 1973, 1983, 1984, and 1990. The study decades registered rainfall ranging from the wet decades of the 1930s, 1950s (especially), and 1960s, to the much drier conditions of the 1940s, 1970s, 1980s (especially), and 1990s. This section's monthly analyses showed patterns of mono-modal (one rainy season) and bimodal (two rainy seasons) annual rainfall regimes. Furthermore, the analysis demonstrated a strong northward rainfall gradient throughout Central West Africa for many study measures (annual rainfall index/totals, multidecadal isohyetal trends, monthly rainfall patterns, number of rain days per year/season/month, and onset/cessation dates of the rainy seasons), with the southern region (below 9.3^{o} N) being less drought-prone especially before 1950. In order to understand the social and economic impacts of these rainfall fluctuations, variations of agricultural practices and output needed to be studied as well. Thus, the next section analyzes selected crops as a further step to determining whether crop yields are dependent more upon rainfall or upon other agricultural inputs such as fertilizer and mechanization. As a result, rainfall/crop yield relationships are considered in Section 4.3.

4.2 Crop Acreage, Production, and Yields

This section focuses on spatial patterns and temporal trends of selected Central West African crops indicative of agricultural change. Here, farming is spread across a variety of zones ranging from high productivity regions to those of extremely low crop output. The goal of this study is to assess the extent to which crop acreage, production, and yield analyses are informative for documenting agricultural change. Thus, this section first focuses on the spatial and temporal variations of crop parameters in each country in order to determine the agricultural regions and types of crops (i.e., cash or staple) that show dominance in annual acreage, production, and yields. Then, analyses are performed to ascertain whether crop production increase is more related to acreage increase than to yield increase and how these three crop parameters explain agricultural changes.

4.2.1 Average Spatial Distribution of Crops: Dominant Geographic Locations

A major purpose of this section is to select dominant regions and major crops on which the study will focus in later sections. The study crops grow almost everywhere in Central West Africa, but with various efficiencies. In some regions, the fraction of land used for an individual crop is large whereas it is limited in others. The higher productivity areas are considered the favorite locations for all crop cultivations. A dominant crop setting is determined from the regional ratio of an individual crop acreage planted to the national acreage for that crop, or from production per agricultural region compared to total production values in each country. A ten-percent threshold is the criterion applied to select a prime region where crop acreage is either heavily planted or highly produced within the twenty-seven agricultural regions of Mali, Burkina Faso, and

Côte d'Ivoire. The analyses utilize all the data collected for cash and staple crops in the three countries. Since data were not available for every crop in every year in each country -- because crop records vary in number and length and contain some missing years, as revealed in Section 3.2.1.2 -- the regional values were computed from all data collected for each of the study crop's parameters of acreage and production, and then yields were calculated from these two parameters. Here, yields are analyzed to produce ratios of regional yields to national yields for individual crops; these results complement the criteria used to select a prime crop region based on acreage and production values.

Figures 4.11*a*,*b*, 4.12*a*-*c*, and 4.13 contain several important results for the spatial distribution of the major crops throughout the Central West African agricultural regions, while Tables 4.15*a*,*b* summarize the dominant and lowest growth regions of each crop for which the periods of analysis are given. Figures 4.12*a*-*c* and 4.13 map the graphical results in Figures 4.11*a*,*b*, which provide all of the raw material but may be somewhat difficult to comprehend. Note that the regional fractions of national acreage/production and the ratios of regional yields to national yields of individual crops typically are positively related -- agricultural regions with larger acreage and production tend to have yields that are up to two times higher than the national yields (e.g., 211% for cocoa in region W of Côte d'Ivoire).

Regarding the cash crops in Mali (Figs. 4.11*a*,*b* and 4.12*a*), cotton is produced largely in two south to south-central regions (So, Ko, in order of average acreage devoted) and peanuts in four southwest to south-central and south regions (Ky, Ko, Su, So). Sugarcane, a more water-demanding crop, is cultivated mainly in the south-central region of Su along the Niger River, one of the two major rivers in Mali. Among the staple crops in

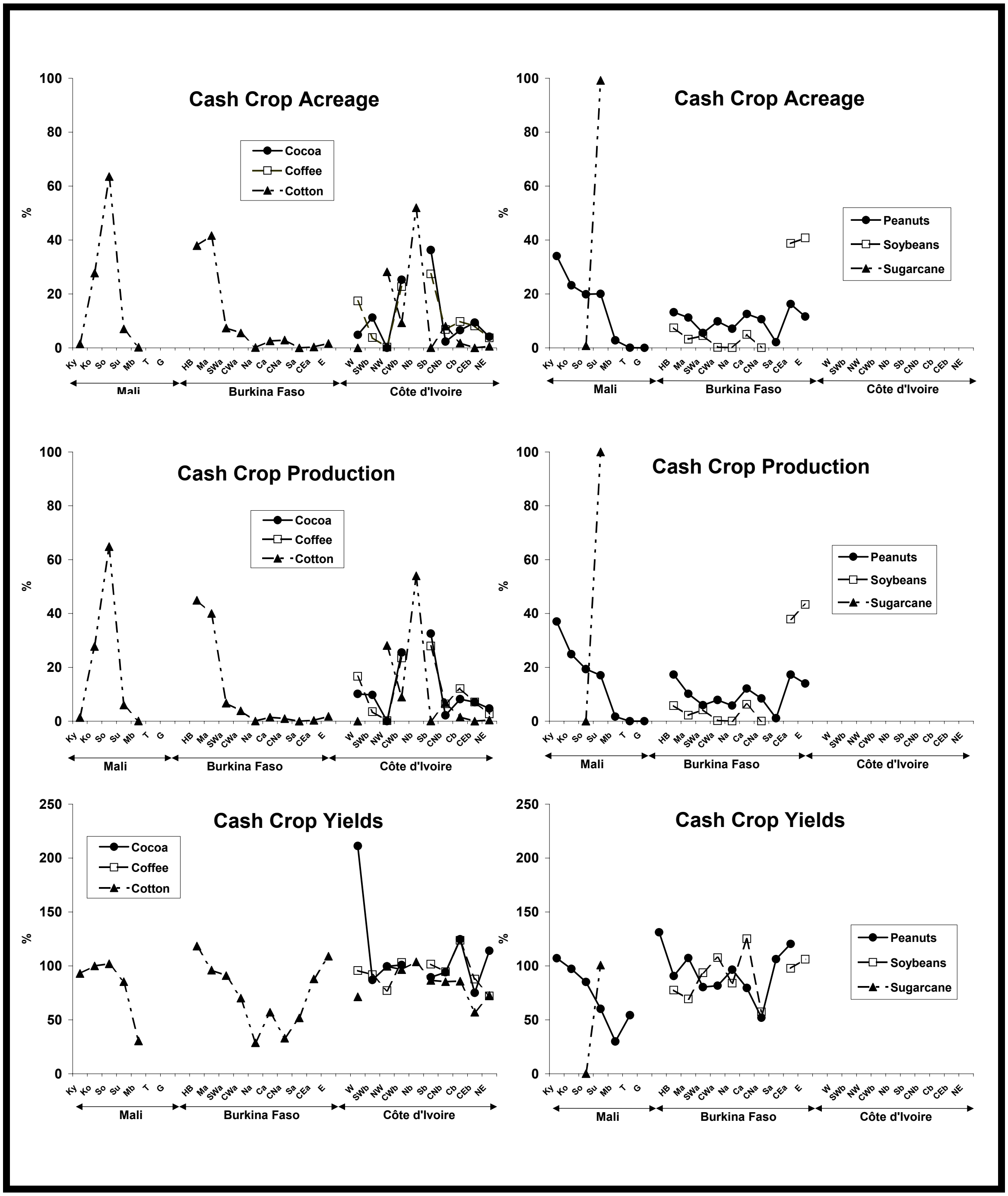


Figure 4.11*a*: Average regional fractions of national acreage/production, and ratios of regional yields to national yields, for individual cash crops in all regions of Mali, Burkina Faso, and Côte d'Ivoire. Analyses draw upon the entire available data set collected for each crop; years for which data are available for individual crops are listed in Table 4.15*b*. See Chapter 3 (Table 3.5 and Fig. 3.3) and Figures 4.12*a-c* for names and locations of the agricultural regions. Regions are ordered geographically from left (west) to right (east) in each country.

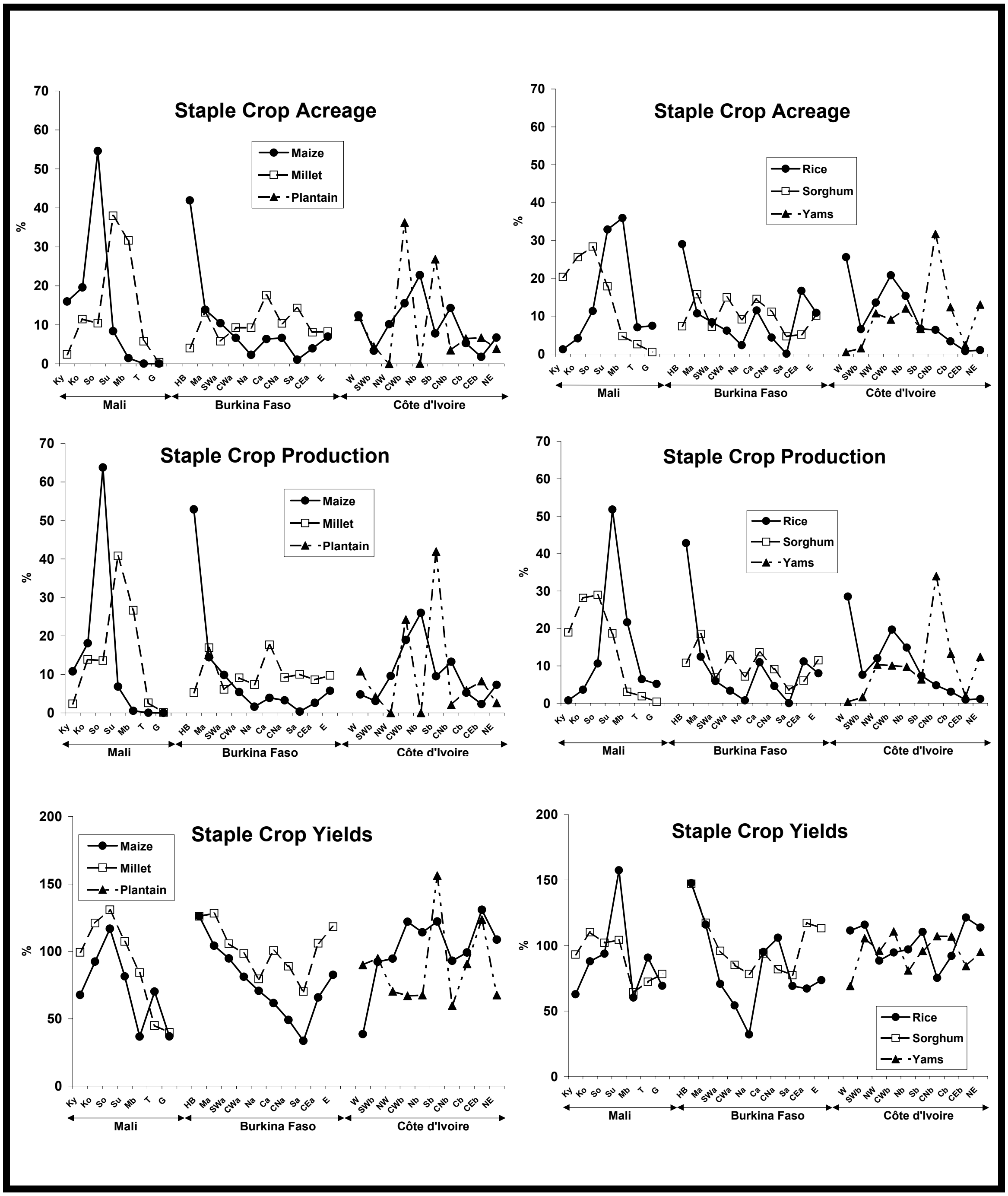


Figure 4.11*b*: Average regional fractions of national acreage/production, and ratios of regional yields to national yields, for individual staple crops in all regions of Mali, Burkina Faso, and Côte d'Ivoire. Analyses draw upon the entire available data set collected for each crop; years for which data are available for individual crops are listed in Table 4.15*b*. See Chapter 3 (Table 3.5 and Fig. 3.3) and Figures 4.12*a-c* for names and locations of the agricultural regions. Regions are ordered geographically from left (west) to right (east) in each country.

this country, maize (So, Ko, Ky) and rice (Mb, Su, So) each are produced largely in three south and southwest to south-central regions, while millet (Su, Mb, Ko, So) and sorghum (So, Ko, Ky, Su) each are cultivated mainly in four south-central and south to southwest regions. Further, the average national yields (kg ha^{-1}) of the Malian crops range from 921 (peanuts) to 69005 (sugarcane) for the cash crops, and from 729 (millet) to 1395 (rice) for the staple crops. The average ratios of regional yields to national yields are as follows (from lowest to highest ratios): 0.08% sugarcane (So -- south) to 109% peanuts (Ky -- southwest) for the cash crops; and 37% maize (Mb -- central, G -- northeast) to 157% rice (Su -- south-central) for the staple crops (see Figs. 4.11*a*,*b*, bottom right and left panels).

For the cash crops in Burkina Faso (Figs. 4.11*a*,*b* and 4.12*b*), cotton is produced largely in two southwest regions (Ma, HB) and peanuts in seven southwest to east regions including central-west, central, central-north, and central-east regions (CEa, HB, Ca, E, Ma, CNa, CWa). Soybeans, a relatively new experimental crop for Burkina Faso, are cultivated in two east to central-east regions (E, CEa). Concerning the staple crops of this country, maize is produced mainly in three southwest regions (HB, Ma, SWa), whereas millet (Ca, Sa, Ma, CNa), rice (HB, CEa, Ca, Ma, E), and sorghum (Ma, Ca, CWa, CNa, E) each are cultivated in four to five southwest to east regions, including central-west, central-north, central, central-east, and north regions. Additionally, the average national yields (kg ha^{-1}) of the Burkinabè crops range from 656 (peanuts) to 1008 (cotton) for the cash crops, and from 546 (millet) to 1470 (rice) for the staple crops. The mean ratios of regional yields to national yields are as follows (from lowest to highest ratios): 29% cotton (Na -- north) to 131% peanuts (HB -- southwest) for the cash crops; and 32% rice (Na -- north) to 148% rice (HB -- southwest) for the staple crops (see Figs. 4.11*a*,*b*, bottom right/left panels).

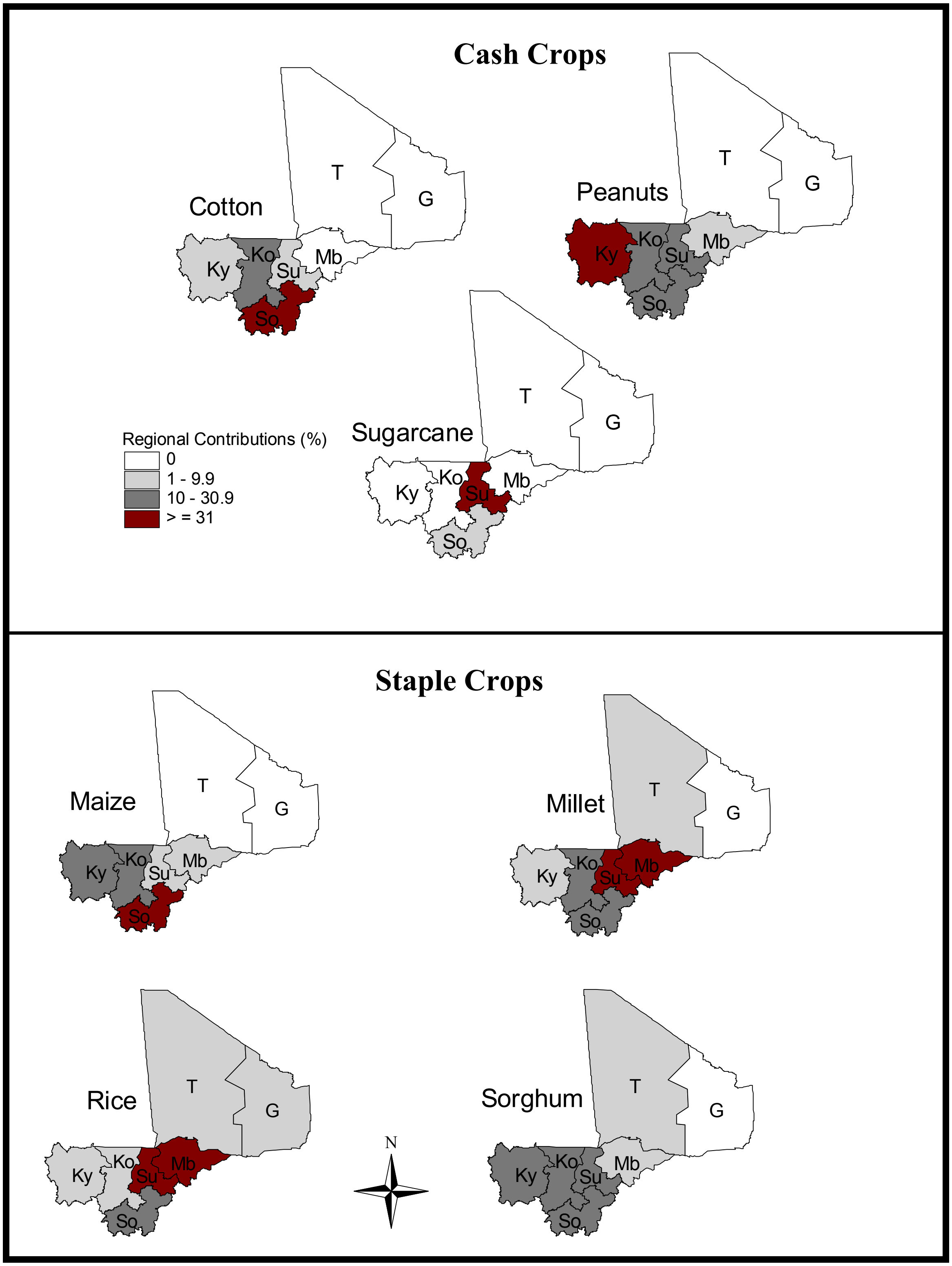


Figure 4.12*a*: Regional contributions (%) to the national acreage of individual cash (cotton, peanuts, sugarcane) and staple (maize, millet, rice, sorghum) crops in Mali. Analyses draw upon the entire available data set collected for each crop; years for which data are available for individual crops are listed in Table 4.15*a*. See Chapter 3 (Table 3.5) for names of agricultural regions. 0% (white areas) represents < 1% regional values rounded down to 0%.

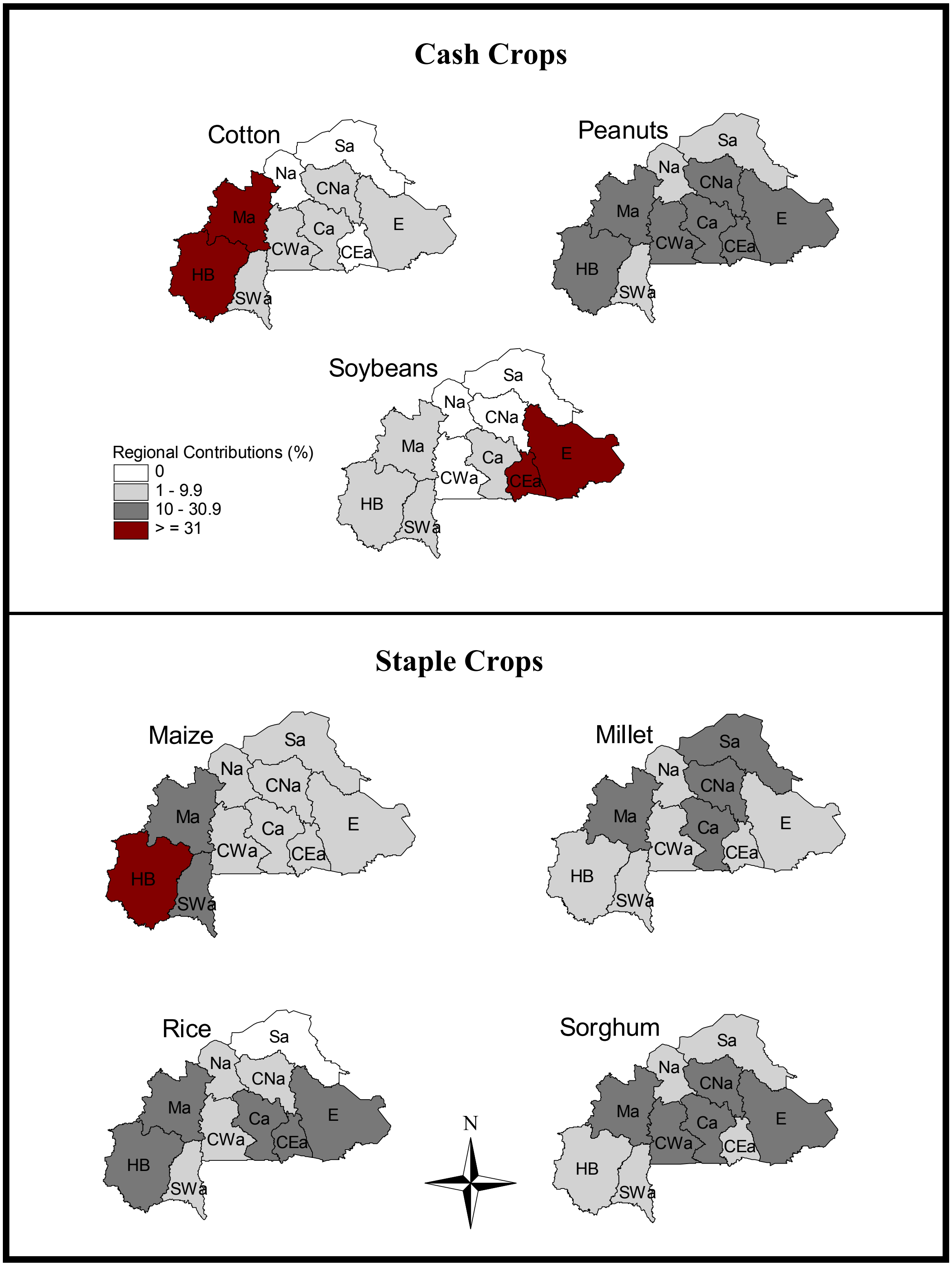


Figure 4.12*b*: Regional contributions (%) to the national acreage of individual cash (cotton, peanuts, soybeans) and staple (maize, millet, rice, sorghum) crops in Burkina Faso. Analyses draw upon the entire available data set collected for each crop; years for which data are available for individual crops are listed in Table 4.15*a*. See Chapter 3 (Table 3.5) for names of agricultural regions. 0% (white areas) represents < 1% regional values rounded down to 0%.

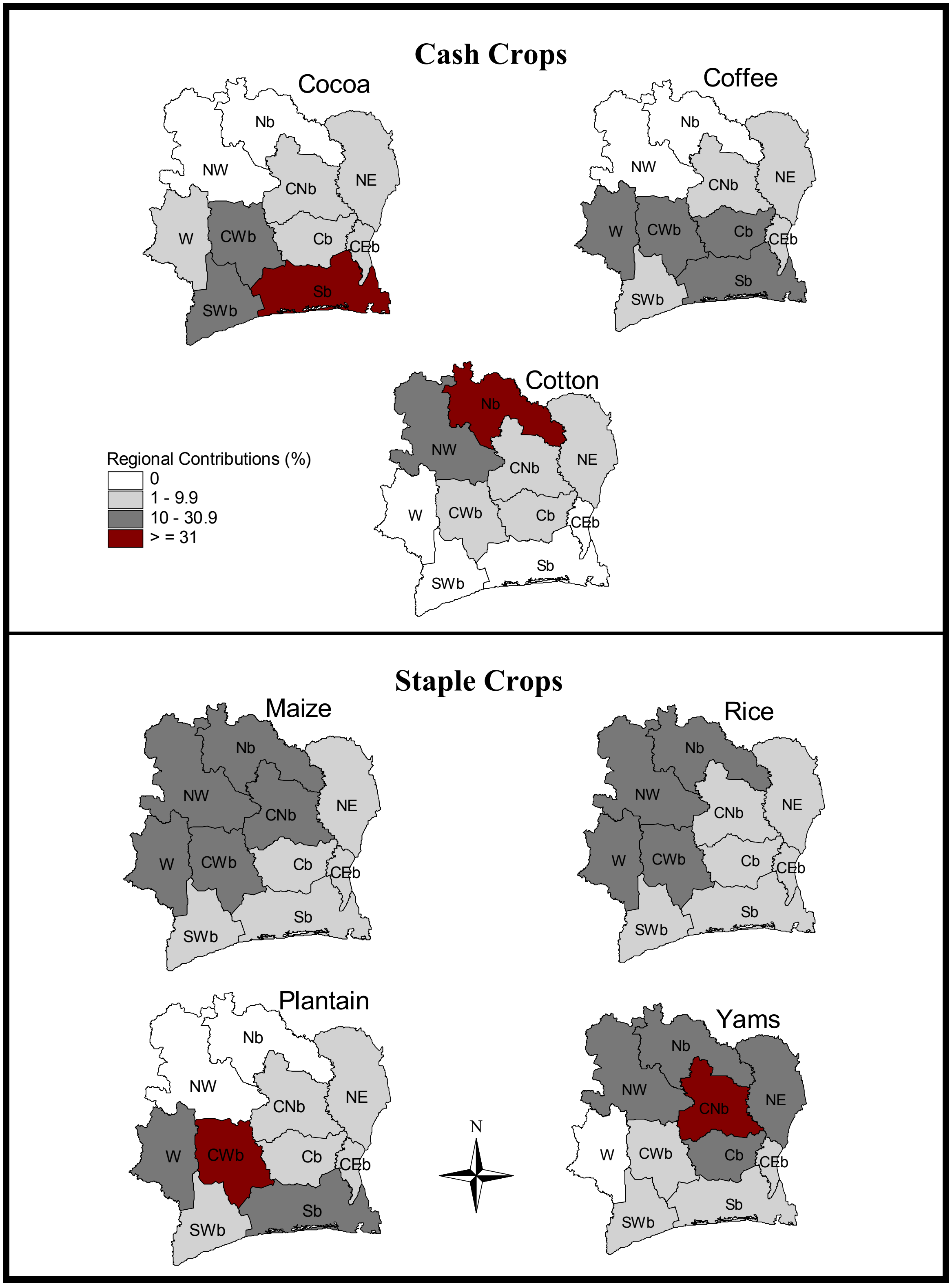


Figure 4.12*c*: Regional contributions (%) to the national acreage of individual cash (cocoa, coffee, cotton) and staple (maize, plantain, rice, yams) crops in Côte d'Ivoire. Analyses draw upon the entire available data set collected for each crop; years for which data are available for individual crops are listed in Table 4.15*a*. See Chapter 3 (Table 3.5) for names of agricultural regions. 0% (white areas) represents < 1% regional values rounded down to 0%.

As far as the cash crops in Côte d'Ivoire (Figs. 4.11*a*,*b* and 4.12*c*) are concerned, cocoa (Sb, CWb, SWb), and coffee (Sb, CWb, W, Cb) each are produced largely in three to four south to central-west regions, including southwest, west, and central regions. Cotton is cultivated predominantly in two north to northwest regions (Nb, NW). For the staple crops of this country, maize (Nb, CWb, CNb, W, NW) and yams (CNb, NE, Cb, Nb, NW) each are produced mainly in five west to northeast regions, including northwest, north, central-north, central-west, and central regions, while plantain is cultivated largely in three central-west to south and west regions (CWb, Sb, W), and rice in four west to central-west and northwest to north regions (W, CWb, Nb, NW). Further, the average national yields (kg ha^{-1}) of the Ivorian crops range from 300 (coffee) to 1186 (cotton) for the cash crops, and from 787 (maize) to 8505 (yams) for the staple crops. The mean ratios of regional yields to national yields are as follows (from lowest to highest ratios): 57% cotton (CEb -- central-east) to 211% cocoa (W -- west) for the cash crops; and 39% maize (W -- west) to 156% plantain (Sb -- south) for the staple crops (see Figs. 4.11*a*,*b*, bottom right and left panels).

Based on a ≥ 10% national acreage or production criterion for a particular crop -- ≥ 10% had to be achieved by only one (not both) of acreage or production values (Figs. 4.12*a*-*c* and Table 4.15*a*) -- it appears that crop regions in Mali (M), Burkina Faso (BF), and Côte d'Ivoire (CI) generally devote larger acreage to staple crops (from 3 to 4 regions for M; 3 to 5 for BF; 3 to 5 for CI) than to cash crops (from 1 to 4 regions for M; 2 to 7 for BF; 2 to 4 for CI). Except for peanuts (4 regions for M; 7 for BF) and coffee (4 regions for CI), only one to three regions per country have larger acreage devoted to the cash crops (from 1 to 2 regions for sugarcane/cotton in M; 2 for cotton/soybeans in BF; from 2 to 3 for cotton/cocoa in CI).

Table 4.15*a*: Dominant growth regions are those in which either crop acreage or production has contributed ≥ 10% of the national crop acreage or production values. Analyses draw upon the entire available data set collected for each crop; years for individual crops are listed in parentheses in left-hand column. Parentheses in three right-hand columns indicate acreage (A) and production (P) percentages. See Chapter 3 (Table 3.5) and Figure 4.13 for names and locations of these dominant agriculture regions. Crops that are labeled as not selected do not have consecutive years of reliable data.

	Crop and Period	Mali (M)	Burkina Faso (BF)	Côte d'Ivoire (CI)
CASH CROPS	**Cocoa** **CI** (A = 48-98 & P = 59-98)	Not grown	Not grown	**Sb** (36 & 33), **CWb** (25 & 25), **SWb** (11 & 10)
CASH CROPS	**Coffee** **CI** (A = 50-98 & P = 59-98)	Not grown	Not grown	**Sb** (27 & 28), **CWb** (23 & 23), **W** (17 & 17), **Cb** (10 & 12)
CASH CROPS	**Cotton** **M** (A & P = 66-97) **BF** (A & P = 70-98) **CI** (A = 51-98 & P = 50-98)	**So** (64 & 65), **Ko** (28 & 28)	**Ma** (42 & 40), **HB** (38 & 45)	**Nb** (52 & 54), **NW** (28 & 28)
CASH CROPS	**Peanuts** **M** (A & P = 66-97) **BF** (A & P = 70-98)	**Ky** (34 & 37), **Ko** (23 & 25), **So** (20 & 19), **Su** (20 & 17)	**CEa** (16 & 17), **HB** (13 & 17), **Ca** (13 & 12), **E** (12 & 14), **Ma** (11 & 10), **CNa** (11 & 8), **CWa** (10 & 8)	Not selected
CASH CROPS	**Soybeans** **BF** (A & P = 70-98)	Not selected	**E** (41 & 43), **CEa** (39 & 38)	Not selected
CASH CROPS	**Sugarcane** **M** (A & P = 84-97)	**Su** (99 & 100)	Not selected	Not selected
STAPLE CROPS	**Maize** **M** (A & P = 66-98) **BF** (A & P = 70-98) **CI** (A & P = 49-98)	**So** (55 & 64), **Ko** (20 & 18), **Ky** (16 & 11)	**HB** (42 & 53), **Ma** (14 & 14), **SWa** (10 & 10)	**Nb** (23 & 26), **CWb** (16 & 19), **CNb** (14 & 13), **W** (12 & 5), **NW** (10 & 10)
STAPLE CROPS	**Millet** **M** (A = 84-98 & P = 67-98) **BF** (A & P = 70-98)	**Su** (38 & 41), **Mb** (32 & 27), **Ko** (11 & 14), **So** (10 & 14)	**Ca** (18 & 18), **Sa** (14 & 10), **Ma** (13 & 17), **CNa** (10 & 9), **E** (8 & 10)	Not selected
STAPLE CROPS	**Plantain** **CI** (A & P = 48-98)	Not grown	Not grown	**CWb** (36 & 24), **Sb** (27 & 42), **W** (12 & 11)
STAPLE CROPS	**Rice** **M** (A & P = 66-98) **BF** (A & P = 70-98) **CI** (A & P = 47-98)	**Mb** (36 & 22), **Su** (33 & 52), **So** (11 & 11)	**HB** (29 & 43), **CEa** (17 & 11), **Ma** (11 & 12), **Ca** (11 & 11), **E** (11 & 8)	**W** (26 & 29), **CWb** (21 & 20), **Nb** (15 & 15), **NW** (14 & 12)
STAPLE CROPS	**Sorghum** **M** (A = 84-98 & P = 67-98) **BF** (A & P = 70-98)	**So** (28 & 29), **Ko** (26 & 28), **Ky** (20 & 19), **Su** (18 & 19)	**Ma** (16 & 19), **Ca** (15 & 14), **CWa** (15 & 13), **CNa** (11 & 9), **E** (10 & 11), **HB** (7 & 11)	Not selected
STAPLE CROPS	**Yams** **CI** (A & P = 48-98)	Not selected	Not selected	**CNb** (32 & 34), **NE** (13 & 12), **Cb** (12 & 13), **Nb** (12 & 10), **NW** (11 & 10), **CWb** (9 & 10)

Further, the dominant regions (Table 4.15*a*) for all crop cultivation and production (based on the ≥ 10% criteria) within each country are as follows: Ky, Ko, Su, So for Mali (from southwest to south-central and south); HB, Ma, Ca, E for Burkina Faso (from southwest to central and east); W, CWb, Cb, Sb for Côte d'Ivoire (from west to central-west and central to south). Most subsequent analyses use these 12 dominant crop regions (Fig. 4.13).

Table 4.15*b*: Regions in which either crop acreage (A) or production (P) has contributed < 1% of the national crop acreage or production values. Analyses draw upon the entire available data set collected for each crop; years for individual crops are listed in parentheses in left-hand column of Table 4.15*a*. N/A = all regions register ≥ 1%. Parentheses in three right-hand columns indicate < 1% of regional acreage (A) or production (P) contributions. See Table 3.5 and Figures 4.13 for names and locations of crop regions. Crops that are labeled as not selected do not have consecutive years of reliable data.

Crop		Mali	Burkina Faso	Côte d'Ivoire
CASH	Cocoa	Not grown	Not grown	**NW** (A, P), **Nb** (A, P)
	Coffee	Not grown	Not grown	**NW** (A, P), **Nb** (A, P)
	Cotton	**Mb** (A, P), **T** (A, P), **G** (A, P)	**Na** (A, P), **Sa** (A, P), **CEa** (A, P)	**W** (A, P), **SWb** (A, P), **Sb** (A, P), **CEb** (A, P)
	Peanuts	**T** (A, P), **G** (A, P)	N/A	Not selected
	Soybeans	Not selected	**CWa** (A, P), **Na** (A, P), **CNa** (A, P), **Sa** (A, P)	Not selected
	Sugarcane	**Ky** (A, P), **Ko** (A, P), **So** (P), **Mb** (A, P), **T** (A, P), **G** (A, P)	Not selected	Not selected
STAPLE	Maize	**T** (A, P), **G** (A, P)	**Sa** (P)	N/A
	Millet	**G** (A, P)	N/A	Not selected
	Plantain	Not grown	Not grown	**NW** (A, P), **Nb** (A, P)
	Rice	N/A	**Sa** (A, P)	N/A
	Sorghum	**G** (A, P)	N/A	Not selected
	Yams	Not selected	Not selected	**W** (A, P)

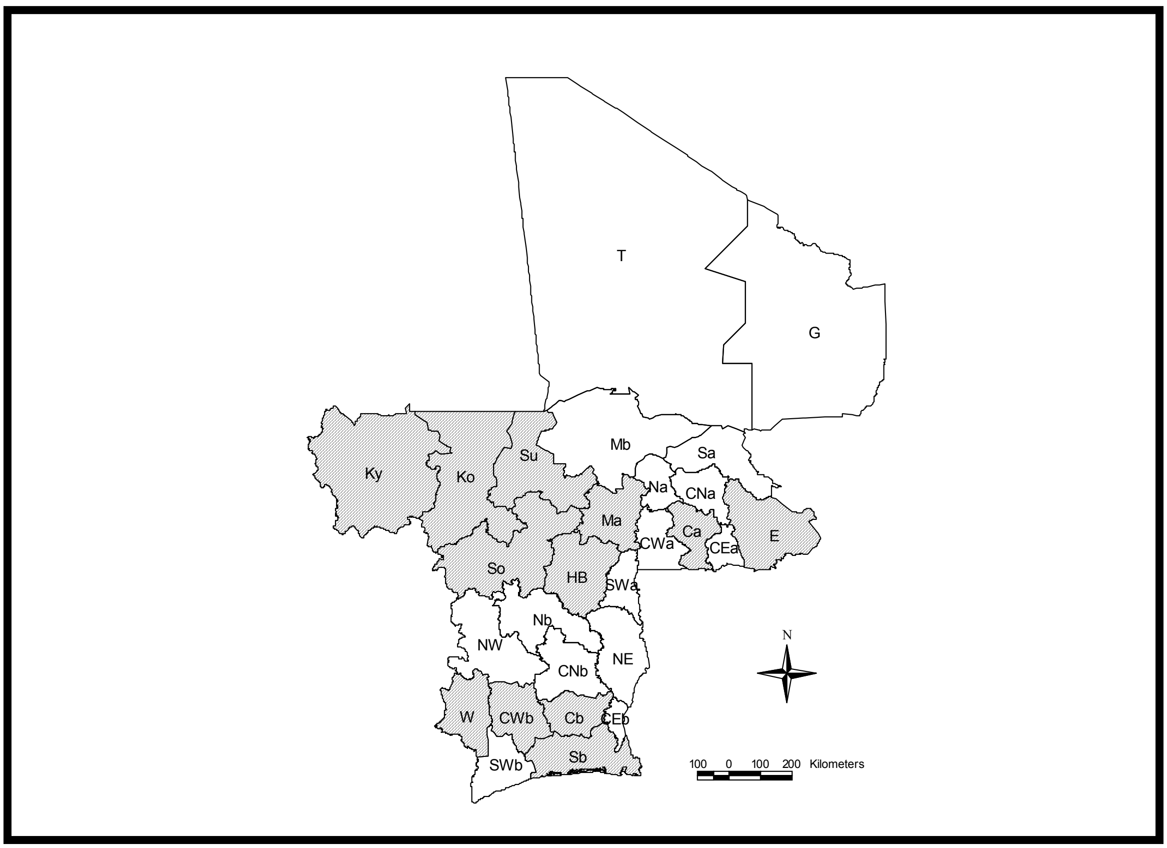
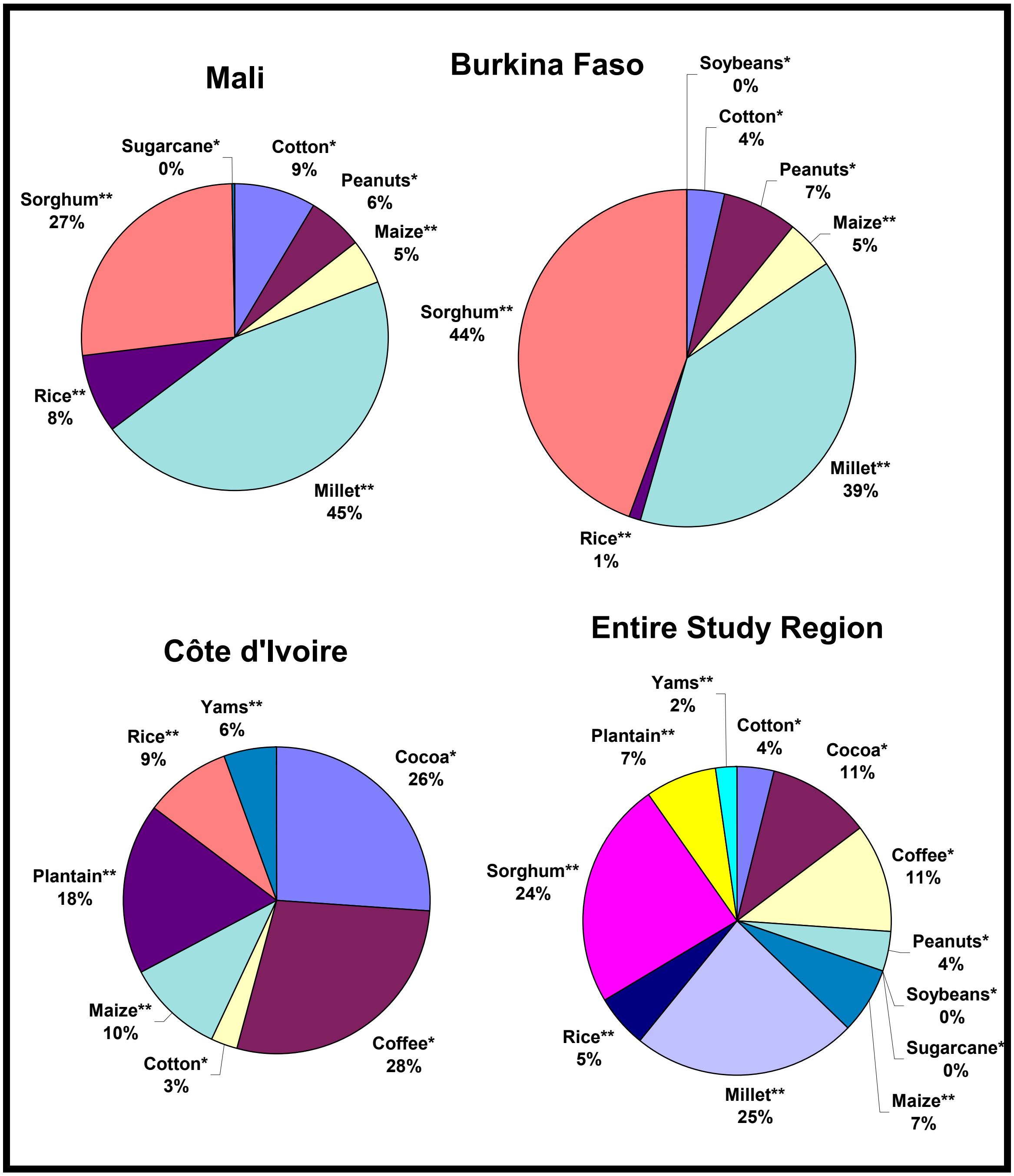


Figure 4.13: Agricultural regions in Central West Africa. Those hatched are the 12 dominant crop regions that are the focus of the analyses discussed in the remainder of the study; especially first part of Section 4.2.2.1 (second part uses all 27 agricultural regions), Section 4.2.2.2, and Section 4.3.2. See Chapter 3 (Table 3.5) for names of crop regions.

Note also that, within each country, there are regions in which < 1% of acreage is devoted to some of the study crops. These less cultivated regions vary from one crop to another and occur more for cash crops, as shown in Table 4.15*b*.

Figure 4.14 presents the relative importance of each crop within the collected data for the individual countries and study region as a whole. Based on the percentages of total national crop acreage for all available years, the major staple crops are millet (45%) and sorghum (27%) for Mali, sorghum (44%) and millet (39%) for Burkina Faso, and plantain (18%) and maize (10%) for Côte d'Ivoire. The dominant cash crops are cotton (9%) and peanuts (6%) for Mali, peanuts (7%) and cotton (4%) for Burkina Faso, and coffee (28%) and cocoa (26%) for Côte d'Ivoire. These eight crops thus are retained as the dominant staple and cash crops for study in the rest of this research. The national crop distributions (Fig. 4.14) also suggest that substantially less (more) land is given to staple (cash) crops in Côte d'Ivoire (43% for staple crops vs. 57% for cash) than in Mali (85% vs. 15%) and Burkina Faso (89% vs. 11%). These ratios confirm that Mali and Burkina Faso have not extensively developed export crops, but instead have focused on staple crops to attain self-sufficient food security goals. In contrast, Côte d'Ivoire's development goals are related to the potential uses of natural resources in order to achieve rapid economic growth, and thus favor more cash crops (see Section 1.4). Both cash and staple crops play a vital role in the socioeconomic development of the study area because they are "dynamic and respond to changes in the social, political, economic, and environmental conditions of an area" (Aryeetey-Attoh, 1997, p. 287). Chapter 5 discusses the environmental implications of the issue of staple versus cash crops.



* Cash crops -- Mali [15%]; Burkina Faso [11%]; Côte d'Ivoire [57%]; entire study region [30%]
** Staple crops -- Mali [85%]; Burkina Faso [89%]; Côte d'Ivoire [43%]; entire study region [70%]

Figure 4.14: Average acreage of individual crops as fractions of the national crop acreage for all crops in each country and in the entire study region. Analyses draw upon the entire available data set for each crop; years for individual crops are listed in left-hand column of Table 4.15*a*. 0% = less than 0.5% values rounded down to 0%.

Table 4.16 summarizes, by country and for entire study region, the 12 dominant crop regions (Fig. 4.13) and eight major crops (derived from Fig. 4.14) on which most of the remainder of this study will focus. Note that these countries share only three crops, namely cotton, maize, and rice, which consequently are the subject of inter-country comparisons (Section 4.3). Those inter-country comparisons will include all 27 agricultural regions (not only the 12 dominant regions identified above) to reveal crop growth similarities and differences among the three countries, especially for the crop regions along the national boundaries.

Table 4.16: Summary of representative agricultural regions and crops for each country (as well as for entire study region) that are used in most of the analyses that follow. Crops and time periods listed for the entire study region include crops common to all countries and consecutive years with few missing data for acreage/production/yields (see Chapter 3, Table 3.8). Table 3.5 and Figure 4.13 give names and locations of agricultural regions.

	Mali	**Burkina Faso**	**Côte d'Ivoire**	**Entire Study Region**
Region	Ky, Ko, Su, So	HB, Ma, Ca, E	W, CWb, Cb, Sb	All 27 crop regions
Cash Crop (Period)	Cotton (1966-98) Peanuts (1966-97)	Cotton (1970-98) Peanuts (1970-98)	Cocoa (1948-98) Coffee (1950-98)	Cotton (1970-98)
Staple Crop (Period)	Millet (1966-98) Sorghum (1967-98)	Millet (1970-98) Sorghum (1970-98)	Maize (1949-98) Plantain (1948-98)	Maize (1970-98) Rice (1970-98)

4.2.2 Agricultural Change Analyses for Periods of Available Crop Data

4.2.2.1 Temporal Variations of Major Crops on National Basis

The temporal variations of the relative acreage dominance of eight major crops for the dominant 12 Central West African crop regions are shown in Figures 4.15*a,b*. The analyses focus on each country separately because the major crops and data periods vary among countries (Table 4.16). Crop acreages show a general increase throughout the study periods in spite of missing years common to all crops (1969-83 for Mali; 1972-74 for Burkina Faso; 1991-95 for Côte d'Ivoire). Some regions experienced more acreage increase than others.

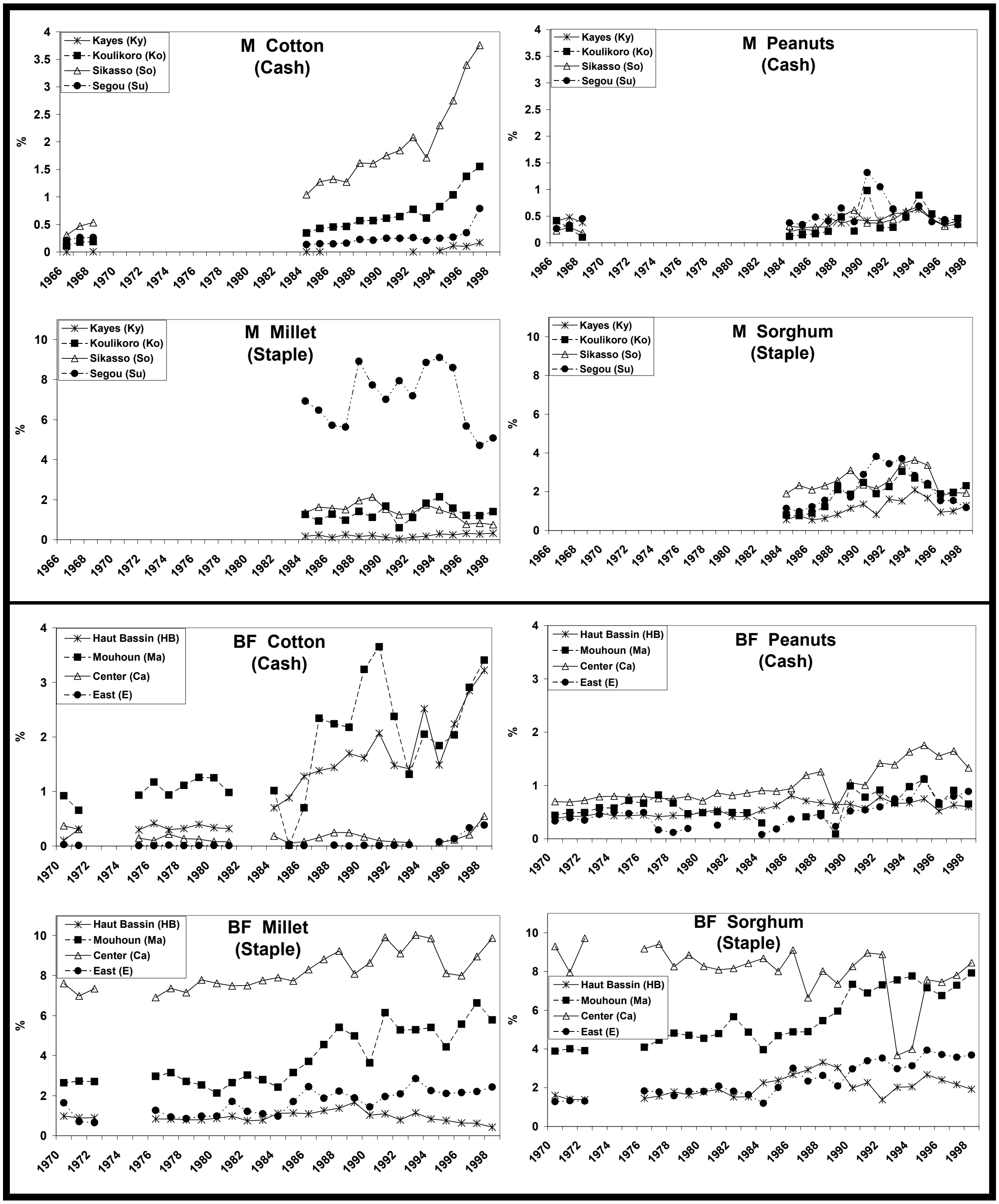


Figure 4.15*a*: Trends of crop acreage (%) for the dominant crop regions in Mali (M, top two rows) and Burkina Faso (BF, bottom two rows). Acreages for individual crops are compared to the total land area of each region. Note the different vertical scales for the cash and staple crops. Analyses draw upon the entire available data set collected for each crop; data are not available for years for which there are no symbol markers. Figure 4.13 gives locations of crop regions.

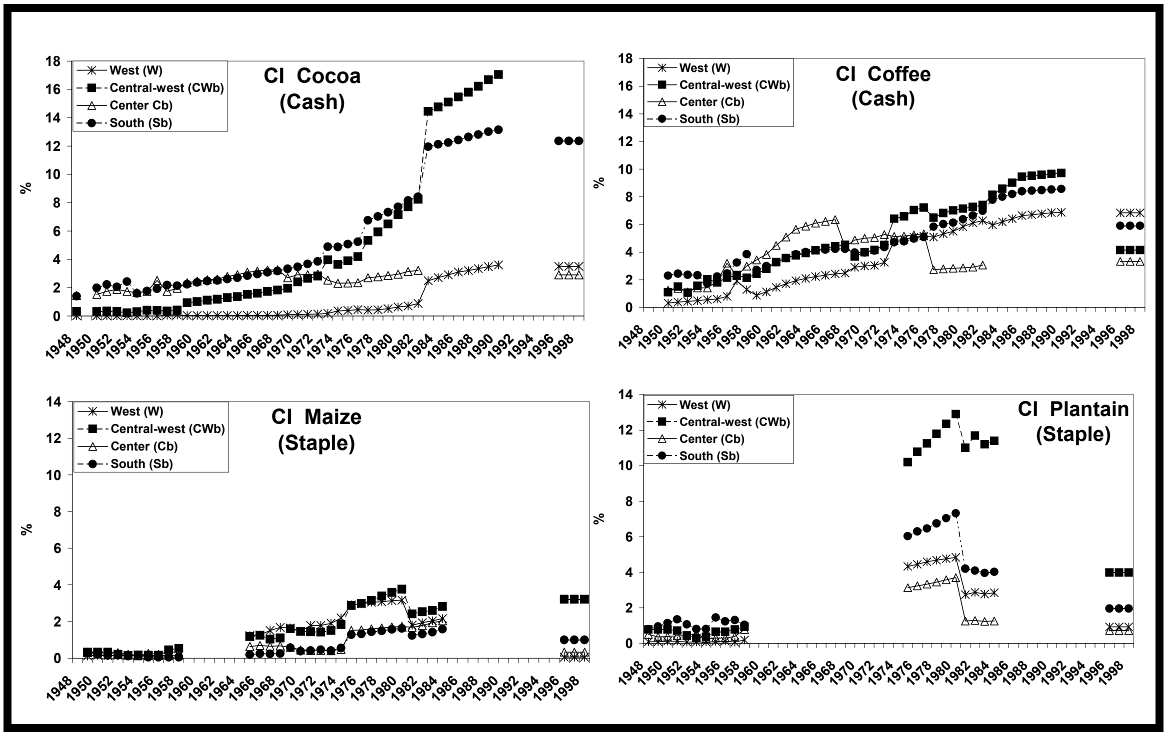


Figure 4.15*b*: Trends of crop acreage (%) for the dominant crop regions in Côte d'Ivoire (CI). Acreages for individual crops are compared to the total land area of each region. Note the different vertical scales for the cash and staple crops. Analyses draw upon the entire available data set collected for each crop; data are not available for years for which there are no symbol markers. Figure 4.13 gives locations of crop regions.

For instance, acreages increase more from south-central to south Mali (Su, Ko, So) than in southwest Mali (Ky), from central to southwest Burkina Faso (Ca, Ma, HB) than in east Burkina Faso (E), and from central-west to south and central Côte d'Ivoire (CWb, Sb, Cb) than in west Côte d'Ivoire (W). One of the main causes of acreage increases is the growing population migration into these areas (Su, Ko, So for Mali; Ca, Ma, HB for Burkina Faso; CWb, Sb, Cb for Côte d'Ivoire) with greater suitability for non-mechanized agriculture, raising the need for subsistence food production (Koli Bi, 1992; Ministère de l'Environnement, 1997). As described in Section 1.3.2, most of the soils in the areas with largest increases are classified as relatively productive because they are naturally fertile. These soils maintain their fertility and rich reddish/yellowish silico-argillaceous character in their surface horizons due to their greater iron content. Consequently, the soils in the areas of increasing crop acreage (listed above) typically support better agricultural productivity. As a result, the southern and south-central regions of all three countries are widely cultivated and can sustain a range of crops including cotton, peanuts, cocoa, coffee, plantain, maize, millet, and sorghum.

Figures 4.16*a-c* document changes of crop acreage (absolute values) as a function of time for available data. Here, also, the analyses focus on each individual country because the crops and available data periods vary within Central West Africa. Unlike previous analyses (Figs. 4.15*a,b*), Figures 4.16*a-c* were constructed using data from all (not only dominant) crop regions in each country. The study first evaluates crop acreages and then compares variations in acreage to variations in production and in yields (Figs. 4.17*a,b*). The goal is to provide the basis for subsequent investigations of whether variations in crop yields are related to variations in rainfall (Section 4.3) or to changes in environmental policies such as governmental decisions for encouraging either staple or cash crops (Chapter 5).

Figure 4.16*a* suggests that cotton acreage in Mali has increased exponentially since 1985, and possibly since 1966. Certainly, the acreage in the mid-1980s was only slightly larger than during 1966-68, after which data are not available until 1984. Peanut acreage in Mali, on the other hand, displays a parabola-like trend and recorded its largest values in 1990 and 1994. Further, the acreages in 1966-1968 and 1984-1987 were to some extent smaller than those recorded since the late 1980s. Millet acreage in Mali shows episodes with an abrupt increase followed by slight declines every four to five years from 1984 to 1998. Sorghum acreage in Mali displays a progressive increase from 1984-93, then a decline through 1996, followed by a slight increase in 1997-98. The acreages of the two Malian cash crops apparently were smaller in the late-1960s than after the mid-1980s. Peanut, sorghum, and millet acreages in Mali were similar from 1996-1998.

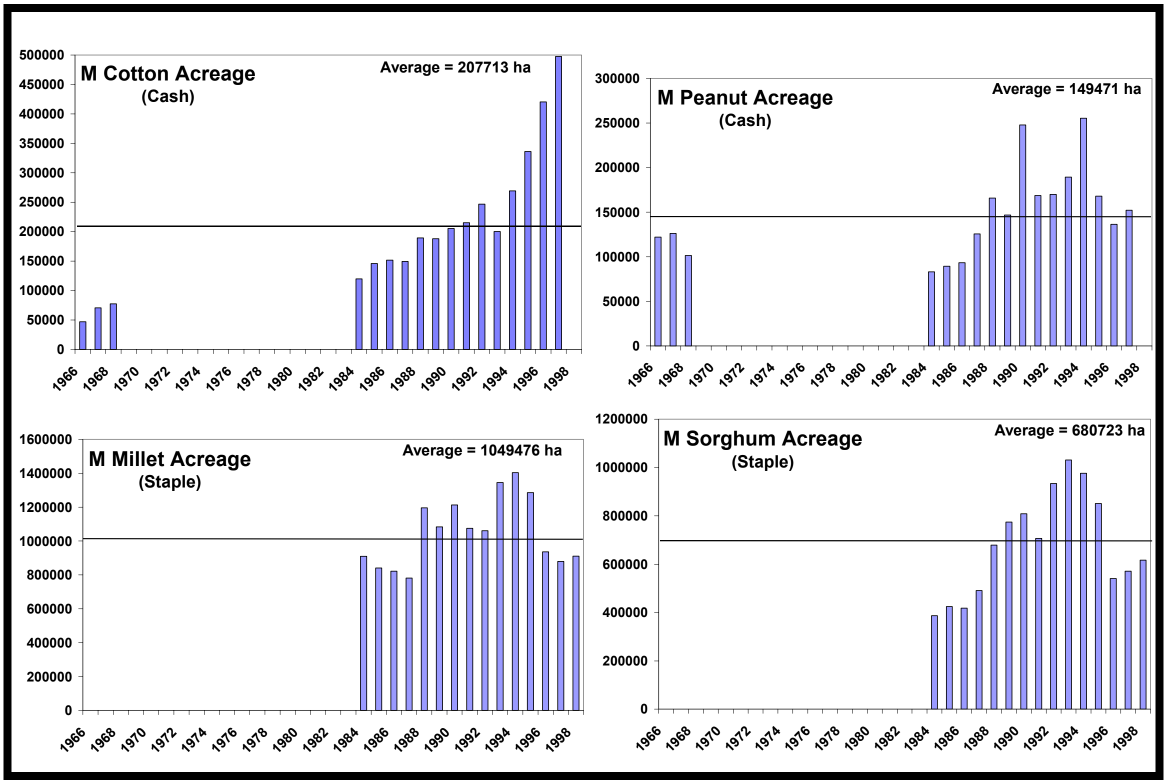


Figure 4.16*a*: Time series of crop acreage (hectares) in Mali (M). Average values obtained from all of the 7 Malian agricultural regions. The horizontal line is the mean for the years when data are available. Data are not available for years for which there are no bars.

For Burkina Faso (Fig. 4.16*b*), cotton acreage generally has increased exponentially since 1970, but with occasional drops in 1993 and 1995. Peanut acreage in Burkina Faso was relatively constant during 1970-1984, after which it increased through 1996 and then decreased slightly. Millet acreage in Burkina Faso decreased linearly from 1970 to 1972 and possibly until 1975 (data for the drought years of 1973-75 are unavailable), then increased from 1976 to 1988, and varied somewhat thereafter. Sorghum

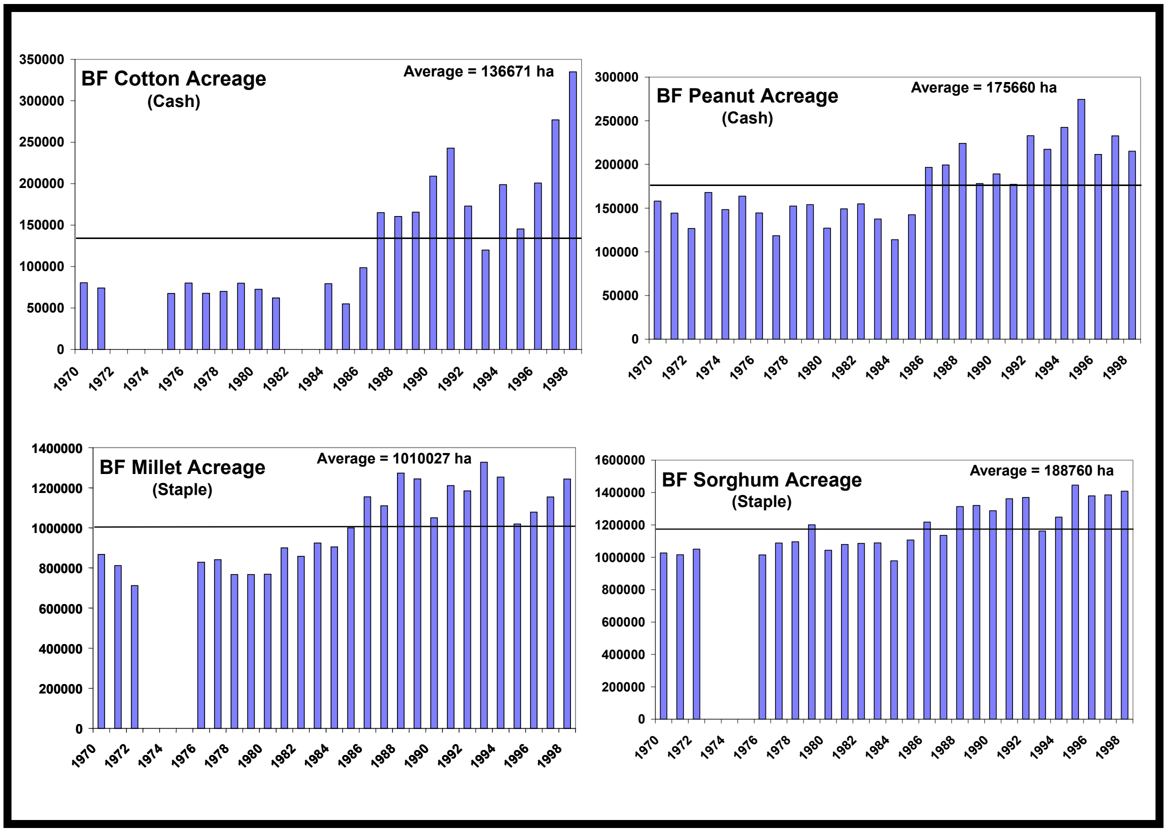


Figure 4.16*b*: Time series of crop acreage (hectares) in Burkina Faso (BF). Average values obtained from the 10 Burkinabè agricultural regions. The horizontal line is the mean for the years when data are available. Data are not available for years for which there are no bars.

acreage in Burkina Faso has increased modestly but progressively since 1976 and possibly since 1970 (data for the drought years of 1973-75 are unavailable). Certainly, the acreage from 1970 to 1985 was only slightly smaller than after the mid-1980s. Overall in Burkina Faso, after the mid-1980s, except for a few years (1987 and 1993 for sorghum; 1993 for cotton), all crops recorded above the mean acreages.

Figure 4.16*c* shows that cocoa acreage (1948-98) in Côte d'Ivoire increased exponentially until quite recently, with smaller acreages from 1948 to 1973 and larger records thereafter through the early 1990s. However, 1996-1998 registered markedly smaller values. Coffee acreage in Côte d'Ivoire increased linearly from 1950 to the early

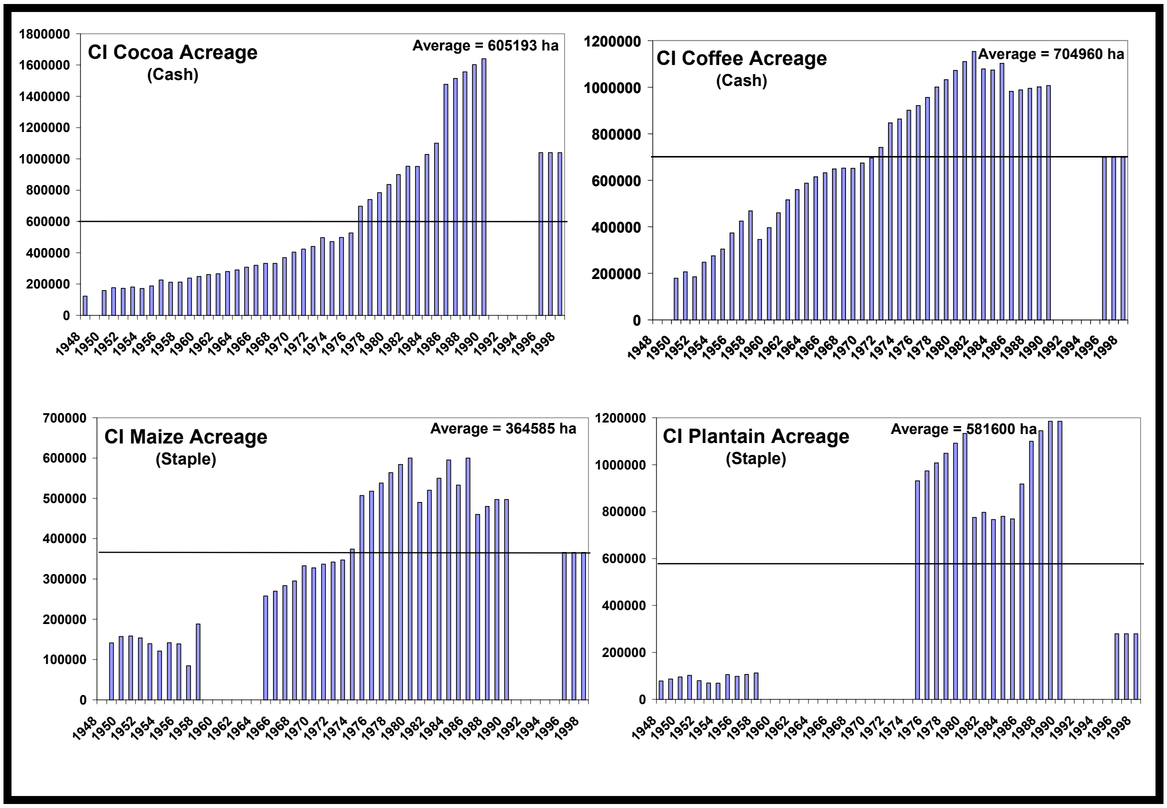


Figure 4.16*c*: Time series of crop acreage (hectares) in Côte d'Ivoire (CI). Average values obtained from the 10 Ivorian agricultural regions. The horizontal line is the mean for the years when data are available. Data are not available for years for which there are no bars.

1980s and declined slightly thereafter. Maize acreage in Côte d'Ivoire also increased linearly from the 1960s through the early 1980s and then decreased. Plantain acreage in Côte d'Ivoire from the mid-1970s through the mid-1990s was much larger than for 1948-58 as well as 1996-98. Still, in spite of its larger than long-term mean values, 1981-1985 registers declines in plantain acreage that coincide with the widespread 1982-84 drought episodes that affected the whole of Central West Africa (see Section 2.1.2.1). Overall, the four Ivorian crops occupied smaller acreages before the mid-1960s (coffee and maize) and mid-1970s (cocoa and plantain) and perhaps in 1996-1998. The constancy of Ivorian acreages for each year during 1996-1998 implies 1997 and 1998 may have been estimated from 1996 figures and may therefore be less reliable.

In summary, the above analyses of crop acreages in Central West Africa show strong variations on time-scales ranging from interannual to multidecadal and from one crop to another. In order to draw overall conclusions on agricultural change, acreages next are compared with both productions and yields (aggregated to a country-level) to make a complete temporal assessment of the trends and relationships among crop parameters. Their variations are determined by the mechanics of regression fitting to the overall data periods, unless otherwise indicated (i.e., longest subperiods of data for cases with at least two consecutive years of missing data).

As in Figures 4.16*a*-*c*, these parameter comparisons encompass all crop regions of each country, allowing for complete assessments about acreages, productions, and yields. The original units for each of the crop parameters are hectares (ha) for acreage, tonnes (t) that were then converted into kilograms (1t = 1,000 kg) for production; thus, the ratio of production over acreage forms the unit of kilograms per hectare (kg ha^{-1}) for yields. However, for the purpose of comparisons among these crop parameters, the time series of absolute values for acreage (ha), production (kg), and yields (kg ha^{-1}) next were converted into ratios of an individual crop in an individual year compared to the national total (summed for all years for which data are available) acreage planted, kilograms produced, and yields obtained (calculated from first two parameters) for all crops within Mali, Burkina Faso, and Côte d'Ivoire. The rationale for these conversions into percentages is to produce time series that ease comparative study, especially when showing crop acreage, production, and yields on the same graph. The aim here is to investigate key issues such as how the three crop parameters vary and relate, as well as years when increased acreage was associated with decreased yields.

Figures 4.17*a*,*b* demonstrate that for many crops, the trends of acreage and production for the overall study periods relate more often than do the trends of acreage-yields and production-yields. In Central West Africa, a production increase (positive slope) or decrease (negative slope) tends to accompany the same change in acreage more frequently than the same change in yields. As is the case with acreage (Figs. 4.16*a*-*c*), production and yields largely exhibit two features, with smaller values (i.e., below average national values) at the beginning of each crop record and relatively larger values (i.e., above average national values) toward the end of the study periods (Figs. 4.17*a*,*b*). In Mali, smallest and largest values are more distinct for cash crop parameters, especially for cotton. For all crops in this country, acreage and production show similar trends, while yields display opposite trends (with the exception of cotton when 1966-68 yields are taken into account; see Table 4.17*a*).

For Burkina Faso, cotton, peanuts, millet, and sorghum show strong variations, with all of their parameters recording smaller values from 1970 to the mid-1980s and larger values thereafter. However, data for the staple crops in Burkina Faso were missing the years 1973-1975, which coincide with the latter part of the most severe period of Sahelian drought during that decade (see Tables 3.7*a*-*c*). Still, here, acreage, production, and yields show similar trends for entire study periods for all crop types with the exception of cotton when only the latter and longer part (1984-98) of yield data are taken into account. Increasing acreage is accompanied by increases in both production and yields for peanuts, millet, and

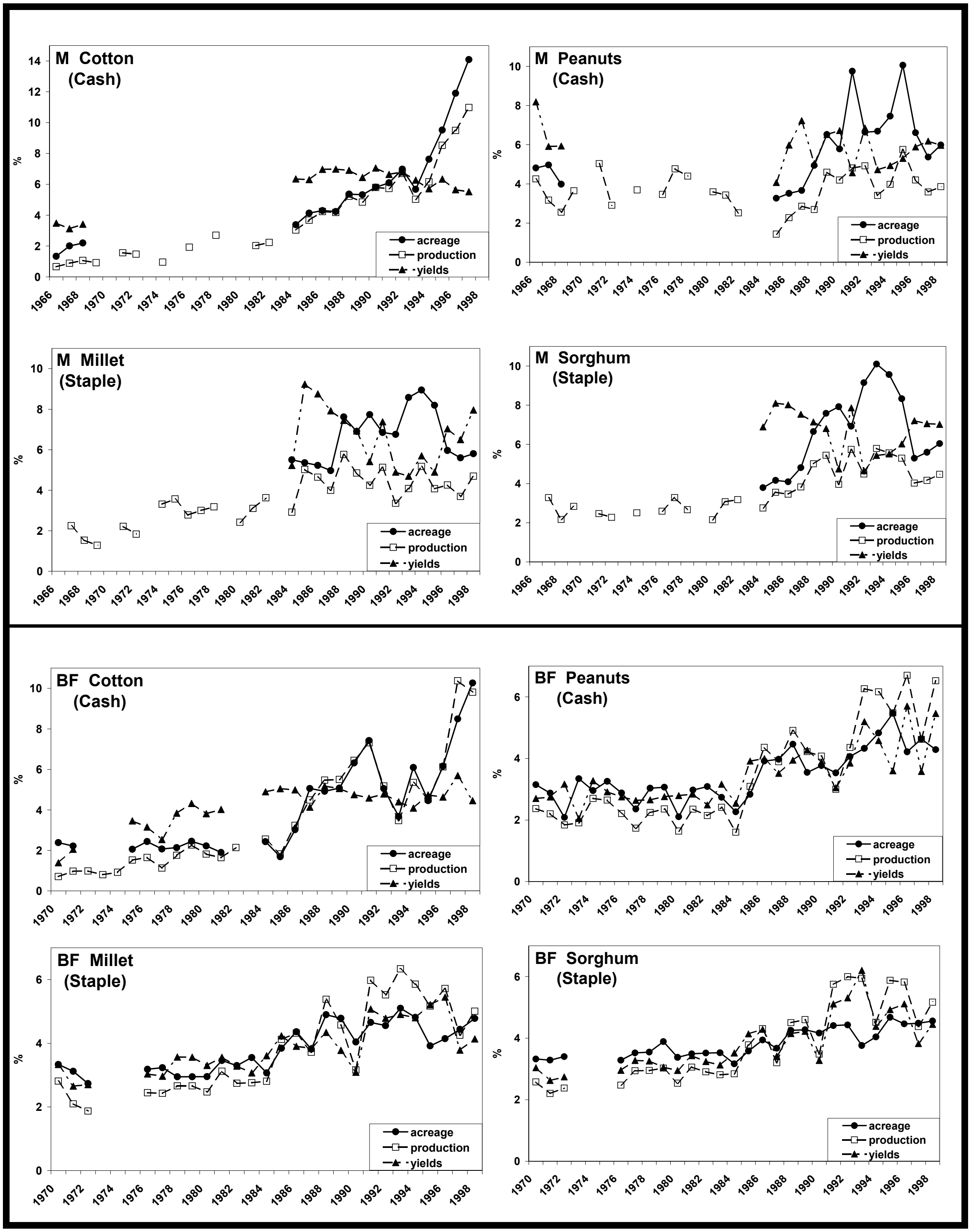


Figure 4.17*a*: Time series comparisons of individual cash/staple crop acreage, production, and yields for Mali (M, top two rows) and Burkina Faso (BF, bottom two rows). Relative annual values for acreage, production, or yields are ratios of each crop (separately) in that year compared to the total (summed for all years for which data are available) crop acreage planted, kilograms produced, or yields calculated, respectively. Data are not available for years for which there are no symbol markers.

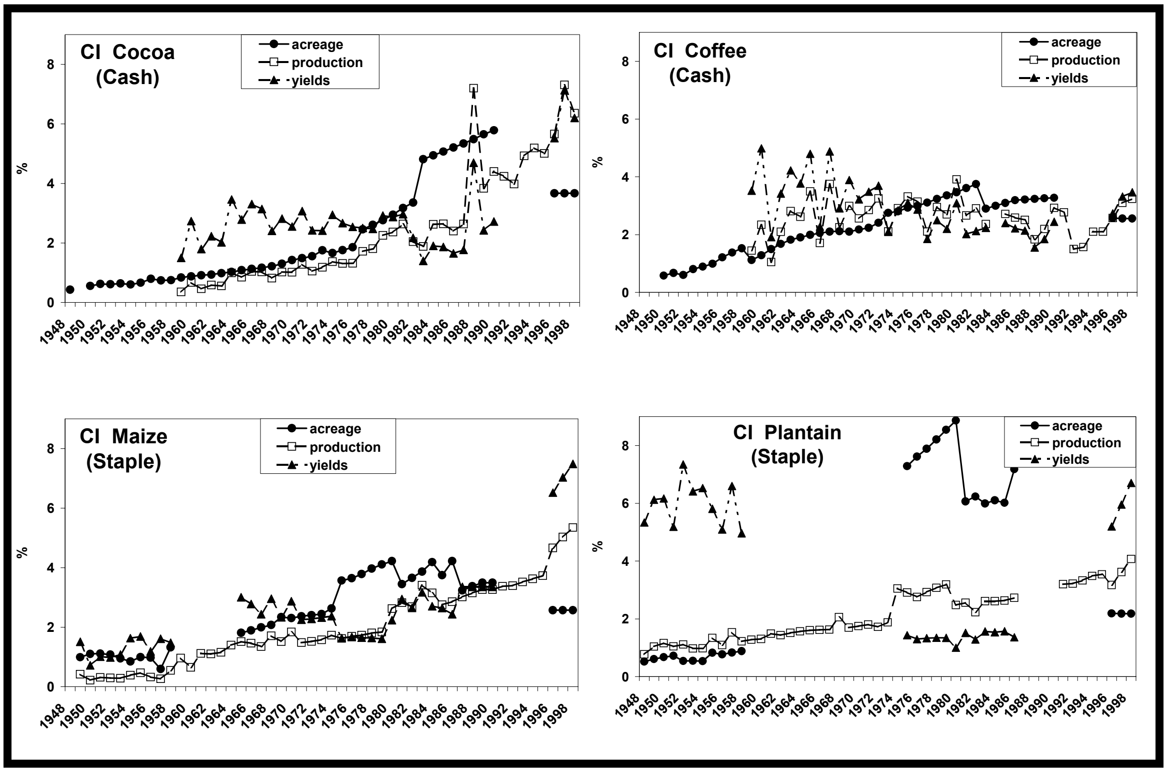


Figure 4.17*b*: Time series comparisons of individual cash/staple crop acreage, production, and yields for Côte d'Ivoire (CI). Relative annual values for acreage, production, or yields are ratios of each crop (separately) in that year compared to the total (summed for all years for which data are available) crop acreage planted, kilograms produced, or yields calculated, respectively. Data are not available for years for which there are no symbol markers.

sorghum (Table 4.17*a*). In Côte d'Ivoire, the relationships among crop parameters vary from one crop to another and the smaller values are more apparent for coffee and maize, while the larger values are more distinct for cocoa and plantain. Acreage, production, and yields increase together for maize (except 1975-80 when acreage increases, but production and yields decrease), whereas only acreage and production increase for cocoa and plantain. The parameters differ for coffee, with acreage increasing, production fluctuating (near-zero slope; i.e., -0.002 ≤ slope ≤ +0.002), and yields decreasing (Table 4.17*a*).

Even though the three parameters show similar variations for all crops in Burkina Faso (except cotton) and maize in Côte d'Ivoire, as well as increased acreage linked to production and yields varying differently for coffee in Côte d'Ivoire, the graphs in Figures 4.17*a*,*b* for all three countries also confirm that in many years production rates are more a function of acreage than are yield rates. For instance, acreage increases may induce increases in production, while yields decrease (especially for all crops in Mali and cocoa and plantain in Côte d'Ivoire). Table 4.17*a* summarizes for the overall study periods the crop parameter characteristics illustrated in Figures 4.17*a*,*b*, while Table 4.17*b* presents their correlation coefficients. Note that when the same correlation analysis is performed on absolute values of the three crop parameters, the results are the same. These correlations further reveal that crop acreage and production tend to be positively correlated, acreage and yields have some negative correlations (especially for Mali and Côte d'Ivoire), and production and yields are somewhat correlated (mostly positively). In other words, Table 4.17*b* shows that crop acreage

Table 4.17*a*: Summary of crop acreage (A), production (P), and yield (Y) variations and relationships for Central West Africa for the overall study periods shown in Figures 4.17*a*,*b*. Regression-based trends of parameters obtained for all years with data (unless otherwise indicated) are expressed by: ↑ = increase (positive slope), ↓ = decrease (negative slope), ≈ = fluctuate (near-zero slope; -0.002 ≤ slope ≤ +0.002).

Mali	**Cotton***	**Peanuts**	**Millet**	**Sorghum**	**Summary**
Regression Lines	Exponential increase (A↑, P↑) & slight decrease (Y↓)	Linear increase (A↑, P↑) & decrease (Y↓)	Linear increase (A↑, P↑) & decrease (Y↓)	Linear increase (A↑, P↑) & decrease (Y↓)	**A & P** show similar trends, while **Y** display opposite trends for all crops
Parameter	A↑, P↑, Y↓	A↑, P↑, Y↓	A↑, P↑, Y↓	A↑, P↑, Y↓	
Similar trend	**A & P**	**A & P**	**A & P**	**A & P**	
Burkina Faso	**Cotton***	**Peanuts**	**Millet**	**Sorghum**	**Summary**
Regression Lines	Exponential (A↑) to linear (P↑) increase & slight decrease (Y↓)	Linear increase (A↑, P↑, Y↑)	Linear increase (A↑, P↑, Y↑)	Linear increase (A↑, P↑, Y↑)	**A, P, & Y** show similar trends for all crop types except for cotton where **A & P** share the same trends, while **Y** display the opposite
Parameter	A↑, P↑, Y↓	A↑, P↑, Y↑	A↑, P↑, Y↑	A↑, P↑, Y↑	
Similar trend	**A & P**	**A, P, & Y**	**A, P, & Y**	**A, P, & Y**	
Côte d'Ivoire	**Cocoa**	**Coffee**	**Maize**	**Plantain**	**Summary**
Regression Lines	Linear increase (A↑, P↑) & decrease (Y↓)	Slight increase (A↑), fluctuate (P≈) & decrease (Y↓)	Linear increase (A↑, P↑, Y↑)	Linear increase (A↑, P↑) & decrease (Y↓)	**A, P, & Y** show similar trends for maize, while only **A & P** display same trends for cocoa and plantain -- **A, P, & Y** differ for coffee
Parameter	A↑, P↑, Y↓	A↑, P≈, Y↓	A↑, P↑, Y↑	A↑, P↑, Y↓	
Similar trend	**A & P**	**None**	**A, P, & Y**	**A & P**	

*** Y for cotton only show a similar increase to A & P when including 1st three years (1966-68) of data for Mali and considering the entire data periods (instead of the last 15 years: 1984-98) for Burkina Faso.**

Table 4.17*b*: Linear correlations between relative annual values of crop acreage, production, and yields in Central West Africa for the overall study periods common to all three crop parameters (see Figs. 4.17*a*,*b*). Correlation coefficients with ≥ 99% significance levels are in bold; those with ≥ 95% & < 99% significance levels are asterisked; correlation coefficients with ≥ 90% & < 95% significance levels are underlined; and those with ≥ 85% & < 90% significance levels are in parentheses. Levels of significance are derived from two-tailed t test. Note when the same correlation analysis is performed on absolute values of crop acreage, production, and yields, the results are the same.

Mali	**Cotton**	**Peanuts**	**Millet**	**Sorghum**
Acreage vs. Production	**+0.98**	**+0.85**	+0.28	**+0.80**
Acreage vs. Yields	+0.32	-0.28	**-0.64**	**-0.81**
Production vs. Yields	+0.50*	+0.24	+0.54*	-0.31
Burkina Faso	**Cotton**	**Peanuts**	**Millet**	**Sorghum**
Acreage vs. Production	**+0.97**	**+0.88**	**+0.91**	**+0.85**
Acreage vs. Yields	+0.48*	**+0.63**	**+0.70**	**+0.68**
Production vs. Yields	**+0.64**	**+0.92**	**+0.93**	**+0.96**
Côte d'Ivoire	**Cocoa**	**Coffee**	**Maize**	**Plantain**
Acreage vs. Production	**+0.70**	<u>+0.32</u>	**+0.65**	**+0.68**
Acreage vs. Yields	+0.10	**-0.66**	(+0.26)	**-0.95**
Production vs. Yields	**+0.76**	**+0.46**	**+0.89**	**-0.53**

and production are generally positively and strongly correlated at ≥ 99% significance levels. The exceptions are millet in Mali (r = +0.28, 68% significance level) and coffee in Côte d'Ivoire (r = +0.32, 94% significance level). The correlation coefficients also suggest that the effects of acreage increases on yields are mainly negative (except in Burkina Faso; cotton in Mali; cotton/maize in Côte d'Ivoire); the positive correlation coefficients for cotton in all three countries are weak and only significant in Burkina Faso (98%). Burkina Faso registers positive and significant correlations for acreage versus yields for peanuts, millet, and sorghum, reflecting the similarity of variations for the crop parameters in this country (Table 4.17*a*). Though not as strongly positive as the effects of acreage on production, the correlations between production and yields show significant positive coefficients despite the non-significant positive (peanuts) and negative (sorghum) correlations in Mali, as well as the negative (plantain) correlations in Côte d'Ivoire. These results led to further analysis in the next section of the crop parameter relationships focusing on the 12 dominant agricultural regions and their eight major crops.

4.2.2.2 Temporal Variations of Major Crops for Dominant Regions

While the previous section studied the temporal variation of the relationships among agricultural parameters for all three countries at the national level (large scale), the present section examines the variations among crop acreage, production, and yields for the 12 dominant agricultural regions (four per country - small scale) and their eight major cash and staple crops, as summarized in Table 4.16. Note that the time periods of available crop data vary among the regions and from one crop to another both within and across countries. The analyses presented here use the entire available data set for each crop, or the longest subperiods in cases of more than two consecutive years of missing data. For each year and dominant region, crop acreage (ha), production (kg), and yields (kg ha^{-1}) were expressed as the percentage in that year of the long-term total (summed for all available years within each region separately) of acreage planted, kilograms produced, or yields calculated, respectively. The results were summarized in 48 graphs (the eight major crops for the dominant 12 regions comprised a total of 48 cases studied) showing the time-varying relations among these relative crop parameters. To illustrate the prevailing trends, Figures 4.18*a*,*b* display the graphs for one crop per region, selected for strength of regional contrasts. The results as a whole are reviewed in Table 4.18, which shows the regression-based trends of increase (positive slope), decrease (negative slope), or fluctuating (near-zero slope) of each crop parameter of acreage, production, and yields as well as the relationships (similar/different) among trends for each country's four dominant regions.

A positive relation between acreage and production may be more intuitively obvious than the relations between acreage and yields or production and yields because added acres can involve lower quality lands. Yet, Figures 4.18*a*,*b* and the results summarized in Table 4.18 reveal that in this study acreage, production, and yields often do follow similar regression-based trends (all increasing, all decreasing, or all fluctuating for entire study periods or subperiods): the low (high) acreage values do affect the decrease (increase) of the other two (i.e., production and yields) for all crop types. Still, there are cases in which the parameters do not follow similar trends, such as where yields decrease in spite of increased acreage and production. For instance, in Mali cotton and peanuts in Ko and sorghum in Ko and Ky display increased acreage and production with decreased yields. For Burkina Faso, cotton and peanuts in HB and sorghum in Ma also have increased acreage and production with decreased yields. Cocoa and coffee in CWb and Sb as well as plantain in Cb and CWb for Côte d'Ivoire likewise show increased acreage and production with decreased yields.

Generally, there are more similarities between acreage and production (e.g., cotton, peanuts, sorghum in Ko for Mali; cotton, peanuts in HB and sorghum in Ma for Burkina Faso; cocoa, coffee, plantain in CWb and Sb for Côte d'Ivoire) than between yields and production (e.g., sorghum in So for Mali; millet in HB for Burkina Faso; coffee in Cb for Côte d'Ivoire). In Table 4.18, for 27 out of the 48 region-crop cases, all of the three crop parameters

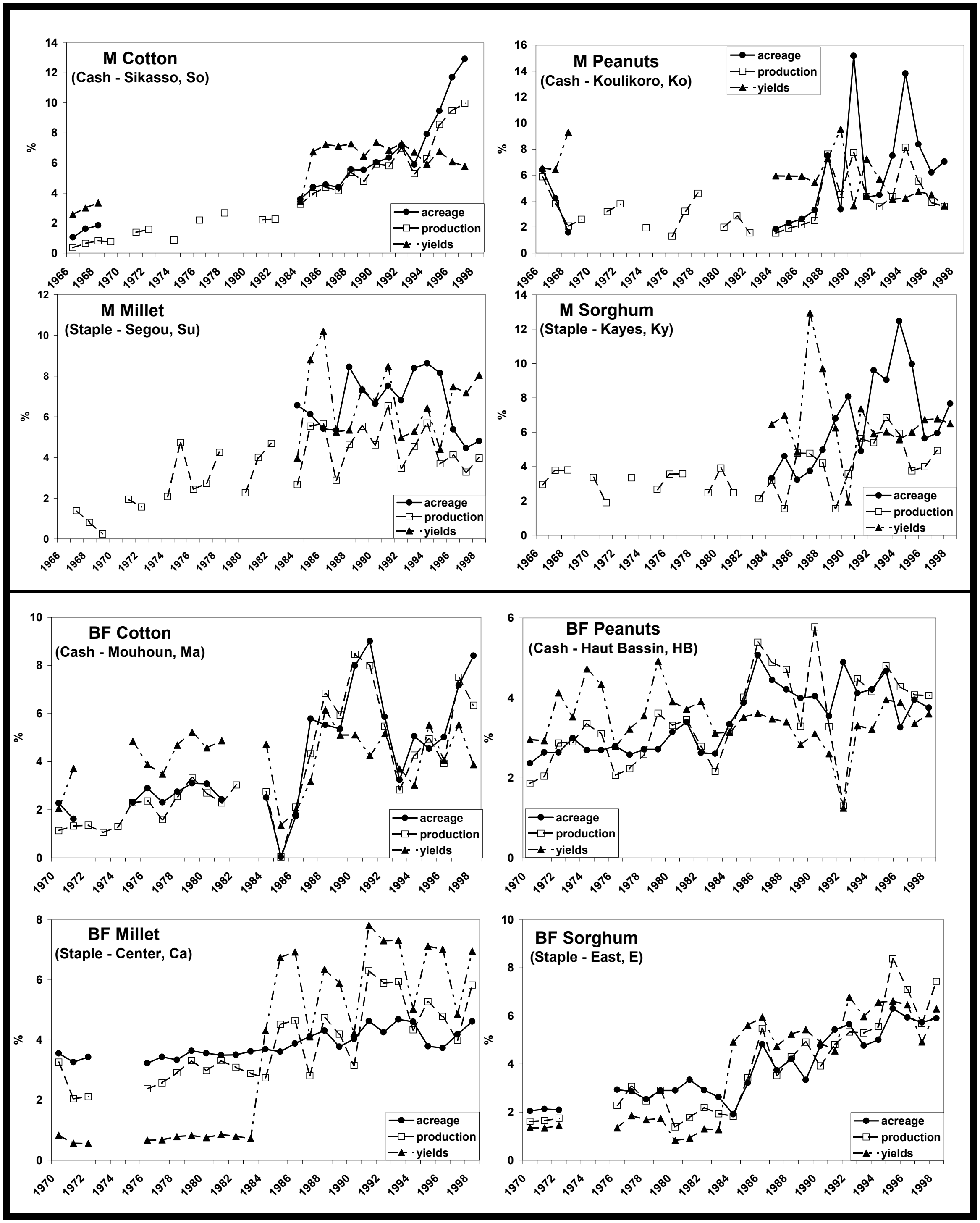


Figure 4.18*a* (counterpart of Fig. 4.17*a*, but at a regional level): Relative temporal variations of crop parameter relations within selected dominant crop regions of Mali (M, top two rows) and Burkina Faso (BF, bottom two rows). Relative annual values for acreage, production, or yields are ratios of each crop (separately) in that year compared to the total (summed for all years for which data are available) crop acreage planted, kilograms produced, or yields calculated, respectively, for the region concerned (see Fig. 4.13). Data are not available for years for which there are no symbol markers.

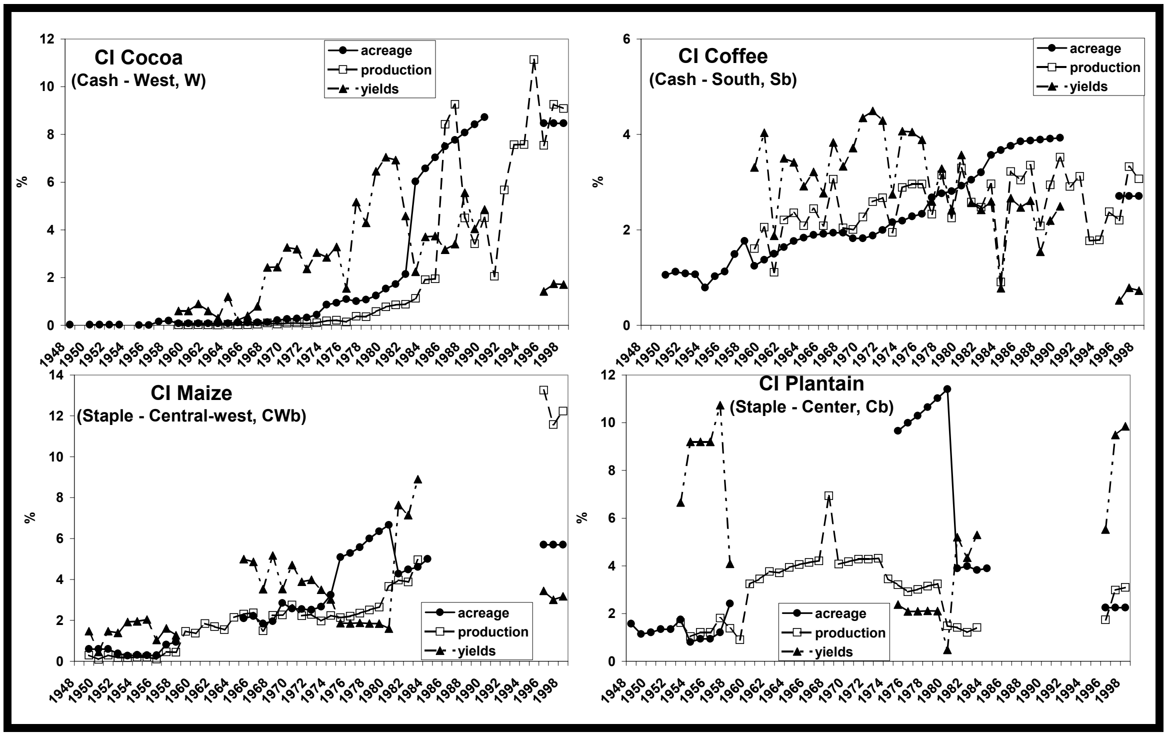


Figure 4.18*b* (counterpart of Fig. 4.17*b*, but at a regional level): Relative temporal variations of crop parameter relations within selected dominant crop regions of Côte d'Ivoire (CI). Relative annual values for acreage, production, or yields are ratios of each crop (separately) in that year compared to the total (summed for all years for which data are available) crop acreage planted, kilograms produced, or yields calculated, respectively, for the region concerned (see Fig. 4.13). Data are not available for years for which there are no symbol markers.

show the same overall regression-based trends of increase, decrease, or fluctuating across the dominant regions of each country. These account for 56% of the 48 cases that occur in both staple (14 cases) and cash (13 cases) crops. There are also a number of situations (about 29% of the 48 cases or 14 cases split between 8 for cash and 6 for staple crops) in which acreage and production have the same variations but yield has the opposite. There are relatively few cases in which only production and yield variations are the same (about 13% of the 48 cases or 6 cases with 4 for staple and 2 for cash crops). Finally, it is very rare that all parameters differ in their individual trends (2% of the 48 cases occurring in 1 case for cash crop) and no situation in which acreage and yields are similar with differing production (0% of the 48 cases). The bottom of Table 4.18 summarizes these variations and their percentages of occurrences.

Table 4.18: Summary of crop acreage (A), production (P), and yield (Y) variations and relationships for the 12 dominant crop regions in Central West Africa (see Fig. 4.13) for the overall study periods shown in Figures 4.18*a*,*b*. Regression-based trends of parameters obtained for all years with data (unless otherwise indicated) are expressed by: ↑ = increase (positive slope), ↓ = decrease (negative slope), ≈ = fluctuate (near-zero slope; -0.002 ≤ slope ≤ +0.002); (+) = 2 or 3 show a similar trend, (-) = at least 1 shows a different trend. C = cash crop and S = staple crop.

Mali	Cotton	Peanuts*	Millet*	Sorghum*
Koulikoro (Ko)	(A↑, P↑)*= + (Y↓)* = -	(A↑, P↑) = + (Y↓) = -	(A↑) = - (P↓, Y↓) = +	(A↑, P↑) = + (Y↓) = -
Kayes (Ky)	(A↑, P↑, Y↑)* = +	(A↑, P↑, Y↑) = +	(A↑, P↑, Y↑) = +	(A↑, P↑) = + (Y↓) = -
Sikasso (So)	(A↑, P↑, Y↑)* = +	(A↑, P↑, Y↑) = +	(A↓, P↓, Y↓) = +	(A↑) = - (P↓, Y↓) = +
Segou (Su)	(A↑, P↑, Y↑) = +	(A↑) = - (P↓, Y↓) = +	(A↓, P↓, Y↓) = +	(A↑, P↑, Y↑) = +
Burkina Faso	**Cotton**	**Peanuts**	**Millet**	**Sorghum**
Center (Ca)	(A↑, P↑, Y↑)* = +	(A↑, P↑, Y↑) = +	(A↑, P↑, Y↑) = +	(A↓) = - (P↑, Y↑) = +
East (E)	(A↑, P↑, Y↑) = +	(A↑, P↑, Y↑) = +	(A↑, P↑, Y↑) = +	(A↑, P↑, Y↑) = +
Haut-Bassin (HB)	(A↑, P↑) = + (Y↓) = -	(A↑, P↑) = + (Y↓) = -	(A↓) = - (P↑, Y↑) = +	(A↑, P↑, Y↑)* = +
Mouhoun (Ma)	(A↑, P↑, Y↑) = +	(A↑, P↑, Y↑)* = +	(A↑, P↑, Y↑) = +	(A↑, P↑)* = + (Y↓)* = -
Côte d'Ivoire	**Cocoa**	**Coffee**	**Maize**	**Plantain**
Center (Cb)	(A↑, P↓, Y≈)* = -	(A↑) = - (P↓, Y↓) = +	(A↑, P↑, Y↑) = +	(A↑, P↑)* = + (Y↓)* = -
Central-west (CWb)	(A↑, P↑) = + (Y↓) = -	(A↑, P↑) = + (Y↓) = -	(A↑, P↑, Y↑) = +	(A↑, P↑) = + (Y↓) = -
South (Sb)	(A↑, P↑) = + (Y↓) = -	(A↑, P↑) = + (Y↓) = -	(A↑, P↑, Y↑) = +	(A↑, P↑) = + (Y↓) = -
West (W)	(A↑, P↑, Y↑) = +	(A↑, P↑, Y↑) = +	(A↑, P↑, Y↑) = +	(A↑, P↑, Y↑) = +
SUMMARY OF ACREAGE, PRODUCTION, AND YIELD RELATIONSHIPS				
Trend Relation	**Mali**	**Burkina Faso**	**Côte d'Ivoire**	**Total**
APY = + (27/48 = 56%)	9 (5C, 4S)	11 (6C, 5S)	7 (2C, 5S)	27 (13C, 14S)
APY = - (1/48 = 2%)	0 (0C, 0S)	0 (0C, 0S)	1 (1C, 0S)	1 (1C, 0S)
AP = +, Y = - (14/48 = 29%)	4 (2C, 2S)	3 (2C, 1S)	7 (4C, 3S)	14 (8C, 6S)
AY = +, P = - (0/48 = 0%)	0 (0C, 0S)	0 (0C, 0S)	0 (0C, 0S)	0 (0C, 0S)
A = -, PY = + (6/48 = 13%)	3 (1C, 2S)	2 (0C, 2S)	1 (1C, 0S)	6 (2C, 4S)
Total	16	16	16	48

*** Cases in which the longest subperiods were used: 1984-97 or 1984-98 for Mali; 1984-98, 1988-98, or removing first 2 years (1970-71) for Burkina Faso; deleting last 3 years (1996-1998) for Côte d'Ivoire.**

The results in Table 4.18 suggest that increased crop production in Central West Africa likely is determined more by increased acreage (e.g., cotton, peanuts, millet in Ky and So for Mali; cotton, peanuts, millet in Ca, E, and Ma for Burkina Faso; and all crops in W for Côte d'Ivoire) than other possible contributors such as mechanization or use of fertilizers, where acreage increases in lower quality lands (Turner and Brush, 1987; Brou et al., 1998; see literature review in Sections 2.2.3-2.2.5 for full discussion of the usage of agricultural technology in the three countries). Indeed, the input of fertilizers would have favored an increasing trend for yields (e.g., sorghum in Ca and millet in HB for Burkina Faso), but appears to have been over-ridden by the poorer quality of some new lands. Further, the perpetual addition of new lands has been stronger in the southern and central portions of each country, where most production areas have undergone an ongoing yearly increase of acreage, as shown in Section 4.2.2.1 and supported by studies such as Koli Bi (1992), Ministère de l'Environnement et du Tourisme (1994), and Ministère de l'Environnement (1997).

The next analyses focus on the temporal variations of rainfall/crop yield relationships. Indeed, crops in the study area show variations that have been tentatively related to several causes, ranging from the effects of rainfall variability to the variety of farming systems, differences in agricultural production, the perpetual addition of new croplands, and the increasing pressure of population (Turner and Brush, 1987; Ouédraogo, 1990; Koli Bi, 1992; Brou et al., 1998; see also Section 4.2.2.1). However, since little research has examined quantitatively the impacts of rainfall variations, these are the potential causes of crop variability of chief interest for this Dissertation. The key issue here is to assess the effect rainfall has on crop yields. Accordingly, Section 4.3 investigates rainfall variability and crop yield variation relationships during 1970-1998.

4.3 Rainfall Variation and Agricultural Yield Relationships

4.3.1 Temporal Analyses

Investigations are now carried out to reveal how variations in crop yields are related to variations in rainfall and how agricultural changes reflect occurrence or non-occurrence of seasonal rainfall extremes. Indeed, authors such as Dancett (1978), Dennett et al. (1981), Sivakumar (1988, 1992), and Camberlin and Diop (1999) recognized in their studies what Stern et al. (1982, p. 223) stated so succinctly: "Rainfall governs crop yields…determines the choice of crops that can be grown…important questions are…the start, end and length of the rainy seasons, the distribution of rainfall amounts through the year, and the risk of dry spells." Before embarking on this discussion, it is important to clarify that the relationships between variability in rainfall and crops are defined here through variability in the crop yields, which integrate both acreage and production and strongly reflect rainfall variability. Not only are yields economically important to farmers, but also they are good indicators for the assessment of agricultural change, by indicating the efficiency with which the environment has been used for farming (Chmielewski and Potts, 1995; Brown and Rosenberg, 1997; Camberlin and Diop, 1999; Lal et al., 1999). Here, the detailed water balance of crops is not considered, only the statistical associations between rainfall and crop yields.

The study treats all 27 agricultural regions of the three countries (7 for Mali, 10 for Burkina Faso, 10 for Côte d'Ivoire); thus, the spatial scale of analysis is a full country. Cotton, maize, and rice are studied for this purpose because they are the three crops whose data are consistently available for Mali, Burkina Faso, and Côte d'Ivoire. Since the periods of coverage should be the same for both rainfall and crops, the analyses focus on the last 29 years (1970-1998) of the overall study period (1930-1998), during which there are adequate crop and rainfall data available for all countries (Table 4.16).

In this analysis, raw crop yield time series (absolute values in kg ha^{-1}; see Section 4.2.1) were used. They were also transformed into detrended crop time series (linear crop trends removed to give annual standardized anomaly values) in order to accentuate interannual variations. This is consistent with the conventional view that "detrending is done when trends obscure shorter-term variations" (Barnston et al. 1996, p. 508). In a physical sense, detrending usually is done to mitigate the positive influence of agricultural technology (e.g., fertilizers, pesticides, mechanization) on crop yields in highly developed agricultural systems. Even though this exercise may not be as imperative for the study of Central West African crops as in the other parts of the world, the detrending performed reduced the influence of the prolonged Sahel drought (see Figs. 2.2 and 4.4 in Sections 2.1.2.1 and 4.1.2.1), ensuring a more comprehensive assessment of interannual rainfall/crop yield relationships. Figures 4.19*a*-*d* illustrate annual rainfall index and crop yield (raw and detrended crop time series) relationships for each country separately and for the entire study region during 1970-1998.

Figures 4.19*a*-*d* and their summary information in Tables 4.19*a*,*b* provide a comprehensive picture of the year-to-year interactions between annual rainfall index time series and cotton/maize/rice yields. With minor differences, both raw and detrended crop time series illustrate that when rainfall changes, crop yields are affected. In general, smaller yields are below the average national yields and coincide with rainfall values that are below the study period mean (e.g., 1977, 1981-1984 for each country and for the entire study region); conversely, larger yields are associated with rainfall values above the mean (e.g., 1989, 1991, and 1996 for each country and for the entire study region). Numerous studies (e.g., Denette et al., 1981; Semenov and Porter, 1995; Phillips et al., 1998; Chmielewski and Köhn, 1999) confirmed these observations and showed the nature and magnitude of production gains and losses for particular crops and regions under different past climate variations and several scenarios of global climate changes for Africa.

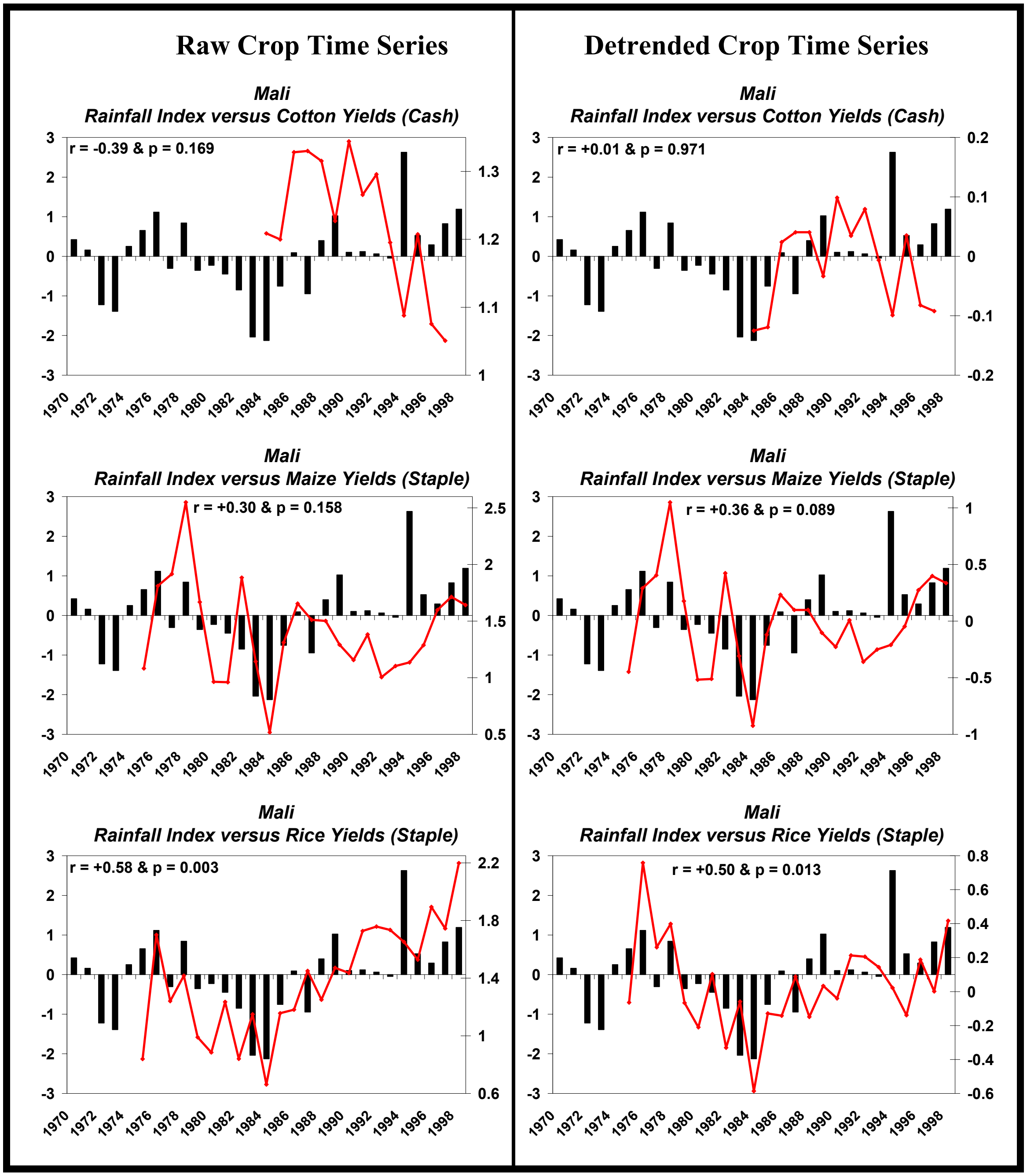


Figure 4.19*a*: Temporal relationships between annual rainfall indices (columns, left ordinate, σ) and crop yields (solid line, right ordinate; 10^3 kg ha^{-1} for raw crop series -- left panels -- see Sections 4.2.1 and 4.2.2.1; standardized anomaly for detrended crop series -- right panels) for Mali during 1970-1998. Data are not available for years for which there are no symbol markers. Note the different vertical scales for each crop time series. See Section 3.1.2.3 for construction of the standardized rainfall time series, for which means and standard deviations were computed for 1970-1998 only. Annual crop yields were transformed into detrended crop series by computing a single linear regression fit to the raw crop time series and subtracting the resulting function from the values for each year. r = correlation coefficient and p = significance levels using two-tailed t test.

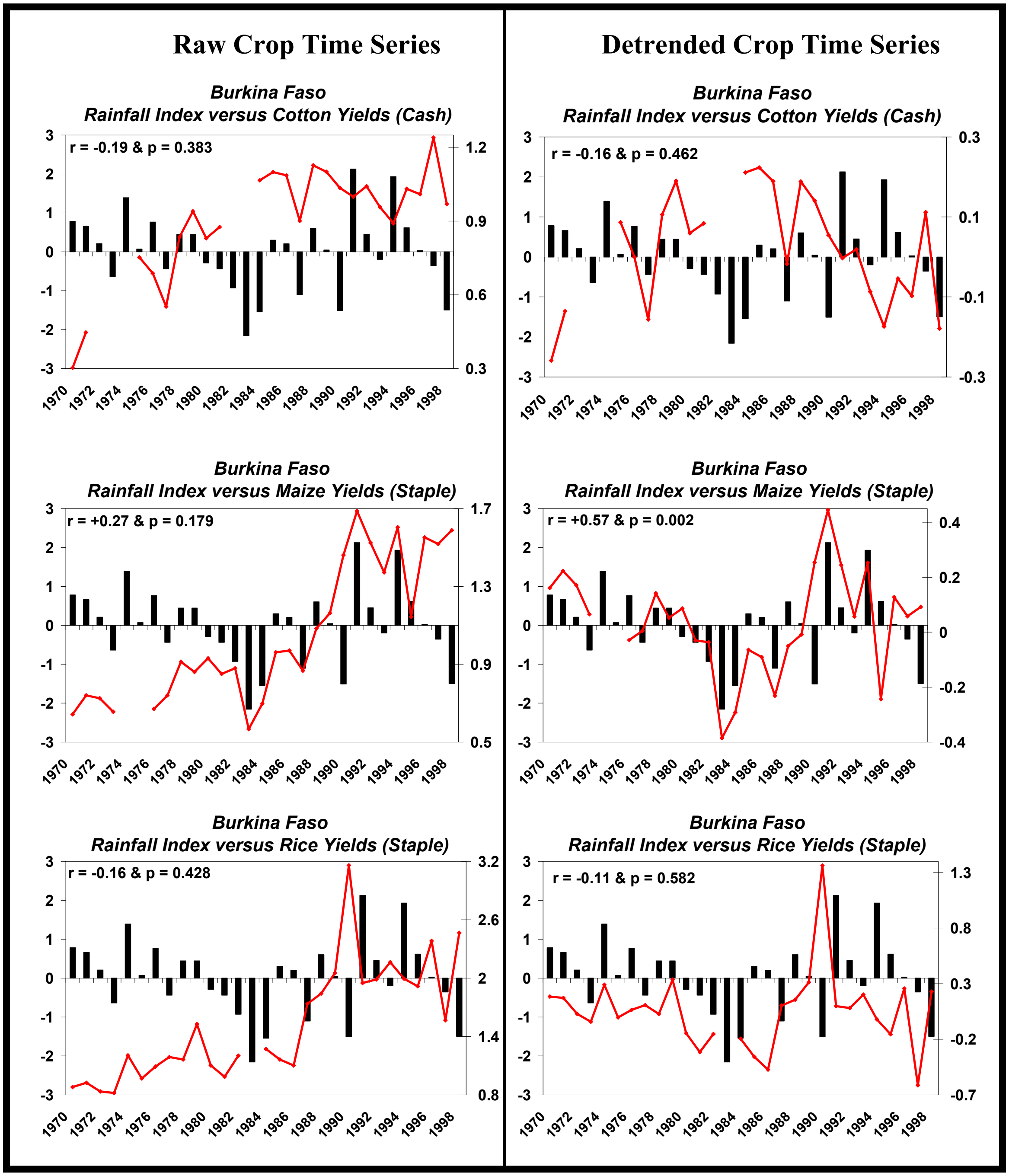


Figure 4.19*b*: Temporal relationships between annual rainfall indices (columns, left ordinate, σ) and crop yields (solid line, right ordinate; 10^3 kg ha^{-1} for raw crop series -- left panels -- see Sections 4.2.1 and 4.2.2.1; standardized anomaly for detrended crop series -- right panels) for Burkina Faso during 1970-1998. Data are not available for years for which there are no symbol markers. Note the different vertical scales for each crop time series. See Section 3.1.2.3 for construction of the standardized rainfall time series, for which means and standard deviations were computed for 1970-1998 only. Annual crop yields were transformed into detrended crop series by computing a single linear regression fit to the raw crop time series and subtracting the resulting function from the values for each year. r = correlation coefficient and p = significance levels using two-tailed t test.

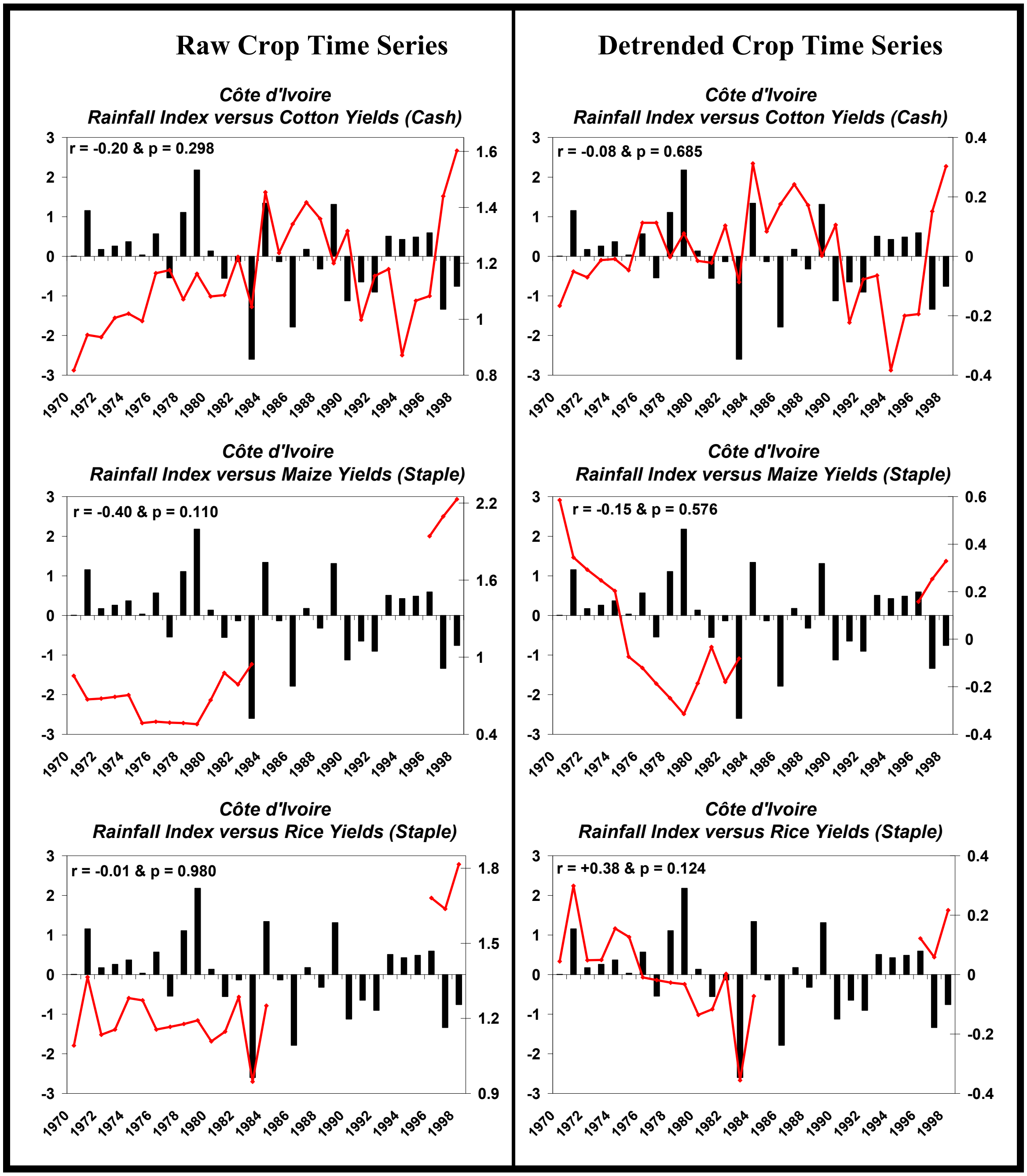


Figure 4.19*c*: Temporal relationships between annual rainfall indices (columns, left ordinate, σ) and crop yields (solid line, right ordinate; 10^3 kg ha^{-1} for raw crop series -- left panels -- see Sections 4.2.1 and 4.2.2.1; standardized anomaly for detrended crop series -- right panels) for Côte d'Ivoire during 1970-1998. Data are not available for years for which there are no symbol markers. Note the different vertical scales for each crop time series. See Section 3.1.2.3 for construction of the standardized rainfall time series, for which means and standard deviations were computed for 1970-1998 only. Annual crop yields were transformed into detrended crop series by computing a single linear regression fit to the raw crop time series and subtracting the resulting function from the values for each year. r = correlation coefficient and p = significance levels using two-tailed t test.

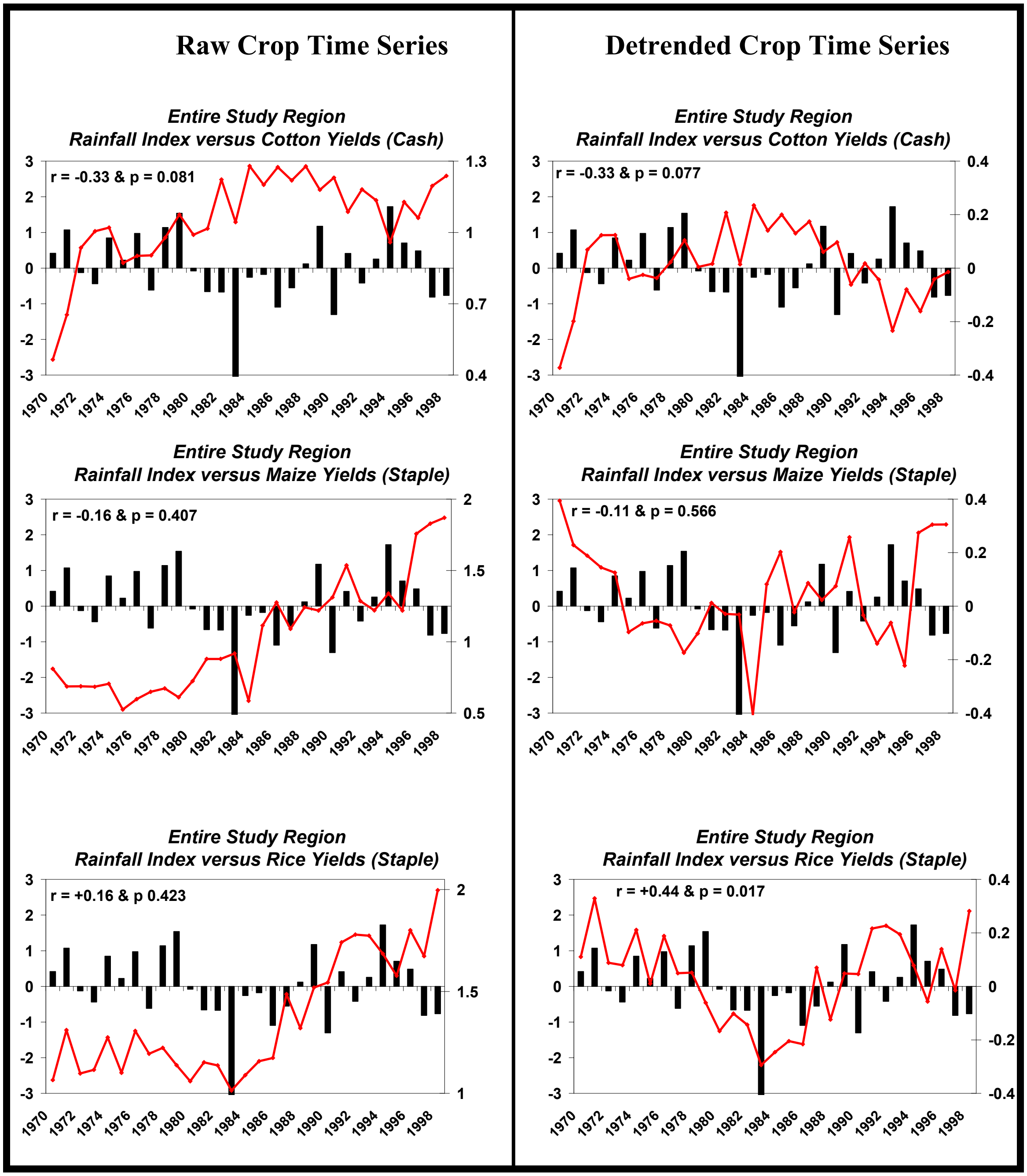


Figure 4.19*d*: Temporal relationships between annual rainfall indices (columns, left ordinate, σ) and crop yields (solid line, right ordinate; 10^3 kg ha^{-1} for raw crop series -- left panels -- see Sections 4.2.1 and 4.2.2.1; standardized anomaly for detrended crop series -- right panels) for entire study region during 1970-1998. Data are not available for years for which there are no symbol markers. Note the different vertical scales for each crop time series. See Section 3.1.2.3 for construction of the standardized rainfall time series, for which means and standard deviations were computed for 1970-1998 only. Annual crop yields were transformed into detrended crop series by computing a single linear regression fit to the raw crop time series and subtracting the resulting function from the values for each year. r = correlation coefficient and p = significance levels using two-tailed t test.

Table 4.19*a*: Summary of the temporal relationships between annual rainfall indices and raw crop time series for Mali, Burkina Faso, Côte d'Ivoire, and entire study region during 1970-98. Table is drawn from Figures 4.19*a-d* (left panels). Years with missing data are given in parentheses for each country. Years of inconsistent rainfall/crop yield relationships are denoted as A (rain is above the mean, yields are below the average national value) and B (rain is below the mean, yields are above the average national value).

RAINFALL				
Departure	**Mali**	**Burkina Faso**	**Côte d'Ivoire**	**Entire Study Region**
Above the Mean (year)	1970-71,74-76,78,86, 88-92,94-98	1970-72,74-76,78-79,85- 86,88-89,91-92,94-96	1970-76,78-80,84,87,89, 93-96	1970-71,74-76,78-79, 88-89,91,93-96
Below the Mean (year)	1972-73,77,79-85,87,93	1973,77,80-84,87,90,93, 97-98	1977,81-83,85-86,88, 90-92,97-98	1972-73,77,80-87,90,92, 97-98
COTTON				
Anomaly	**Mali (1970-83, 98)**	**Burkina Faso (1972-74, 1982-83)**	**Côte d'Ivoire**	**Entire Study Region**
Above Average National Yields	1984-93,95	1984-86,88-92,95-98	1982,84-90,97-98	1982,84-90,92-93,95, 97-98
Below Average National Yields	1994,96-97	1970-71,75-81,87,93-94	1970-81,83,91-96	1970-81,83,91,94,96
Inconsistent Rainfall/Cotton Relationship	**A** = 1994,96-97 **B** = 1984-85,87,93	**A** = 1970-71,75-76, 78-79,94 **B** = 1984,90,97-98	**A** = 1970-76,78-80,93-96 **B** = 1982,85-86,88,90, 97-98	**A** = 1970-71,74-76, 78-79,91,94,96 **B** = 1982,84-87,90,92, 97-98
MAIZE				
Anomaly	**Mali (1970-74)**	**Burkina Faso (1974-75)**	**Côte d'Ivoire (1984-95)**	**Entire Study Region**
Above Average National Yields	1976-79,82,86-88,91,96-98	1989-94,96-98	1981,83,96-98	1985-98
Below Average National Yields	1975,80-81,83-85,89-90, 92-95	1970-73,76-88,95	1970-80,82	1970-84
Inconsistent Rainfall/Maize Relationship	**A** = 1975,89-90,92,94-95 **B** = 1977,79,82,87	**A** = 1970-72,76,78-79, 85-86,88,95 **B** = 1990,93,97-98	**A** = 1970-76,78-80 **B** = 1981,83,97-98	**A** = 1970-71,74-76,78-79 **B** = 1985-87,90,92, 97-98
RICE				
Anomaly	**Mali (1970-74)**	**Burkina Faso (1983)**	**Côte d'Ivoire (1985-95)**	**Entire Study Region**
Above Average National Yields	1976,87,89,91-98	1979,87-98	1971,96-98	1987,89-98
Below Average National Yields	1975,77-86,88,90	1970-78,80-82,84-86	1970,72-84	1970-86,88
Inconsistent Rainfall/Rice Relationship	**A** = 1975,78,86,88,90 **B** = 1987,93	**A** = 1970-72,74-76,78, 85-86 **B** = 1987,90,93,97-98	**A** = 1970,72-76,78-80,84 **B** = 1997-98	**A** = 1970-71,74-76, 78-79,88 **B** = 1987,90,92,97-98

As in the previous analyses of time series of crop acreages and relationships among crop parameters (Section 4.2), the temporal variations of the relations between annual rainfall indices and crop yields in Central West Africa display two patterns of behavior -- below-the-study-mean rainfall and national crop yields before the mid-1980s, and above-the-study-

Table 4.19*b*: Summary of the temporal relationships between annual rainfall indices and detrended crop time series for Mali, Burkina Faso, Côte d'Ivoire, and entire study region during 1970-98. Table is drawn from Figures 4.19*a-d* (right panels). Years with missing data are given in parentheses for each country. Years of inconsistent rainfall/crop yield relationships are denoted as A (rain is above the mean, yields are below the long-term average value) and B (rain is below the mean, yields are above the long-term average value).

RAINFALL				
Departure	**Mali**	**Burkina Faso**	**Côte d'Ivoire**	**Entire Study Region**
Above the Mean (year)	1970-71,74-76,78,86, 88-92,94-98	1970-72,74-76,78-79,85- 86,88-89,91-92,94-96	1970-76,78-80,84,87,89, 93-96	1970-71,74-76,78-79, 88-89,91,93-96
Below the Mean (year)	1972-73,77,79-85,87,93	1973,77,80-84,87,90,93, 97-98	1977,81-83,85-86,88, 90-92,97-98	1972-73,77,80-87,90,92, 97-98
COTTON				
Anomaly	**Mali (1970-83, 98)**	**Burkina Faso (1972-74, 1982-83)**	**Côte d'Ivoire**	**Entire Study Region**
Above Long-term Average Yields	1986-88,90-93,95	1975,78-81,84-86,88-90, 97	1976-77,79,82,84-88,90, 97-98	1972-74,78-79,81-82, 84-90,92
Below Long-term Average Yields	1984-85,89,94,96-97	1970-71,76-77,87,91-96, 98	1970-75,78,80-81,83,89, 91-96	1970-71,75-77,80,83,91, 93-98
Inconsistent Rainfall/Cotton Relationship	**A** = 1989,94,96-97 **B** = 1987,93	**A** = 1970-71,76,91-92, 94-96 **B** = 1980-81,84,90,97	**A** = 1970-75,78,80,89, 93-96 **B** = 1977,82,85-86,88, 90,97-98	**A** = 1970-71,75-76,91, 93-96 **B** = 1972-73,81-82, 84-87,90,92
MAIZE				
Anomaly	**Mali (1970-74)**	**Burkina Faso (1974-75)**	**Côte d'Ivoire (1984-95)**	**Entire Study Region**
Above Long-term Average Yields	1976-79,82,86-88,91, 96-98	1970-73,78-80,90-94, 96-98	1970-74,96-98	1970-74,85-86,88,90-91, 96-98
Below Long-term Average Yields	1975,80-81,83-85,89-90, 92-95	1976-77,81-89,95	1975-83	1975-84,87,89,92-95
Inconsistent Rainfall/Maize Relationship	**A** = 1975,89-90,92,94-95 **B** = 1977,79,82,87	**A** = 1976,85-86,88-89,95 **B** = 1973,80,90,93,97-98	**A** = 1975-76,78-80 **B** = 1997-98	**A** = 1975-76,78-79,89, 93-95 **B** = 1972-73,85-86,90, 97-98
RICE				
Anomaly	**Mali (1970-74)**	**Burkina Faso (1983)**	**Côte d'Ivoire (1985-95)**	**Entire Study Region**
Above Long-term Average Yields	1976-78,81,87,91-93,96, 98	1970-71,74,76-77,79, 87-93,96,98	1970-75,96-98	1970-78,87,89-94,96,98
Below Long-term Average Yields	1975,79-80,82-86,88-90, 94-95,97	1972-73,75,78,80-82, 84-86,94-95,97	1976-84	1979-86,88,95,97
Inconsistent Rainfall/Rice Relationship	**A** = 1975,86,88-90, 94-95,97 **B** = 1977,81,87,93	**A** = 1972,75,78,85-86, 94-95 **B** = 1977,87,90,93,98	**A** = 1976,78-80,84 **B** = 1997-98	**A** = 1979,88,95 **B** = 1972-73,77,87,90, 92,98

mean rainfall and national crop yields thereafter (from the mid-1980s to late 1990s). Within each of these two extended periods, rainfall and yields for all countries registered individual or multiple years of either decrease or increase. Particularly prominent years of low rainfall/yields were: 1975, 1980, and 1983-85 for maize/rice in Mali; 1976-77 for cotton/maize and 1981-82 for maize/rice in Burkina Faso; 1976-80 for maize/rice in Côte d'Ivoire; 1975-77 for cotton/maize, 1979-81 and 1983 for maize/rice in the entire study region. Major years of high rainfall/yields were: 1987, 1991 for all crops, 1986, 1988 for cotton/maize, and 1992-93 for cotton/rice in Mali; 1990 for all crops, 1988-89 for cotton/rice, and 1997 for cotton/maize in Burkina Faso; 1997-98 for all crops in Côte d'Ivoire; 1990 for all crops, 1985-86, 1988 for cotton/maize, and 1991, 1996 for maize/rice in the entire study region.

However, there are also year(s) of inconsistent rainfall/crop yield relationships, such as 1971, 1975, 1984, 1987, 1994, and 1998, when yields do not decrease (increase) in spite of declined (enhanced) rainfall. For instance, the above-the-mean rainfall in 1970 and 1994 was not accompanied by larger yields (e.g., cotton/maize in Mali; cotton in Burkina Faso, Côte d'Ivoire, and in the entire study area) and, conversely, while low rainfall occurred in 1997 and 1998, yields registered average and above national values (maize in Burkina Faso and the entire study area; all crops in Côte d'Ivoire; see inconsistent rainfall/yield relationship rows in Tables 4.19*a*,*b*). In spite of some years of inconsistent rainfall/crop yield relationships, rainfall variability has emerged as a dominant constraint to agricultural productivity in Central West Africa. Therefore, these observations suggest the utility of correlation analyses in order to verify and measure the strength and significance of rainfall/crop yield associations.

4.3.2 Correlation Analyses

A study of the effects of rainfall on crop yields requires a precise measurement of the relationships. Here, correlation analyses are used to further observe and quantify the impact of rain variations. Since the aim also is to give an insight into the potential utility of seasonal rainfall prediction, concurrent and one-year lag correlations are computed. The concurrent correlations use the time series data plotted in Figures 4.19*a-d*, in which both rainfall and crop yield data span the years 1970-1998. The lag correlations express crop yields in year $y_i + 1$ as a function of rainfall in year y_i, meaning rainfall input began in 1970 and ended in 1997, while crop yield input began in 1971 and ended in 1998. Table 4.20 summarizes the correlation results between annual standardized rainfall and yearly crop yields (raw and detrended crop series) for each country and entire study region.

Table 4.20: Linear correlations between annual rainfall indices and cotton/maize/rice yields during 1970-98. Rainfall indices were computed from representative stations within each country and entire study region (Section 4.1.1 and Fig. 4.2). Raw (Section 4.2.1) and detrended (Section 4.3.1) crop time series were calculated for all crop regions within each country and entire study area (Fig. 4.13). Concurrent correlations use the time series data plotted in Figures 4.19*a-d*, while lag correlations express crop yields in year $y_i + 1$ as a function of rainfall in year y_i in those time series, as explained in text. Correlation coefficients with ≥ 99% significance levels are in bold; those with ≥ 95% & < 99% significance levels are asterisked; correlation coefficients with ≥ 90% & < 95% significance levels are underlined; those with ≥ 85% & < 90% significance levels are in parentheses; and correlation coefficients with ≥ 80% & < 85% significance levels are double-asterisked. Levels of significance are derived from two-tailed t test.

MALI				
	Concurrent Correlation (1970-1998)		**Lag Correlation (1970-98 & 1971-97)**	
Crop	**Raw Crop Series**	**Detrended Crop Series**	**Raw Crop Series**	**Detrended Crop Series**
Cotton	-0.39**	+0.01	-0.06	+0.48
Maize	+0.30**	+0.36	+0.26	+0.22
Rice	**+0.58**	**+0.50**	+0.46*	+0.42*
BURKINA FASO				
	Concurrent Correlation (1970-1998)		**Lag Correlation (1970-98 & 1971-97)**	
Crop	**Raw Crop Series**	**Detrended Crop Series**	**Raw Crop Series**	**Detrended Crop Series**
Cotton	-0.19	-0.16	-0.12	-0.11
Maize	+0.27**	**+0.57**	+0.11	+0.17
Rice	-0.16	-0.11	+0.02	+0.14
CÔTE D'IVOIRE				
	Concurrent Correlation (1970-1998)		**Lag Correlation (1970-98 & 1971-97)**	
Crop	**Raw Crop Series**	**Detrended Crop Series**	**Raw Crop Series**	**Detrended Crop Series**
Cotton	-0.20	-0.08	-0.39*	(-0.31)
Maize	(-0.40)	-0.15	-0.29	-0.20
Rice	-0.01	(+0.38)	-0.23	-0.07
ENTIRE STUDY REGION				
	Concurrent Correlation (1970-1998)		**Lag Correlation (1970-98 & 1971-97)**	
Crop	**Raw Crop Series**	**Detrended Crop Series**	**Raw Crop Series**	**Detrended Crop Series**
Cotton	-0.33	-0.33	-0.17	-0.19
Maize	-0.16	-0.11	+0.11	+0.10
Rice	+0.16	+0.44*	+0.05	+0.11

Table 4.20 documents an apparently complex dependence of Central West African crop yields upon rainfall for both concurrent and one-year lag correlation analyses. Less than half of the concurrent and lag correlation coefficients (significant and non-significant) are positive (23 positive out of 48 coefficients), showing that the coincidence of increased rainfall and increased crop yields was far from universal. Positive significant and non-significant correlation coefficients occur for maize and rice in Mali, maize in Burkina Faso, and rice in the entire study area. However, improvements in farming practices with fertilizer and pesticide uses, as well as mechanization, can weaken the correlation coefficients and even produce negative associations between rainfall and crop yields (especially for raw crop series). Indeed, correlation coefficients for both raw and detrended crop series tend to be mostly negative and weak for the cash crop of cotton in Burkina Faso, Côte d'Ivoire, and when the three countries are combined. Negative correlations for maize in Côte d'Ivoire may also indicate that too much rainfall (e.g., producing flooding) can decrease yields. Moreover, the correlation coefficients between standardized rainfall indices and crop yields are more strongly positive/negative and significant for concurrent (12 significants at ≥ 80% significance levels out of 24 concurrent correlation coefficients) than lag (5 out of 24) correlations when the three countries are studied separately or together (Table 4.20). The significant positive/negative coefficients are: 5 (4 positive and 1 negative) concurrent correlations versus 3 (all positive) lag correlations for Mali; 2 (both positive) versus 0 for Burkina Faso; 2 (1 positive and 1 negative) versus 2 (both negative) for Côte d'Ivoire; and 3 (1 positive and 2 negative) versus 0 for entire study region.

In detail, the concurrent correlation analysis between crop yields (both raw and detrended crop series) and annual rainfall indices presented in Table 4.20 shows 10 positive and 14 negative correlation coefficients (both significant and non-significant). Eight of the positive coefficients are significant and range from moderate (r = +0.27, 82% significance level for maize in Burkina Faso) to strong (r = +0.58, 99% significance level for rice in Mali). Raw rice yields (r = +0.58, Mali) and detrended maize yields (r = +0.57, Burkina Faso) register the strongest and most significant positive coefficients at ≥ 99% significance levels. Some of the concurrent correlation coefficients are more strongly positive and more significant when the linear crop trends are removed (e.g., maize in Burkina Faso -- raw crop series: r = +0.27, 82% significance level, detrended crop series: r = +0.57, 99% significance level; rice in entire study region -- raw crop series: r = +0.16, 42% significance level, detrended crop series: r = +0.44, 98% significance level). On the other hand, cotton for the entire study region has the same moderate negative coefficients for both raw and detrended crop series (r = -0.33, 92% significance level), and rice for Mali has a stronger positive coefficient for the raw crop series (r = +0.58) than for the detrended crop series (r = +0.50), though both are significant at ≥ 99% significance levels. For the overall concurrent correlation analyses (both raw and detrended crop series), Mali has 5 positive out of 6 coefficients, Burkina Faso has 2 positive out of 6 coefficients, and Côte d'Ivoire has only 1 positive out of 6 coefficients. The dominance of correlation coefficients (significant and non-significant) with positive signs in Mali reflects that this country of rain-fed agriculture (especially staple crops), located mostly in the semi-arid to arid portion of the study area, depends heavily on rainfall occurrences to increase crop yields.

In Table 4.20, the one-year lag correlations (both significant and non-significant) between the annual rainfall indices and crop yields (both raw and detrended crop series) display 13 positive coefficients (3 coefficients -- for cotton and rice in Mali -- are stronger and more significant at ≥ 90% and < 99% than the other 10 positive coefficients) and 11 negative coefficients (2 coefficients -- for cotton in Côte d'Ivoire -- are stronger and more significant at ≥ 85% and < 99% than the other 9 negative coefficients). For Mali, detrended cotton yields (r = +0.48, 92% significance level) as well as raw and detrended rice yields (r = +0.46, 98% significance level and r = +0.42, 96% significance level, respectively) register the strongest positive correlation coefficients, while raw and detrended cotton in Côte d'Ivoire (r = -0.39, 96% significance level and r = -0.31, 89% significance level, respectively) record the strongest negative correlation coefficients. Some of the one-year lag correlations tend to be more strongly positive and significant when the linear crop trends are removed (e.g., cotton in Mali, raw crop series: r = -0.06, 84% significance level, detrended crop series: r = +0.48, 92% significance level). However, rice in Mali has a stronger positive coefficient for the raw crop series (r = +0.46, 98% significance level) than the detrended crop series (r = +0.42, 96% significance level). Still, the difference in the coefficient signs between the raw crop series (6 positive and 6 negative coefficients) and the detrended crop series (7 positive and 5 negative coefficients) is negligible.

Although the results of the one-year lag correlations are weaker than those of the concurrent correlations, the occurrence of positive coefficients (both significant and non-significant) in just over half of the lag correlation cases (13 positive out of 24 coefficients) verifies the possible influence of soil moisture carried over from the previous year. This, taken with the results of concurrent correlations, suggests the potential utility of seasonal rainfall prediction to improve crop yields in the study area. Indeed, empirical or statistical methods can be a viable alternative to dynamical or climate model techniques to predict seasonal rainfall and support its connection to crop productivity. So, both the concurrent and lag correlations (though with admittedly weak coefficients) performed in this study show that accurate seasonal rainfall prediction could influence what crops are grown since they provide empirical evidence that variations in rain are sufficient to influence the yields obtained.

The correlation analyses between rainfall indices and crop yields for 1970-98 were extended to include other rainfall measures such as specific rainy season months and overall rainy seasons (see Section 4.1.2). Note that only concurrent correlations with end-of season yields are considered in the next analyses. The intent is to seek more detailed information on what months or combinations of months the rainfall has the greatest influence on crop yields for each country and when the three countries are combined or studied by zones (Tables 4.21*a*,*b*).

Relationships between the yields of the three crops and monthly/seasonal/annual rainfall indices are presented in Tables 4.21*a*,*b*. For Mali (Table 4.21*a*), crops have more strongly positive and significant correlations with rainfall for the individual month of September, the May-October-centered rainy season, and the annual rainfall indices (each with 2 significant positive coefficients and 1 significant negative coefficient for raw crop series; 2 significant positive coefficients for detrended crop series) than with rainfall for the month of October (1 significant positive for raw crop series; 2 significant positive for detrended crop series) and the July-September-centered rainy season (1 significant positive coefficient for both raw and detrended crop series). The other individual months during May-August do not have strongly positive and significant coefficients. For example, the relationship for detrended rice yields in July is moderate ($r = +0.31$, 86% significance level), while raw cotton yields in June have a relatively strong negative and significant correlation coefficient ($r = -0.41$, 85% significance level).

Table 4.21*a*: Linear correlations between monthly/seasonal/annual rainfall indices (Section 4.1.2.3) and end-of-season cotton/maize/rice yields during 1970-1998. Rainfall indices were computed from representative stations within each country (see Fig. 4.2). Raw (Sections 4.2.1) and detrended (Section 4.3.1) crop time series were calculated from all crop regions within each country (Fig. 4.13). Correlation coefficients with ≥ 99% significance levels are in bold; those with ≥ 95% & < 99% significance levels are asterisked; correlation coefficients with ≥ 90% & < 95% significance levels are underlined; those with ≥ 85% & < 90% significance levels are in parentheses; and correlation coefficients with ≥ 80% & < 85% significance levels are double-asterisked. Levels of significance are derived from two-tailed t test.

MALI									
Raw Crop Series									
Crop	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Jul-Sep**	**May-Oct**	**Annual**
Cotton	-0.04	(-0.41)	+0.09	-0.17	-0.37**	-0.35	-0.27	(-0.41)	-0.39**
Maize	+0.17	+0.16	+0.18	-0.13	+0.38	+0.29**	+0.20	(+0.32)	+0.30**
Rice	-0.03	+0.24	+0.09	+0.26	+0.42*	+0.25	+0.42*	+0.46*	**+0.58**
Detrended Crop Series									
Crop	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Jul-Sep**	**May-Oct**	**Annual**
Cotton	+0.21	-0.12	+0.15	+0.03	-0.25	-0.24	-0.06	-0.09	+0.01
Maize	+0.12	+0.21	+0.15	-0.09	+0.43*	+0.27**	+0.24	+0.35	+0.36
Rice	+0.26	+0.09	(+0.31)	+0.10	(+0.32)	**+0.50**	+0.36	**+0.52**	**+0.50**
BURKINA FASO									
Raw Crop Series									
Crop	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Jul-Sep**	**May-Oct**	**Annual**
Cotton	+0.11	(+0.33)	-0.40*	-0.28**	-0.25	+0.06	-0.44*	-0.23	-0.19
Maize	+0.18	(+0.28)	-0.07	+0.27**	+0.06	+0.21	+0.17	+0.37	+0.27**
Rice	-0.06	+0.11	-0.27**	+0.09	-0.01	+0.01	-0.04	-0.03	-0.16
Detrended Crop Series									
Crop	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Jul-Sep**	**May-Oct**	**Annual**
Cotton	+0.05	+0.09	-0.12	-0.36	-0.25	-0.06	-0.39	(-0.34)	-0.16
Maize	(+0.30)	+0.01	+0.45*	+0.44*	-0.03	+0.28	+0.42*	**+0.59**	**+0.57**
Rice	-0.19	-0.34	+0.16	+0.20	+0.01	-0.10	+0.18	-0.03	-0.11

CÔTE D'IVOIRE†									
Raw Crop Series									
Crop	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Cotton	-0.13	-0.13	-0.26**	+0.09	-0.01	+0.09	-0.17	+0.06	-0.05
Maize	-0.31	+0.11	-0.30	+0.07	+0.14	-0.12	-0.41	+0.04	-0.05
Rice	-0.07	+0.31	-0.41	(+0.35)	+0.32**	+0.05	-0.26	+0.21	+0.01
Detrended Crop Series									
Crop	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Cotton	-0.06	-0.24	-0.14	+0.21	-0.06	+0.12	-0.01	-0.06	-0.10
Maize	+0.01	+0.02	(-0.40)	+0.11	+0.08	-0.02	+0.13	+0.02	-0.23
Rice	+0.25	(+0.36)	-0.46*	+0.54*	+0.32**	+0.21	+0.21	+0.24	-0.04

Raw Crop Series						
Crop	**Mar-Jun**	**Jul-Sep**	**Oct-Nov**	**May-Oct**	**Mar-Nov**	**Annual**
Cotton	-0.18	-0.04	+0.03	-0.09	-0.13	-0.20
Maize	-0.18	-0.19	+0.01	-0.28	-0.26	(-0.40)
Rice	+0.06	+0.06	+0.17	+0.11	+0.14	-0.01
Detrended Crop Series						
Crop	**Mar-Jun**	**Jul-Sep**	**Oct-Nov**	**May-Oct**	**Mar-Nov**	**Annual**
Cotton	-0.05	+0.02	-0.09	+0.04	-0.05	-0.08
Maize	-0.15	+0.10	-0.10	-0.03	-0.06	-0.15
Rice	+0.25	(+0.35)	+0.18	+0.47*	+0.48*	(+0.38)

† More months are shown for Côte d'Ivoire because most of its selected rainfall stations are bimodal and therefore have more rainy season months (Tables 4.9*a*,*b*).

Table 4.21*b*: Linear correlations between seasonal/annual rainfall indices (Section 4.1.2.3) and end-of-season cotton/maize/rice yields in the entire study region (CWA) and the zones north/south of 9.3° N (Section 4.1.2.3, Table 4.9*b*) during 1970-1998. Rainfall indices were computed from representative stations within Central West Africa (Fig. 4.2). Raw (Sections 4.2.1) and detrended (Section 4.3.1) crop time series were calculated from all 27 agricultural regions in the study area (Fig. 4.13). Correlation coefficients with ≥ 99% significance levels are in bold; those with ≥ 95% & < 99% significance levels are asterisked; correlation coefficients with ≥ 90% & < 95% significance levels are underlined; those with ≥ 85% & < 90% significance levels are in parentheses; and correlation coefficients with ≥ 80% & < 85% significance levels are double-asterisked. Levels of significance are derived from two-tailed t test.

Raw Crop Series					
Crop	**CWA (Jul-Sep)**	**CWA (May-Oct)**	**CWA (annual)**	**North of 9.3° N†**	**South of 9.3° N†**
Cotton	-0.25**	<u>-0.34</u>	<u>-0.33</u>	-0.42*	-0.09
Maize	-0.05	-0.09	-0.16	+0.06	<u>-0.33</u>
Rice	+0.06	+0.17	+0.16	+0.25**	-0.01
Detrended Crop Series					
Crop	**CWA (Jul-Sep)**	**CWA (May-Oct)**	**CWA (annual)**	**North of 9.3° N†**	**South of 9.3° N†**
Cotton	-0.24**	-0.36*	<u>-0.33</u>	**-0.51**	+0.01
Maize	+0.09	+0.03	-0.11	(+0.25)	**-0.45**
Rice	+0.26**	**+0.45**	+0.44*	**+0.52**	+0.16

† Annual indices

More complex correlation relations are apparent between crop yields and rainfall for the rainy season months, overall rainy seasons, and annual rainfall indices for Burkina Faso, Côte d'Ivoire, and when the three countries are combined or studied by zones. Their correlation coefficients are dominated by weaker positive and more negative (Tables 4.21*a*,*b*). For Burkina Faso, the correlations between end-of-season crop yields and rainfall for the specific months of September (both raw and detrended crop series), May (raw crop series), and October (raw crop series) attest to the above conclusions. All other rainy season months, overall rainy seasons, and annual rainfall indices each register only 1 or 2 significant positive/negative correlation coefficients for raw and/or detrended crop series. For Côte d'Ivoire, the individual months of March, August, October, and November, as well as the March-June- and October-November-centered rainy seasons do not have any significant correlations with end-of-season crop yields. However, the correlations between crop yields and rainfall for the specific rainy season months during April-July and

September, as well as the overall rainy seasons of July-September, May-October, and March-November, and the annual rainfall indices each also record only 1 or 2 significant positive/negative correlation coefficients for raw and/or detrended crop series. When the three countries are combined or studied by zones (Table 4.21*b*), the correlations between crop yields and overall rainy seasons as well as between crop yields and annual rainfall indices each register only 1 or 2 significant positive/negative coefficients for raw and/or detrended crop series.

The rainfall correlations (significant and non-significant) with both raw and detrended crop series generally show more positive than negative signs, especially for Mali (Table 4.21*a*). The raw crop series for Mali comprise 17 positive, 10 negative coefficients; the detrended crop series comprise 21 positive and 6 negative coefficients. Both raw and detrended crop series for Burkina Faso show the same results of 14 positive and 13 negative coefficients. For Côte d'Ivoire, the raw crop series actually display more negative (25) than positive (20) coefficients; however, the detrended crop series have more positive (24) than negative (21) coefficients. These results illustrate the earlier point that correlation coefficients tend to be stronger, more positive, and more significant when the linear crop trends are removed.

It is evident from these findings (Table 4.21*a*) that the geographic locations of the countries and their resulting rain variations have great agricultural impact, especially in Mali where agroclimatology tends to assist in coordinating rainfall and crops (Chapter 5). Indeed, Mali features 12 significant (≥ 80%) coefficients for raw crop series (8 positive and 4 negative) versus 10 significant (≥ 80%) coefficients for detrended crop series (all positive), while Burkina Faso features 9 (5 positive and 4 negative) versus 11 (7 positive and 4 negative). Both these countries are located in the northern drier part of the study area (especially Mali, which receives the least rainfall of the entire study area), favor more staple crops (see Section 4.1.2 and Fig. 4.14) that are entirely rainfall-dependent, and register more significant positive correlation coefficients than Côte d'Ivoire. The latter country has 6 significant coefficients for raw crop series (2 positive and 4 negative) versus 9 significant coefficients for detrended crop series (7 positive and 2 negative). Côte d'Ivoire is in the humid rainy south and favors more cash crops that are more frequently subject to pesticides and fertilizer uses (Dennett et al., 1981; Koli Bi, 1992; Ministère de l'Environnement, 1997; Ministère de l'Agriculture, 1998), reducing their overall rainfall dependence.

Detrending is employed to control for the effects of pesticides and fertilizers; the fact that cotton yields for Côte d'Ivoire still retain negative coefficients in the detrended crop series may indicate that this crop can succumb to too much rain, resulting in decreased crop yields with increased rainfall. Note that the staple crops in this country tend to be entirely rainfall-dependent, especially rice, shown by its dominant positive correlation coefficients (both raw and detrended crop series). The results of both raw and detrended crop yields reinforce that in Central West Africa crops are not only vulnerable to lack of rainfall (especially in Mali), but also yields in Côte d'Ivoire and, to a lesser extent, Burkina Faso may be vulnerable to too much rainfall.

Moreover, when the three countries are combined or studied by zones (Table 4.21*b*), more strongly positive correlation coefficients (both significant and non-significant) occur with the detrended crop series (9 positive and 6 negative) than with the raw crop series (5 positive and 10 negative). The cash crop of cotton registers more negative correlation coefficients in both raw and detrended crop series (9 negative and 1 positive for cotton vs. 6 negative and 4 positive for maize and 1 negative and 9 positive for rice) because this crop has been subject to changed production technology through improved cropping techniques and fertilizer uses, and therefore depends less on rainfall variability. In other words, weaker positive and more negative correlations can be related to the adherence of farmers to adaptive methods. For instance, agricultural mechanization combined with implementation of agricultural policies (e.g., replacement of crops with long vegetative cycles by those with shorter ones and use of drought-resistant crops) might influence crop yields (Dennett et al., 1981; Koli Bi, 1992; Ministère de l'Agriculture, 1998). Indeed, the zone south of 9.3° N, totally comprised of Côte d'Ivoire, shows several weaker positive and stronger negative correlation coefficients (e.g., maize for both raw and detrended crop series), reflecting the overall focus of this country on cash crops (see Section 4.1.2 and Fig. 4.14), which often do not solely depend on rainfall to grow and develop since they may be subject to pesticides and fertilizers. The zone north of 9.3° N, mainly comprised of Mali and Burkina Faso, shows more strongly positive and significant correlation coefficients (e.g., rice for both raw and detrended crop series and maize for detrended crop series), reflecting the greater dependence of these countries upon rain-fed agriculture due to their focus on staple crops.

Crop yields are also related to the duration of the rainy seasons (Sivakumar, 1988; Camberlin and Diop, 1999) by using the onset and cessation dates, in this study, as proxies. It is possible that cumulative monthly, seasonal, and annual rainfall indices may not be as essential for the growth and development of crops as the onset/cessation dates of the rainy seasons. To investigate this possibility, the analyses first focused on the geographic location of the study crop regions (see Fig. 4.13) and their corresponding PCA-based rainfall regions (see Figs. 4.1*e*,*f*) for each country. Figures 4.20*a*,*b* help situate a crop region in a PCA-based

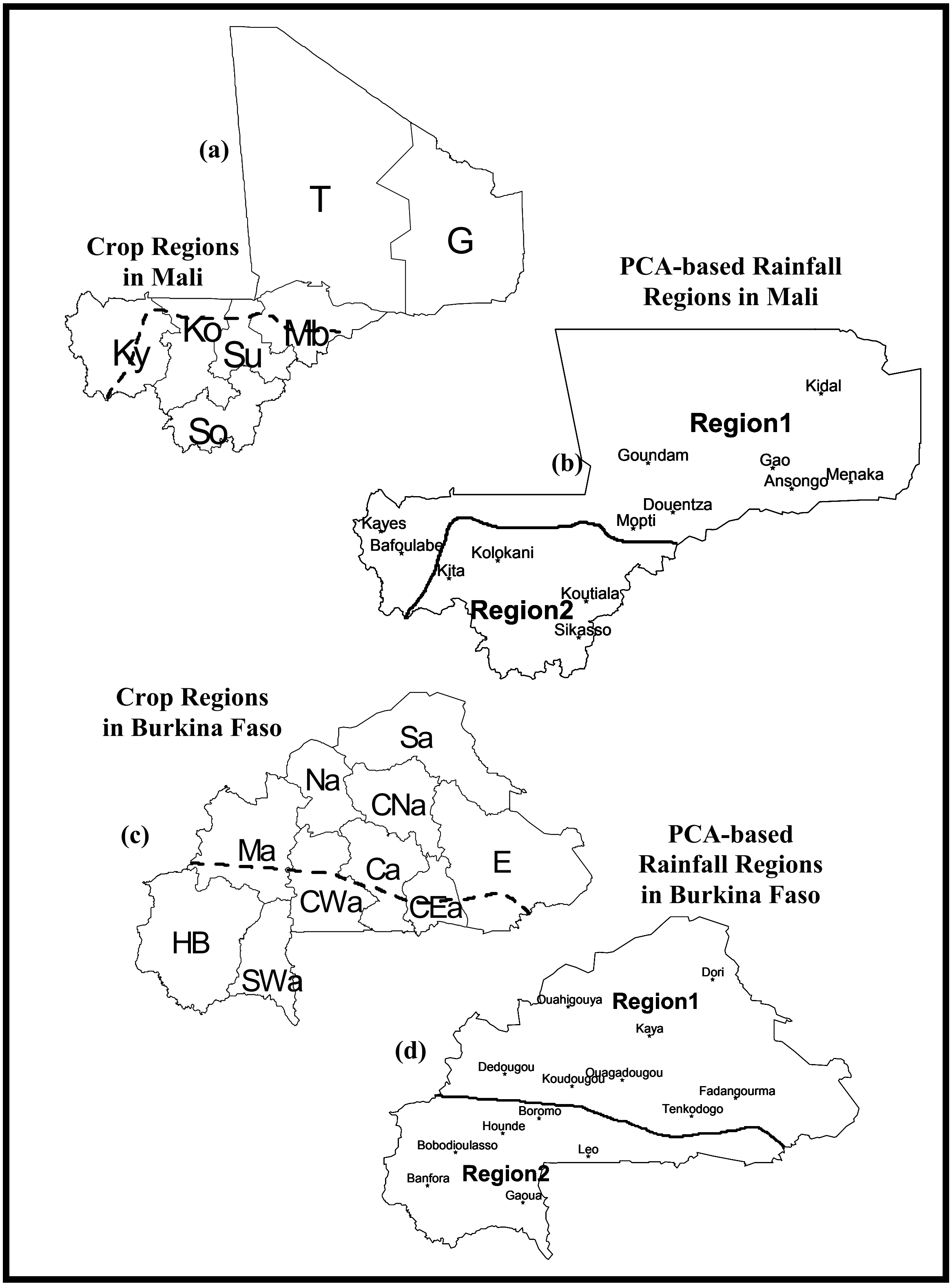


Figure 4.20*a*: Crop regions (panels a & c) and PCA-based rainfall regions (panels b & d, with rainfall stations shown) within Mali and Burkina Faso. Note that rainfall region boundaries are inserted as broken lines on crop region maps for ease of interpretation. See Table 4.22 for names of crop regions.

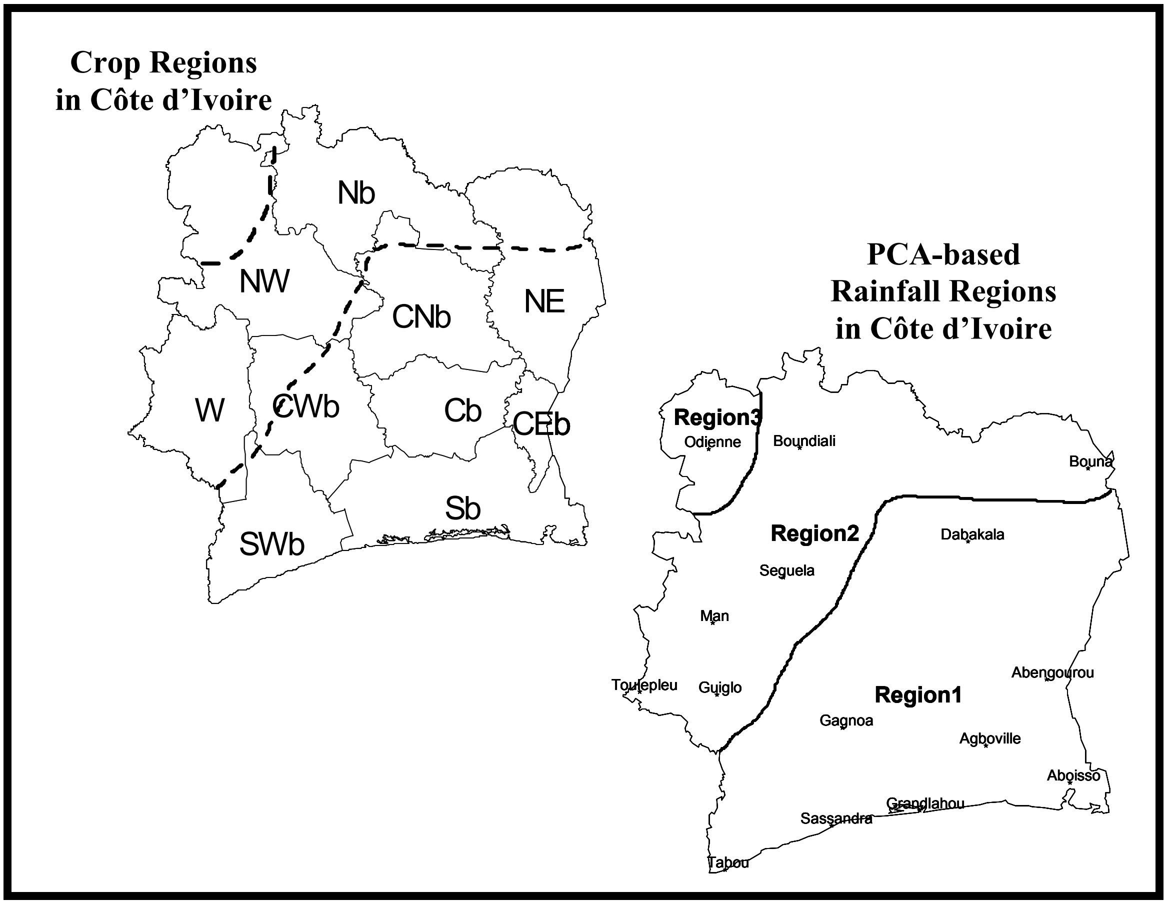


Figure 4.20*b*: Crop regions (top) and PCA-based rainfall regions (bottom, with rainfall stations shown) within Côte d'Ivoire. Note that rainfall region boundaries are inserted as broken lines on crop region map for ease of interpretation. See Table 4.22 for names of crop regions.

rainfall region. Then, the results of the matching crop/rainfall regions are summarized in Table 4.22 and used for further correlation analyses of the rainfall/crop yield relationships, presented in Tables 4.24*a*,*b* (Mali), 4.25*a*,*b* (Burkina Faso), and 4.26*a-c* (Côte d'Ivoire). The rainfall information used station totals instead of departures because the PCA-based rainfall regions are relatively small areas in which the south-north rainfall gradient is minimal. Thus, rainfall totals were averaged across each PCA-based rainfall region. The analyses were performed at each individual crop region level in order to obtain geographically detailed information on the correlations between end-of-season crop yields and rainfall for the rainy season months, overall rainy seasons, annual totals, and onset/cessation dates of rainy seasons in Central West Africa.

Table 4.22: Selected crops and their associated agricultural/PCA-based rainfall regions used for further correlation analyses in Tables 4.24*a,b*, 4.25*a,b*, and 4.26*a-c*. PCA-based rainfall regions are denoted for each country as r1, r2, or r3. See Figures 4.20*a,b* for locations of crop and rainfall regions.

PCA-BASED RAINFALL REGION	ASSOCIATED CROP REGION		
	Mali	**Burkina Faso**	**Côte d'Ivoire**
1	Tombouctou (T), Gao (G), Mopti (Mb), Koulikoro (Ko), and Kayes (Ky)	Sahel (Sa), Central-north (CNa), North (Na), Mouhoun (Ma), Center (Ca), and East (E)	Southwest (SWb), South (Sb), Center (Cb), and Central-east (CEb)
2	Sikasso (So) and Segou (Su)	Southwest (SWa), Haut-Bassin (HB), Central-west (CWa), and Central-east (CEa)	North (Nb), Northeast (NE), Central-north (CNb), Central-west (CWb), and West (W)
3	Not applicable	Not applicable	Northwest (NW)

SELECTED CROP AND ASSOCIATED AGRICULTURAL/PCA-BASED RAINFALL REGION			
Crop	**Mali**	**Burkina Faso**	**Côte d'Ivoire**
Cocoa beans	Not grown	Not grown	CEb (r1), Sb (r1), CWb (r2), W (r2)
Coffee beans	Not grown	Not grown	CEb (r1), Sb (r1), SWb (r1), CWb (r2), W (r2)
Cotton	Ko (r1), So (r2), Su (r2)	Ma (r1), CWa (r2), SWa (r2), HB (r2)	CNb (r2), Nb (r2), NW (r3)
Peanuts	Mb (r1), Ko (r1), Ky (r1), So (r2), Su (r2)	Ca (r1), CWa (r2), SWa (r2), HB (r2)	Not selected
Sugarcane	Su (r2)	Not selected	Not selected
Soybeans	Not selected	Ca (r1), CEa (r2)	Not selected
Maize	Ko (r1), Ky (r1), So (r2), Su (r2)	Ca (r1), CNa (r1), Ma (r1), CEa (r2), CWa (r2), SWa (r2), HB (r2)	SWb (r1), Sb (r1), Cb (r1), CNb (r2), CWb (r2), W (r2), NW (r3)
Millet	T (r1), G (r1), Mb (r1), Ko (r1), Ky (r1), So (r2), Su (r2)	Sa (r1), CNa (r1), Na (r1), Ma (r1), Ca (r1), E (r1), SWa (r2), HB (r2), CWa (r2), CEa (r2)	Not selected
Plantain	Not grown	Not grown	CEb (r1), Sb (r1), SWb (r1), NE (r2), CWb (r2), W (r2)
Rice	G (r1), Mb (r1), Ko (r1), Ky (r1), So (r2), Su (r2)	E (r1), Ca (r1), SWa (r2), HB (r2)	SWb (r1), Sb (r1), Cb (r1), CEb (r1), CNb (r2), CWb (r2), W (r2), Nb (r2), NW (r3)
Sorghum	T (r1), G (r1), Mb (r1), Ko (r1), Ky (r1), So (r2), Su (r2)	Sa (r1), CNa (r1), Na (r1), Ma (r1), Ca (r1), E (r1), SWa (r2), HB (r2), CWa (r2), CEa (r2)	Not selected
Yams	Not selected	Not selected	SWb (r1), Sb (r1), Cb (r1), CEb (r1), CNb (r2), CWb (r2), NE (r2), Nb (r2), NW (r3)

As for the analyses in Tables 4.21*a*,*b* and their accompanying explanation in the text, only concurrent correlations between rainfall (for several measures) and end-of-season crop yields are considered. While the previous analyses used both raw and detrended crop data, the present analyses use raw crop yields only. In spite of the correlation coefficients tending to be more strongly positive and significant when the linear crop trends are removed, the detrended crop yields were not used in the remaining analyses. Instead, the raw crop series were used because they reflect the more prominent role played by crops that are entirely rainfall dependent across the study area (almost all cash and staple crops in Mali and Burkina Faso; almost all staple crops and many cash crops in Côte d'Ivoire). Moreover, many of the detrended crop series followed patterns similar to those shown by the raw crop series; it is therefore possible that analyses using raw crop yields may produce results that anticipate the outcome of analyses using detrended crop yields. Further, Tables 4.23*a*,*b* reveal that crop water requirements and phenologic cycles (see Chapter 2, Table 2.1) are in direct proportion to the length of the growing season, while Table 4.23*c* shows that rainfall occurrence supports two farming operations (i.e., planting and harvesting, see Chapter 2, Table 2.2) about which farmers can make direct decisions.

Based on information presented in Figures 4.20*a*,*b* and Tables 4.22 and 4.23*a*-*c*, correlation analyses were carried out using the geographical (location) consistency of crop/PCA-based rainfall regions. Here, all of the 12 study crops and 27 agricultural regions were potentially considered. However, each crop was only analyzed within the regions that have the most complete and longest data. Consequently, the number of crop regions retained per crop varies from one crop to another. The analyses could have spanned 1966-1998 for Mali,

Table 4.23*a*: Average annual rainfall (Table 4.9*a*), onset/cessation dates of rainy seasons (Tables 4.13*a*,*b*), and corresponding length of growing seasons (Table 4.14) for each PCA-based rainfall region (Fig. 4.1*e*) within Central West Africa. Regional averages were computed from station values in Tables 4.9*a*, 4.13*a*,*b*, and 4.14.

PCA-based Rainfall Region	Stations per Rainfall Region	Average Annual Rainfall (mm)	Average Rainy Season Onset Date (s)	Average Rainy Season Cessation Date (s)	Average Length of Growing Season (s)
Mali Region 1	Ansongo, Bafoulabe, Douentza, Gao, Goundam, Kayes, Kidal, Menaka, Mopti	417	2 Jul	30 Sep	90 days
Mali Region 2	Kita, Kolokani, Koutiala, Sikasso	1043	21 May	24 Oct	156 days
Burkina Faso Region 1	Dedougou, Dori, Fada N'gourma, Kaya, Koudougou, Ouagadougou, Ouahigouya, Tenkodogo	809	26 May	13 Oct	140 days
Burkina Faso Region 2	Banfora, Boromo, Bobo Dioulasso, Gaoua, Hounde, Leo	1037	5 May	24 Oct	172 days
Côte d'Ivoire Region 1*	Abengourou, Aboisso, Agboville, Dabakala, Gagnoa, Grand Lahou, Sassandra, Tabou	1551	20 Mar → & 14 Sep →	13 Aug → & 27 Nov →	146 days & 74 days Total = 220 days
Côte d'Ivoire Region 2*	Bouna, Boundiali, Guiglo, Man, Seguela, Toulepleu	1467	30 Mar → & 7 Sep →	8 Sep → & 26 Nov →	162 days & 80 days Total = 242 days
Côte d'Ivoire Region 3	Odienne	1503	21 Apr	20 Nov	213 days

*** PCA-based rainfall regions 1 and 2 for Côte d'Ivoire (except Boundiali) contain bimodal rainfall stations with four seasons (Table 4.9*b*) and therefore have two onset/cessation dates. Note that the regional average cessation dates of the first rainy season differ by about one month (13 Aug and 14 Sep for region 1) or overlap (Sep and 7 Sep 8 for region 2) with the regional average onset dates of the second rainy season, as explained in Section 4.1.2.5.**

Table 4.23*b*: Comparisons between water requirements (rainfall)/phenologic cycles of crops (see Chapter 2, Table 2.1) and PCA-based rainfall regions (based on characteristics from Table 4.23*a*). M = Mali, BF = Burkina Faso, and CI = Côte d'Ivoire.

Crop	Water Requirement (Rainfall in mm)	Phenologic Cycle (to maturation)	PCA-based Rainfall Region Meeting Previous Two Criteria
Cocoa beans	1,300-2,000	160-200 days	All regions for CI
Coffee beans	1,500-1800	Few weeks	All regions for CI
Cotton	700-1,300	150-180 days	M (region 2) & all regions for BF/CI
Peanuts*	400-700	90,105,120 days	All regions for M/BF/CI
Sugarcane	1,000-2,000	9-24 months	M/BF (region 2) & CI (all regions)
Soybeans	450-700	100-130 days	All regions for M/BF/CI
Maize*	500-800	60-90,90-120,120-150 days	M (region 2) & all regions for BF/CI
Millet*	≤ 1,000	60-90,90-120 days	All regions for M/BF/CI
Plantain	1,300-2,000	Annual plant	All regions for CI
Rice	≥ 1,000	90-150 days	M/BF (region 2) & CI (all regions)
Sorghum	450-650	90-120 days	All regions for M/BF/CI
Yams	700-1,300	Annual plant	M (region 2) & all regions for BF/CI

*** Peanuts, maize, and millet undergo varying vegetative cycles (i.e., shorter to longer) depending on the species (see Chapter 2, Table 2.1)**

Table 4.23*c*: Comparisons between agricultural operation calendars for planting and harvesting (see Chapter 2, Table 2.2) and suitable regional rainy season onset/cessation dates (Table 4.23*a*). Best-fit rainfall regions are selected based on information in Figures 4.12*a-c*, Tables 4.23*a*,*b*, and region for which crop data are available (i.e., most complete and longest data). M = Mali, BF = Burkina Faso, CI = Côte d'Ivoire, and r1, r2, or r3 = PCA-based rainfall regions.

CROP	AGRICULTURAL OPERATION		BEST-FIT RAINFALL REGION
	Planting	Harvesting	Rainfall Onset/Cessation Date
Cocoa beans	May	Oct-Dec	20 Mar-13 Aug (CI-r1) & 30 Mar-8 Sep (CI-r2)
Coffee beans	Mar-Jun	Sep-Jan	20 Mar-13 Aug (CI-r1) & 30 Mar-8 Sep (CI-r2)
Cotton	Jun	Nov-Dec	2 Jul-30 Sep (M-r1), 21 May-24 Oct (M-r2), 28 May-12 Oct (BF-r1), 5 May-24 Oct (BF-r2), 30 Mar-8 Sep (CI-r2), & 21 Apr-20 Nov (CI-r3)
Peanuts	Late Jun-Jul	Late Oct-Early Nov	2 Jul-30 Sep (M-r1), 21 May-24 Oct (M-r2), 28 May-12 Oct (BF-r1), & 5 May-24 Oct (BF-r2)
Sugarcane	May-Jun	Dec	21 May-24 Oct (M-r2)
Soybeans	Apr-Jul	Jul-Oct	28 May-12 Oct (BF-r1) & 5 May-24 Oct (BF-r2)
Maize	Apr-Jun	Jul-Oct	2 Jul-30 Sep (M-r1), 21 May-24 Oct (M-r2), 28 May-12 Oct (BF-r1), 5 May-24 Oct (BF-r2), 20 Mar-13 Aug (CI-r1), 30 Mar-8 Sep (CI-r2), & 21 Apr-20 Nov (CI-r3)
Millet	May-Jul	Oct	2 Jul-30 Sep (M-r1), 21 May-24 Oct (M-r2), 28 May-12 Oct (BF-r1), & 5 May-24 Oct (BF-r2)
Plantain	Mar-Jul	Oct-Apr	20 Mar-13 Aug (CI-r1) & 30 Mar-8 Sep (CI-r2)
Rice	Mar-Jul	Jul-Nov	2 Jul-30 Sep (M-r1), 21 May-24 Oct (M-r2), 28 May-12 Oct (BF-r1), 5 May-24 Oct (BF-r2), 20 Mar-13 Aug (CI-r1), 30 Mar-8 Sep (CI-r2), & 21 Apr-20 Nov (CI-r3)
Sorghum	Mid-Jun	Oct	2 Jul-30 Sep (M-r1), 21 May-24 Oct (M-r2), 28 May-12 Oct (BF-r1), & 5 May-24 Oct (BF-r2)
Yams	Jan-Jun	Jun-Feb	20 Mar-13 Aug (CI-r1), 30 Mar-8 Sep (CI-r2), & 21 Apr-20 Nov (CI-r3)

1970-98 for Burkina Faso, and 1947-98 for Côte d'Ivoire, although certain crop data within a particular region might start later (or include missing data years), as noted in Chapter 3 (Tables 3.6*a*-*c* and Tables 3.7*a*-*c*). Tables 4.24*a*,*b* (Mali), 4.25*a*,*b* (Burkina Faso), and 4.26*a*-*c* (Côte d'Ivoire) present the results of these correlations, which specify the periods for which the analyses were performed.

A brief overview of the correlations between end-of-season raw crop yields for selected Central West African agricultural regions and rainfall for several measures such as individual rainy season months, overall rainy seasons, and annual rainfall totals (Tables 4.24*a*, 4.25*a*, and 4.26*a*,*b*), as well as onset and cessation dates of the rainy seasons (Tables 4.24*b*, 4.25*b*, and 4.26*c*), reveals that crop yields correlate most positively, strongly, and significantly with both onset and cessation dates of the rainy seasons. The sign convention is that early onset and early cessation are each indicated by negative coefficients, while late onset and late cessation are each symbolized by positive coefficients. The correlations are dominated by either significant positive (i.e., late onset and late cessation) or significant negative (i.e., early onset and early cessation) coefficients. Thus, crop yields in the study area are likely to be reduced in years of either late onset and early cessation of rains or early onset and early cessation dates. This underscores that the crucial farming operations of planting and harvesting could benefit from seasonal rainfall forecasting.

In Tables 4.24*a*,*b*, for the significant correlation coefficients between rainfall and end-of-season raw crop yields, the positive signs dominate all of the four staple crops (maize, millet, rice, sorghum) as well as peanuts and sugarcane (cash crops), while the negative signs dominate the cash crop of cotton. In detail, Table 4.24*a* shows that crop yield

Table 4.24*a*: Linear correlations between monthly/seasonal/annual rainfall totals and raw crop yields in Mali for periods indicated. Rainfall information was averaged for each PCA-based rainfall region (Fig. 4.20*a*, panel b). Yields were only computed for crop regions (see Fig. 4.20*a*, panel a and Table 4.22) that have the most complete and longest data for each study crop (Tables 3.6*a*, 3.7*a*). Correlation coefficients with ≥ 99% significance levels are in bold; those with ≥ 95% & < 99% significance levels are asterisked; correlation coefficients with ≥ 90% & < 95% significance levels are underlined; those with ≥ 85% & < 90% significance levels are in parentheses; and correlation coefficients with ≥ 80% & < 85% significance levels are double-asterisked. Levels of significance are derived from two-tailed t test. C = Cash and S = Staple.

Cotton (C: '66-97)		**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Jul-Sep**	**May-Oct**	**Annual**
Region 1	Ko	-0.24	-0.19	-0.01	-0.14	-0.43	+0.08	(-0.40)	-0.52*	-0.57*
Region 2	So	-0.32**	+0.14	+0.01	-0.43	(-0.39)	-0.22	-0.43	-0.43	-0.30
	Su	(-0.39)	+0.29	-0.25	-0.16	+0.19	+0.34**	-0.11	-0.02	+0.01
Maize (S: '66-98)		**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Jul-Sep**	**May-Oct**	**Annual**
Region 1	Ko	-0.02	+0.15	-0.12	+0.08	+0.33	+0.07	+0.19	+0.28**	(+0.31)
	Ky	-0.12	-0.10	-0.27**	+0.08	+0.28**	+0.22	+0.02	+0.02	+0.01
Region 2	So	+0.35	-0.11	-0.05	+0.10	(+0.29)	+0.19	+0.17	+0.25**	+0.15
	Su	-0.01	-0.05	+0.34	+0.36	+0.24	**+0.53**	+0.43*	**+0.50**	+0.39*
Millet (S: '84-98)		**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Jul-Sep**	**May-Oct**	**Annual**
Region 1	T	-0.30	**+0.70**	+0.16	-0.05	+0.59*	-0.34	(+0.44)	+0.47	+0.47
	G	+0.16	-0.23	-0.33	(+0.51)	+0.56	+0.38	+0.61*	+0.65*	+0.67*
	Mb	-0.24	+0.24	-0.24	+0.08	+0.21	-0.06	+0.06	+0.10	+0.11
	Ko	-0.47	+0.58*	+0.27	+0.07	-0.04	-0.34	+0.16	+0.17	+0.17
	Ky	+0.09	-0.15	+0.20	+0.11	-0.15	-0.04	+0.09	+0.02	+0.05
Region 2	So	-0.24	-0.13	+0.08	-0.25	-0.17	-0.24	-0.18	-0.24	-0.36**
	Su	-0.03	-0.02	+0.31	+0.28	+0.30	-0.03	(+0.40)	+0.29	+0.14
Peanuts (C: '66-97)		**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Jul-Sep**	**May-Oct**	**Annual**
Region 1	Mb	+0.17	+0.30	+0.29	-0.31	-0.08	+0.11	-0.10	+0.03	+0.06
	Ko	-0.13	+0.14	+0.10	+0.36**	+0.04	-0.29	+0.28	+0.26	+0.27
	Ky	-0.01	+0.21	+0.14	-0.03	+0.45	+0.10	+0.32	+0.41	+0.41
Region 2	So	-0.13	+0.19	-0.24	+0.19	+0.35**	+0.22	+0.17	+0.21	+0.05
	Su	(-0.40)	-0.07	+0.43	+0.32	+0.05	-0.15	(+0.39)	+0.14	+0.01
Rice (S: '66-98)		**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Jul-Sep**	**May-Oct**	**Annual**
Region 1	G	-0.08	+0.08	-0.01	+0.24	-0.13	-0.19	+0.04	-0.01	-0.02
	Mb	+0.17	(-0.28)	-0.12	-0.04	+0.12	+0.46*	-0.02	+0.04	+0.04
	Ko	+0.23	+0.03	+0.04	-0.35	-0.09	+0.17	-0.21	-0.07	-0.02
	Ky	+0.26	+0.04	+0.07	-0.02	-0.18	+0.02	-0.08	+0.01	+0.04
Region 2	So	-0.03	+0.42*	-0.01	(+0.29)	+0.45*	+0.07	+0.37	+0.39*	**+0.48**
	Su	-0.05	+0.45*	+0.14	+0.22	+0.43*	+0.19	+0.37	+0.44*	**+0.54**
Sorghum (S: '84-98)		**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Jul-Sep**	**May-Oct**	**Annual**
Region 1	T	-0.12	+0.30	-0.30	+0.19	**+0.73**	-0.26	(+0.39)	(+0.42)	(+0.40)
	G	-0.09	-0.22	**-0.71**	+0.37**	+0.15	+0.52*	+0.06	+0.16	+0.14
	Mb	+0.02	+0.06	+0.14	-0.15	+0.54*	-0.16	+0.26	+0.22	+0.24
	Ko	-0.18	(+0.40)	+0.56*	-0.16	+0.06	-0.17	+0.24	+0.23	+0.24
	Ky	-0.37**	+0.18	-0.26	+0.12	-0.07	-0.10	-0.09	-0.07	-0.07
Region 2	So	+0.06	-0.06	-0.47	-0.58*	-0.11	-0.22	-0.53*	(-0.43)	-0.47
	Su	-0.09	+0.13	+0.59*	+0.52*	(+0.40)	+0.03	**+0.68**	+0.54*	+0.49
Sugarcane (C:'84-97)		**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Jul-Sep**	**May-Oct**	**Annual**
Region 2	Su	+0.11	**+0.68**	+0.14	+0.21	+0.49	+0.46	(+0.41)	+0.61*	**+0.69**

Table 4.24*b*: Linear correlations between the onset/cessation dates of the July-September-centered rainy season and raw crop yields in Mali for periods indicated. Onset/cessation dates (Table 4.22*a*) were averaged for each year for each PCA-based rainfall region (Fig. 4.20*a*, panel b). Yields were only computed for crop regions (see Fig. 4.20*a*, panel a) that have the most complete and longest data (Tables 3.6*a*, 3.7*a*). Correlation coefficients with ≥ 99% significance levels are in bold; those with ≥ 95% & < 99% significance levels are asterisked; correlation coefficients with ≥ 90% & < 95% significance levels are underlined; those with ≥ 85% & < 90% significance levels are in parentheses; and correlation coefficients with ≥ 80% & < 85% significance levels are double-asterisked. Levels of significance are derived from two-tailed t test.

Cotton (Cash: 1966-97)		**Onset**	**Cessation**
Region 1	Koulikoro (Ko)	-0.21	<u>+0.42</u>
Region 2	Sikasso (So)	+0.53*	<u>+0.46</u>
	Segou (Su)	+0.55*	<u>+0.45</u>
Maize (Staple: 1966-98)		**Onset**	**Cessation**
Region 1	Koulikoro (Ko)	+0.06	**-0.48**
	Kayes (Ky)	-0.08	+0.08
Region 2	Sikasso (So)	-0.45*	**-0.48**
	Segou (Su)	-0.09	-0.16
Millet (Staple: 1984-98)		**Onset**	**Cessation**
Region 1	Tombouctou (T)	-0.35	-0.14
	Gao (G)	(+0.50)	+0.42**
	Mopti (Mb)	-0.33	-0.25
	Koulikoro (Ko)	**-0.71**	-0.54*
	Kayes (Ky)	-0.05	+0.20
Region 2	Sikasso (So)	-0.09	-0.12
	Segou (Su)	+0.10	+0.03
Peanuts (Cash: 1966-97)		**Onset**	**Cessation**
Region 1	Mopti (Mb)	-0.55*	<u>-0.43</u>
	Koulikoro (Ko)	-0.35**	**-0.59**
	Kayes (Ky)	+0.06	+0.18
Region 2	Sikasso (So)	-0.10	-0.04
	Segou (Su)	-0.27	-0.21
Rice (Staple: 1966-98)		**Onset**	**Cessation**
Region 1	Gao (G)	(-0.29)	-0.23
	Mopti (Mb)	+0.16	+0.18
	Koulikoro (Ko)	+0.18	+0.17
	Kayes (Ky)	+0.13	+0.15
Region 2	Sikasso (So)	**+0.57**	**+0.50**
	Segou (Su)	**+0.86**	**+0.72**
Sorghum (Staple: 1984-98)		**Onset**	**Cessation**
Region 1	Tombouctou (T)	+0.12	-0.10
	Gao (G)	+0.25	+0.07
	Mopti (Mb)	-0.26	-0.19
	Koulikoro (Ko)	**-0.63**	<u>-0.44</u>
	Kayes (Ky)	(-0.41)	-0.15
Region 2	Sikasso (So)	+0.11	+0.22
	Segou (Su)	+0.28	+0.16
Sugarcane (Cash: 1984-97)		**Onset**	**Cessation**
Region 2	Segou (Su)	<u>+0.49</u>	(+0.43)

Table 4.25*a*: Linear correlations between monthly/seasonal/annual rainfall totals and raw crop yields in Burkina Faso for periods indicated. Rainfall information was averaged for each PCA-based rainfall region (Fig. 4.20*a*, panel d). Yields were only computed for crop regions (see Fig. 4.20*a*, panel c and Table 4.22) that have the most complete and longest data (Tables 3.6*b*, 3.7*b*). Correlation coefficients with ≥ 99% significance levels are in bold; those with ≥ 95% & < 99% significance levels are asterisked; correlation coefficients with ≥ 90% & < 95% are underlined; those with ≥ 85% & < 90% significance levels are in parentheses; and correlation coefficients with ≥ 80% & < 85% significance levels are double-asterisked. Levels of significance are derived from two-tailed t test. C = Cash and S = Staple.

Cotton (C: '70-98)		May	Jun	Jul	Aug	Sep	Oct	Jul-Sep	May-Oct	Annual
Region 1	Ma	-0.06	+0.14	-0.28**	+0.09	-0.37	-0.26	-0.26	-0.21	-0.06
Region 2	CWa	+0.13	-0.09	-0.16	-0.13	-0.05	+0.15	-0.19	-0.15	-0.16
	SWa	-0.02	+0.15	-0.15	(-0.30)	-0.05	+0.21	-0.34	-0.25	-0.23
	HB	-0.01	+0.15	-0.35	-0.44*	-0.16	+0.06	-0.48*	-0.38	(-0.34)
Maize (S: '70-98)		**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Jul-Sep**	**May-Oct**	**Annual**
Region 1	Ca	+0.01	+0.17	+0.02	**+0.53**	+0.20	+0.04	+0.46*	+0.33	+0.33
	CNa	+0.17	+0.14	+0.22	**+0.59**	+0.36	+0.19	**+0.73**	**+0.62**	**+0.56**
	Ma	-0.03	+0.11	+0.04	+0.46*	-0.06	-0.01	(+0.29)	+0.27**	+0.35
Region 2	CEa	-0.37	+0.11	+0.10	-0.19	-0.17	+0.24	-0.15	-0.16	-0.05
	CWa	-0.35	+0.10	+0.10	+0.14	+0.12	+0.06	+0.15	+0.05	+0.11
	SWa	-0.17	+0.28**	+0.01	+0.13	+0.19	+0.37	+0.10	+0.22	+0.18
	HB	-0.01	+0.28**	-0.01	+0.08	-0.04	(+0.29)	+0.01	+0.16	+0.16
Millet (S: '70-98)		**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Jul-Sep**	**May-Oct**	**Annual**
Region 1	Sa	**+0.57**	+0.29**	-0.01	+0.13	+0.47*	+0.39*	+0.34	+0.42*	+0.46*
	CNa	**+0.57**	+0.19	+0.10	+0.22	+0.45*	+0.26**	+0.46*	**+0.49**	**+0.50**
	Na	+0.35	+0.27**	+0.07	+0.18	+0.19	+0.19	+0.28**	+0.27**	+0.33
	Ma	+0.11	+0.20	-0.16	+0.27**	+0.10	-0.01	+0.21	+0.23	+0.25
	Ca	+0.21	(+0.30)	-0.15	(+0.31)	+0.20	-0.03	+0.27**	+0.25	(+0.31)
	E	+0.17	+0.37	-0.12	+0.22	+0.27**	+0.20	+0.24	+0.23	+0.21
Region 2	CEa	-0.09	+0.05	+0.03	+0.19	-0.06	-0.21	-0.01	-0.18	-0.19
	CWa	+0.06	+0.06	+0.07	+0.28**	+0.22	-0.02	+0.27**	+0.27**	+0.20
	SWa	+0.14	+0.17	+0.02	-0.20	-0.05	+0.37	-0.13	+0.08	+0.09
	HB	+0.11	+0.22	-0.01	+0.22	+0.19	-0.22	+0.23	+0.25	+0.16
Peanuts (C: '70-98)		**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Jul-Sep**	**May-Oct**	**Annual**
Region 1	Ca	+0.04	+0.19	-0.15	(+0.31)	+0.17	+0.02	+0.20	+0.12	+0.13
Region 2	CWa	-0.12	-0.26**	+0.16	+0.25**	+0.12	-0.14	+0.22	+0.01	+0.03
	SWa	-0.02	+0.19	-0.06	+0.16	+0.15	+0.08	+0.06	+0.08	+0.03
	HB	+0.03	-0.04	+0.24	-0.09	+0.25**	-0.09	+0.13	+0.08	+0.09
Rice (S: '70-98)		**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Jul-Sep**	**May-Oct**	**Annual**
Region 1	Ca	-0.08	+0.15	-0.06	+0.39*	+0.07	+0.05	+0.27**	+0.24	+0.22
	E	+0.12	+0.12	-0.01	-0.33	(+0.29)	+0.02	-0.12	-0.13	+0.01
Region 2	SWa	+0.03	+0.20	-0.22	+0.13	-0.12	+0.22	-0.10	+0.03	+0.07
	HB	-0.35	-0.08	-0.35	-0.08	-0.08	-0.04	-0.20	-0.35	-0.34
Sorghum (S:'70-98)		**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Jul-Sep**	**May-Oct**	**Annual**
Region 1	Sa	**+0.55**	+0.34	-0.08	+0.01	+0.12	+0.42*	+0.03	+0.33	+0.39*
	CNa	**+0.49**	+0.23	+0.01	(+0.32)	+0.46*	+0.35	**+0.49**	**+0.64**	**+0.62**
	Na	(+0.30)	+0.08	+0.12	(+0.29)	+0.28**	+0.18	+0.40*	(+0.29)	(+0.31)
	Ma	+0.14	+0.23	-0.11	+0.02	-0.04	+0.17	-0.04	+0.18	+0.18
	Ca	+0.23	+0.28**	-0.18	+0.42*	+0.16	-0.01	(+0.31)	(+0.31)	+0.37
	E	+0.04	(+0.30)	-0.20	+0.29**	**+0.52**	+0.04	+0.38	+0.28**	(+0.31)
Region 2	CEa	+0.10	+0.21	-0.12	+0.26**	+0.22	-0.11	+0.13	+0.14	+0.07
	CWa	+0.08	+0.08	+0.05	+0.27**	+0.21	+0.08	+0.22	+0.25	+0.22
	SWa	+0.19	+0.24	-0.15	-0.03	-0.09	+0.11	-0.13	+0.03	+0.05
	HB	-0.04	+0.14	-0.02	-0.02	+0.06	+0.03	-0.03	-0.03	-0.08
Soybeans (C: '85-98)		**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Jul-Sep**	**May-Oct**	**Annual**
Region 1	Ca	(-0.49)	+0.03	-0.42	-0.35	-0.14	(-0.52)	+0.04	-0.10	-0.04
Region 2	CEa	-0.01	-0.52	-0.08	-0.03	+0.17	-0.15	-0.14	(-0.51)	-0.57

Table 4.25*b*: Linear correlations between the onset/cessation dates of the July-September-centered rainy season and raw crop yields in Burkina Faso for periods indicated. Onset/cessation dates (Table 4.13*a*) were averaged for each year for each PCA-based rainfall region (Fig. 4.20*a*, panel d). Yields were only computed for crop regions (see Fig. 4.20*a*, panel c) that have the most complete and longest data (Tables 3.6*b*, 3.7*b*). Correlation coefficients with ≥ 99% significance levels are in bold; those with ≥ 95% & < 99% significance levels are asterisked; correlation coefficients with ≥ 90% & < 95% significance levels are underlined; those with ≥ 85% & < 90% significance levels are in parentheses; and correlation coefficients with ≥ 80% & < 85% significance levels are double-asterisked. Levels of significance are derived from two-tailed t test.

Cotton (Cash: 1970-98)		**Onset**	**Cessation**
Region 1	Mouhoun (Ma)	+0.19	+0.18
Region 2	Central-west (CWa)	**+0.64**	**+0.68**
	Southwest (SWa)	**+0.86**	**+0.85**
	Haut-Bassin (HB)	**+0.52**	+0.45*
Maize (Staple: 1970-98)		**Onset**	**Cessation**
Region 1	Center (Ca)	**+0.58**	**+0.58**
	Central-north (CNa)	**+0.47**	**+0.47**
	Mouhoun (Ma)	+0.24	+0.26**
Region 2	Central-east (CEa)	+0.10	+0.12
	Central-west (CWa)	**+0.56**	**+0.60**
	Southwest (SWa)	**+0.78**	**+0.77**
	Haut-Bassin (HB)	**+0.70**	**+0.71**
Millet (Staple: 1970-98)		**Onset**	**Cessation**
Region 1	Sahel (Sa)	**+0.69**	**+0.70**
	Central-north (CNa)	+0.41*	+0.44*
	North (Na)	**+0.54**	**+0.56**
	Mouhoun (Ma)	(+0.31)	(+0.30)
	Center (Ca)	**+0.61**	**+0.59**
	East (E)	**+0.60**	**+0.63**
Region 2	Central-east (CEa)	**+0.73**	**+0.74**
	Central-west (CWa)	+0.29**	(+0.30)
	Southwest (SWa)	**+0.64**	**+0.66**
	Haut-Bassin (HB)	+0.11	+0.16
Peanuts (Cash: 1970-98)		**Onset**	**Cessation**
Region 1	Center (Ca)	**+0.72**	**+0.73**
Region 2	Central-west (CWa)	+0.40*	**+0.47**
	Southwest (SWa)	**+0.75**	**+0.79**
	Haut-Bassin (HB)	-0.17	-0.18
Rice (Staple: 1970-98)		**Onset**	**Cessation**
Region 1	Center (Ca)	+0.45*	+0.42*
	East (E)	+0.35	+0.35
Region 2	Southwest (SWa)	**+0.80**	**+0.86**
	Haut-Bassin (HB)	+0.34	+0.38*
Sorghum (Staple: 1970-98)		**Onset**	**Cessation**
Region 1	Sahel (Sa)	**+0.56**	**+0.57**
	Central-north (CNa)	+0.43*	+0.41*
	North (Na)	**+0.50**	**+0.54**
	Mouhoun (Ma)	+0.11	+0.09
	Center (Ca)	**+0.68**	**+0.67**
	East (E)	**+0.59**	**+0.60**
Region 2	Central-east (CEa)	**+0.69**	**+0.73**
	Central-west (CWa)	**+0.61**	**+0.63**
	Southwest (SWa)	**+0.77**	**+0.79**
	Haut-Bassin (HB)	+0.29**	+0.22
Soybeans (Cash: 1985-98)		**Onset**	**Cessation**
Region 1	Center (Ca)	-0.06	-0.19
Region 2	Central-east (CEa)	(+0.48)	+0.43**

Table 4.26*a*: Linear correlations between monthly totals† and raw crop yields in Côte d'Ivoire for periods indicated. Rainfall information was averaged for each PCA-based rainfall region (Fig. 4.20*b*, bottom). Yields were only computed for crop regions (see Fig. 4.20*b*, top and Table 4.22) that have the most complete and longest data (Tables 3.6*c*, 3.7*c*). Correlation coefficients with ≥ 99% significance levels are in bold; those with ≥ 95% & < 99% significance levels are asterisked; correlation coefficients with ≥ 90% & < 95% significance levels are underlined; those with ≥ 85% & < 90% significance levels are in parentheses; and correlation coefficients with ≥ 80% & < 85% significance levels are double-asterisked. Levels of significance are derived from two-tailed t test. C = Cash and S = Staple.

Cocoa (C: '59-98)		Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Region 1	CEb	(-0.25)	+0.30	-0.20	+0.29	+0.09	-0.21	(-0.28)	-0.03	+0.19
	Sb	(-0.27)	-0.12	(-0.25)	-0.07	(-0.27)	+0.06	-0.05	+0.10	-0.11
Region 2	CWb	+0.15	+0.22**	+0.07	-0.21	-0.08	+0.09	+0.05	+0.12	-0.03
	W	-0.01	-0.03	-0.08	-0.34*	+0.07	+0.21	-0.23**	-0.39*	-0.23**
Coffee (C: '59-98)		**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Region 1	CEb	+0.02	+0.31	+0.02	**+0.41**	+0.17	-0.13	-0.03	-0.24**	+0.19
	Sb	+0.12	(+0.28)	+0.13	**+0.44**	+0.02	-0.21	-0.13	-0.29	(+0.27)
	SWb	-0.34*	+0.20	-0.13	+0.15	-0.12	+0.03	-0.22**	-0.32	-0.05
Region 2	CWb	+0.19	+0.22	(+0.26)	+0.05	+0.08	-0.09	+0.22**	+0.36*	+0.18
	W	-0.02	+0.09	+0.15	+0.29	+0.19	-0.14	+0.30	+0.19	+0.05
Cotton (C: '51-98)		**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Region 2	CNb	+0.04	+0.04	+0.04	-0.28	-0.03	+0.01	-0.34*	-0.27	-0.15
	Nb	-0.01	-0.03	-0.03	-0.10	+0.01	+0.18	**-0.45**	-0.36*	-0.32*
Region 3	NW	+0.01	+0.01	+0.06	-0.33*	+0.03	-0.20**	-0.34*	-0.16	-0.28
Maize (S: '49-98)		**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Region 1	Cb	-0.36*	+0.10	-0.36*	-0.06	+0.20	+0.19	(-0.28)	-0.31	-0.31
	Sb	-0.36*	-0.02	-0.33	-0.10	-0.05	+0.07	-0.23**	-0.13	-0.25**
	SWb	(-0.29)	+0.07	-0.30	+0.13	+0.20	+0.17	-0.14	+0.11	+0.07
Region 2	CWb	-0.01	+0.15	+0.03	+0.13	+0.08	+0.08	(-0.29)	-0.09	-0.12
	W	+0.04	+0.01	+0.01	-0.01	+0.12	-0.09	-0.09	+0.01	-0.07
	CNb	-0.06	-0.06	+0.10	-0.11	-0.19	+0.18	**-0.45**	-0.22	-0.04
Region 3	NW	-0.22	-0.05	+0.03	-0.02	-0.08	-0.16	-0.09	(-0.27)	-0.12
Plantain (S: '48-98)		**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Region 1	CEb	+0.08	+0.08	-0.27	+0.30**	-0.05	-0.14	+0.01	(+0.33)	+0.36
	Sb	+0.07	+0.17	-0.29**	+0.38	+0.01	-0.11	+0.01	+0.37	(+0.34)
	SWb	-0.15	+0.17	-0.31**	+0.25	+0.01	-0.16	-0.12	+0.26	+0.18
Region 2	CWb	+0.11	+0.11	(-0.33)	(+0.33)	+0.42*	-0.09	**+0.50**	+0.49*	-0.03
	W	-0.14	+0.24	-0.19	+0.01	+0.16	-0.10	-0.01	+0.13	-0.05
	NE	+0.03	-0.26	-0.19	+0.03	+0.43*	-0.11	+0.29**	+0.37	-0.02
Rice (S: '47-98)		**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Region 1	Cb	-0.31	+0.05	(-0.25)	-0.03	-0.01	-0.08	-0.24**	-0.30	-0.32
	CEb	-0.35*	-0.03	(-0.26)	(-0.26)	+0.17	+0.13	-0.23**	-0.36*	**-0.46**
	Sb	-0.38*	-0.01	-0.40*	-0.05	+0.13	+0.04	-0.22**	-0.24**	-0.35*
	SWb	(-0.25)	-0.05	-0.34*	-0.17	+0.11	+0.08	(-0.27)	-0.28	**-0.56**
Region 2	CWb	-0.01	+0.18	+0.21	-0.07	+0.05	+0.14	-0.28	-0.21	-0.24**
	W	-0.01	+0.10	+0.30	-0.15	+0.02	+0.23**	-0.34*	-0.18	-0.11
	CNb	+0.19	(+0.25)	+0.12	+0.03	+0.24**	+0.31	-0.03	-0.14	(-0.27)
	Nb	+0.14	+0.07	+0.20	+0.04	+0.01	+0.02	**-0.48**	-0.21	-0.10
Region 3	NW	-0.09	-0.01	+0.08	-0.12	+0.30	-0.16	-0.03	-0.10	**-0.43**
Yams (S: '48-98)		**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
Region 1	Cb	-0.10	-0.11	-0.34*	+0.08	+0.19	+0.33	-0.09	-0.12	-0.39*
	CEb	-0.37*	-0.05	-0.21	-0.24**	+0.11	+0.31	-0.20	-0.23**	-0.19
	Sb	+0.24**	-0.01	-0.32	+0.15	+0.15	+0.20	-0.15	+0.05	-0.18
	SWb	-0.18	-0.05	-0.33	+0.03	+0.33	**+0.45**	-0.14	-0.17	-0.04
Region 2	CWb	+0.18	+0.16	-0.16	+0.18	+0.23**	+0.01	+0.05	-0.09	-0.33
	CNb	+0.03	+0.21	+0.16	-0.02	-0.03	+0.07	(-0.29)	-0.06	-0.08
	Nb	-0.02	+0.09	+0.15	-0.01	-0.19	-0.14	**-0.47**	**-0.47**	-0.34*
	NE	+0.04	-0.07	+0.01	-0.16	+0.14	+0.11	(-0.28)	-0.17	-0.19
Region 3	NW	-0.23	+0.01	-0.04	-0.05	-0.06	-0.25**	-0.05	(-0.28)	-0.21

† Côte d'Ivoire focuses on more months than Mali/Burkina Faso because most of its selected rainfall stations are bimodal and therefore register more rainy months (Table 4.9*a*,*b*).

Table 4.26*b*: Linear correlations between seasonal/annual rainfall totals† and raw crop yields in Côte d'Ivoire for periods indicated. Rainfall information was averaged for each PCA-based rainfall region (Fig. 4.20*b*, bottom). Yields were only computed for crop regions (see Fig. 4.20*b* (top and Table 4.22) that have the most complete and longest data (Tables 3.6*c*, 3.7*c*). Correlation coefficients with ≥ 99% significance levels are in bold; those with ≥ 95% & < 99% significance levels are asterisked; correlation coefficients with ≥ 90% & < 95% significance levels are underlined; those with ≥ 85% & < 90% significance levels are in parentheses; and correlation coefficients with ≥ 80% & < 85% significance levels are double-asterisked. Levels of significance are derived from two-tailed t test. C = Cash and S = Staple.

Cocoa (C: '59-98)		**Mar-Jun**	**Jul-Sep**	**Oct-Nov**	**May-Oct**	**Mar-Nov**	**Annual**
Region 1	CEb	+0.13	-0.13	+0.08	-0.04	+0.01	-0.02
	Sb	-0.25**	-0.15	-0.02	-0.23**	(-0.26)	(-0.28)
Region 2	CWb	+0.08	+0.08	+0.06	+0.08	+0.13	+0.12
	W	-0.23**	+0.02	-0.36*	-0.21	-0.23**	(-0.25)
Coffee (C: '59-98)		**Mar-Jun**	**Jul-Sep**	**Oct-Nov**	**May-Oct**	**Mar-Nov**	**Annual**
Region 1	CEb	+0.35*	+0.03	-0.02	+0.18	+0.23**	+0.29
	Sb	**+0.44**	-0.13	-0.02	+0.08	+0.17	+0.24**
	SWb	+0.01	-0.17	(-0.25)	-0.21	-0.19	-0.16
Region 2	CWb	+0.31	+0.18	+0.32	+0.34*	+0.38*	**+0.41**
	W	(+0.25)	+0.19	+0.19	+0.34*	+0.32	+0.34*
Cotton (C: '51-98)		**Mar-Jun**	**Jul-Sep**	**Oct-Nov**	**May-Oct**	**Mar-Nov**	**Annual**
Region 2	CNb	-0.10	-0.14	-0.26	(-0.24)	(-0.23)	-0.30
	Nb	-0.10	-0.12	**-0.39**	-0.22**	-0.26	-0.33*
Region 3	NW	-0.18	-0.27	(-0.24)	-0.32*	-0.32*	-0.33*
Maize (S: '49-98)		**Mar-Jun**	**Jul-Sep**	**Oct-Nov**	**May-Oct**	**Mar-Nov**	**Annual**
Region 1	Cb	-0.31	+0.01	-0.36*	(-0.26)	-0.31	-0.33
	Sb	-0.37*	-0.11	-0.20	(-0.28)	-0.34	-0.38*
	SWb	-0.13	+0.09	+0.11	+0.05	+0.03	-0.01
Region 2	CWb	+0.13	-0.05	-0.12	-0.05	-0.04	-0.05
	W	+0.02	-0.03	+0.01	+0.01	+0.01	+0.01
	CNb	-0.11	-0.19	-0.21	-0.23	-0.25**	(-0.28)
Region 3	NW	-0.11	-0.20	(-0.26)	-0.23	(-0.27)	(-0.29)
Plantain (S: '48-98)		**Mar-Jun**	**Jul-Sep**	**Oct-Nov**	**May-Oct**	**Mar-Nov**	**Annual**
Region 1	CEb	+0.13	-0.05	+0.40	+0.14	+0.21	+0.21
	Sb	+0.20	-0.01	+0.42*	+0.21	+0.27	+0.27
	SWb	+0.05	-0.09	+0.28**	+0.06	+0.10	+0.10
Region 2	CWb	+0.19	+0.38	+0.43*	+0.45*	+0.47*	+0.50*
	W	+0.01	+0.03	+0.11	+0.04	+0.06	+0.05
	NE	-0.15	+0.24	(+0.34)	+0.25	+0.20	+0.21
Rice (S: '47-98)		**Mar-Jun**	**Jul-Sep**	**Oct-Nov**	**May-Oct**	**Mar-Nov**	**Annual**
Region 1	Cb	-0.24**	-0.14	-0.35*	-0.29	-0.35*	-0.37*
	CEb	**-0.44**	+0.02	**-0.48**	-0.31	**-0.41**	**-0.46**
	Sb	-0.37*	-0.03	-0.33*	(-0.26)	-0.34*	-0.38*
	SWb	-0.40*	-0.05	**-0.46**	-0.33	**-0.43**	**-0.47**
Region 2	CWb	+0.10	-0.02	(-0.27)	-0.08	-0.09	-0.12
	W	+0.07	-0.03	-0.22	-0.07	-0.08	-0.12
	CNb	+0.22**	(+0.27)	-0.21	+0.19	+0.20	+0.17
	Nb	+0.15	-0.19	-0.23**	-0.17	-0.16	-0.17
Region 3	NW	-0.09	-0.03	-0.28	-0.08	-0.17	-0.18
Yams (S: '48-98)		**Mar-Jun**	**Jul-Sep**	**Oct-Nov**	**May-Oct**	**Mar-Nov**	**Annual**
Region 1	Cb	-0.22	+0.17	-0.25**	-0.02	-0.13	-0.15
	CEb	-0.41*	+0.06	(-0.27)	-0.22	(-0.29)	-0.31
	Sb	-0.06	+0.09	-0.03	+0.03	+0.01	+0.01
	SWb	(-0.27)	(+0.26)	-0.17	+0.01	-0.06	-0.07
Region 2	CWb	+0.15	+0.16	-0.17	+0.13	+0.13	+0.09
	CNb	+0.12	-0.11	-0.09	-0.09	-0.07	-0.07
	Nb	+0.08	-0.35*	**-0.50**	-0.35*	-0.36*	-0.37*
	NE	-0.12	+0.01	-0.19	-0.07	-0.11	-0.14
Region 3	NW	-0.14	-0.31	-0.33	-0.34	-0.38*	-0.38*

† Côte d'Ivoire has many rainy seasons because it has more rainy season months (Table 4.26*a*).

Table 4.26*c*: Linear correlations between the onset/cessation dates of the March-June-(M-J)/October-November-(O-N; regions 1& 2) and July-September- (J-S; region 3) centered rainy seasons and raw crop yields in Côte d'Ivoire for periods indicated. Onset/cessation dates were averaged for each year for each PCA-based rainfall region (Fig. 4.20*b*, bottom). Yields were only computed for regions (see Fig. 4.20*b*, top) that have the most complete and longest data (Tables 3.6*c*, 3.7*c*). Correlation coefficients with ≥ 99% significance levels are in bold; those with ≥ 95% & < 99% significance levels are asterisked; correlation coefficients with ≥ 90% & < 95% significance levels are underlined; those with ≥ 85% & < 90% significance levels are in parentheses; and correlation coefficients with ≥ 80% & < 85% significance levels are double-asterisked. Levels of significance are derived from two-tailed t test.

Cocoa (Cash: 1959-98)		Onset (M-J)	Cessation (M-J)	Onset (O-N)	Cessation (O-N)
Region 1†	Central-east (CEb)	+0.28	**+0.50**	**+0.45**	**+0.53**
	South (Sb)	**+0.70**	**+0.64**	**+0.56**	+0.05
Region 2†	Central-west (CWb)	-0.01	(+0.25)	-0.24**	-0.16
	West (W)	**+0.69**	**+0.72**	**+0.61**	**+0.74**
Coffee (Cash: 1959-98)		**Onset (M-J)**	**Cessation (M-J)**	**Onset (O-N)**	**Cessation (O-N)**
Region 1	Central-east (CEb)	**-0.46**	(-0.27)	-0.36*	+0.33*
	South (Sb)	**-0.48**	-0.24**	-0.34*	+0.29
	Southwest (SWb)	(+0.26)	+0.39*	+0.33*	**+0.54**
Region 2	Central-west (CWb)	-0.37*	-0.35*	**-0.64**	-0.39*
	West (W)	-0.33*	**-0.55**	-0.39*	**-0.46**
Cotton (Cash: 1951-98)		**Onset (M-J/J-S)**	**Cessation (M-J/J-S)**	**Onset (O-N)**	**Cessation (O-N)**
Region 2	Central-north (CNb)	**+0.55**	**+0.81**	+0.32*	**+0.75**
	North (Nb)	**+0.77**	**+0.94**	**+0.56**	**+0.89**
Region 3	Northwest (NW)	**+0.45**	**+0.54**	N/A	N/A
Maize (Staple: 1949-98)		**Onset (M-J/J-S)**	**Cessation (M-J/J-S)**	**Onset (O-N)**	**Cessation (O-N)**
	Center (Cb)	**+0.67**	**+0.64**	**+0.67**	+0.36*
Region 1	South (Sb)	**+0.78**	**+0.67**	**+0.83**	+0.36*
	Southwest (SWb)	**+0.52**	+0.40*	**+0.60**	**+0.57**
Region 2	Central-west (CWb)	**+0.77**	**+0.55**	**+0.49**	**+0.59**
	West (W)	**+0.47**	+0.20	+0.21	+0.33
	Central-north (CNb)	**+0.69**	**+0.75**	**+0.70**	**+0.68**
Region 3	Northwest (NW)	+0.32	**+0.48**	N/A	N/A
Plantain (Staple: 1948-98)		**Onset (M-J)**	**Cessation (M-J)**	**Onset (O-N)**	**Cessation (O-N)**
Region 1	Central-east (CEb)	-0.17	-0.29**	-0.02	**+0.79**
	South (Sb)	-0.19	(-0.35)	-0.06	**+0.79**
	Southwest (SWb)	+0.11	-0.05	+0.25	**+0.80**
Region 2	Central-west (CWb)	-0.44*	**-0.71**	**-0.74**	**-0.66**
	West (W)	+0.40	+0.16	+0.08	+0.27
	Northeast (NE)	-0.41*	**-0.66**	**-0.61**	**-0.58**
Rice (Staple: 1947-98)		**Onset (M-J/J-S)**	**Cessation (M-J/J-S)**	**Onset (O-N)**	**Cessation (O-N)**
Region 1	Center (Cb)	**+0.69**	**+0.81**	**+0.78**	-0.18
	Central-east (CEb)	**+0.76**	**+0.87**	**+0.76**	-0.35*
	South (Sb)	**+0.73**	**+0.86**	**+0.84**	-0.04
	Southwest (SWb)	**+0.85**	**+0.78**	**+0.81**	+0.10
Region 2	Central-west (CWb)	**+0.76**	**+0.79**	**+0.67**	**+0.74**
	West (W)	**+0.80**	**+0.89**	**+0.84**	**+0.86**
	Central-north (CNb)	**+0.68**	**+0.62**	**+0.53**	**+0.62**
	North (Nb)	**+0.83**	**+0.83**	**+0.80**	**+0.83**
Region 3	Northwest (NW)	**+0.63**	**+0.61**	N/A	N/A
Yams (Staple: 1948-98)		**Onset (M-J/J-S)**	**Cessation (M-J/J-S)**	**Onset (O-N)**	**Cessation (O-N)**
Region 1	Center (Cb)	**+0.71**	**+0.69**	**+0.70**	-0.09
	Central-east (CEb)	**+0.75**	**+0.73**	**+0.83**	+0.01
	South (Sb)	**+0.48**	**+0.43**	**+0.44**	+0.18
	Southwest (SWb)	**+0.55**	**+0.56**	**+0.56**	+0.16
Region 2	Central-west (CWb)	**+0.53**	**+0.49**	**+0.48**	**+0.53**
	Central-north (CNb)	**+0.62**	**+0.61**	**+0.63**	**+0.66**
	North (Nb)	**+0.69**	**+0.60**	**+0.68**	**+0.70**
	Northeast (NE)	**+0.86**	**+0.72**	**+0.71**	**+0.77**
Region 3	Northwest (NW)	**+0.59**	**+0.54**	N/A	N/A

† PCA-based regions 1 & 2 comprise bimodal stations with two onset/cessation dates (Table 4.23*a*).

regions in Mali correlate most positively, strongly, and significantly with rainfall for the month of September (13 significant positive coefficients and 2 significant negative coefficients), the July-September-centered rainy season (10 significant positive and 3 significant negative), the May-October-centered rainy season (11 significant positive and 3 significant negative), and with the annual rainfall totals (10 significant positive and 3 significant negative). Generally, weaker and more negative correlations were obtained for the specific months during May-August (1 significant positive and 5 significant negative, 6 significant positive and 1 significant negative, 4 significant positive and 3 significant negative, 6 significant positive and 3 significant negative, respectively) and October (5 significant positive and no significant negative).

Further, Table 4.24*b* shows that several of the correlations between crop yields and the onset (6 significant positive for late onset and 7 significant negative for early onset) and cessation (7 significant positive for late cessation and 6 significant negative for early cessation) dates of the July-September-centered rainy season are strong, many reaching ≥ 99% significance levels (e.g., positive significant for onset/cessation in So and Su for cotton and rice, in G for millet; negative significant for onset/cessation in So for maize and Ko for millet, peanuts, and sorghum). These correlation coefficients suggest that Mali is equally subject to years with late onset and late cessation dates (significant positive correlations) and years with early onset and early cessation dates (significant negative correlations). For late onset and late cessation dates, the rainy seasons can range from normal (average length) to long and crop yields could benefit from accurate seasonal forecasts in order to avoid the replanting of crop seeds. For early onset and early cessation dates, plant growth and development would rely on the soil moisture carried over from the shorter rainy season. In addition, the dominance of strongly positive and significant correlation coefficients for Koulikoro (e.g., millet), Kayes (e.g., peanuts), Sikasso (e.g., rice), and Segou (e.g. sugarcane) supports that the influence of rainfall on agriculture is greatest in these prime Malian agricultural regions, implying their strong sensitivity and high vulnerability to low rainfall (see Tables 4.24*a*,*b*).

For Burkina Faso also, Table 4.25*a* shows that the significant correlation coefficients between rainfall and end-of-season raw crop yields are mostly positive for the staple crops of maize, millet, rice, sorghum, and the cash crop of peanuts, while they are mostly negative for the cash crop of soybeans and cotton. Here, crop yields correlate most positively, strongly, and significantly with rainfall for the individual rainy season months during May-June (6 significant positive and 4 significant negative, 9 significant positive and 2 significant negative, respectively), August-September (15 significant positive and 3 significant negative, 9 significant positive and 1 significant negative, respectively), with the July-September-centered rainy season (13 significant positive and 2 significant negative) and May-October-centered rainy season (12 significant positive and 3 significant negative), as well as with the annual totals (12 significant positive and 3 significant negative). The exceptions occur for the correlations between end-of-season crop yields and rainfall for the rainy season months of July (3 significant negative coefficients) and October (7 significant positive and 1 significant negative), which have only three to eight significant positive/negative coefficients.

In addition, almost all of the correlations between crop yields and the onset (34 significant positive coefficients for late onset and no significant negative) and cessation

(34 significant positive coefficients for late cessation and no significant negative) dates of the July-September-centered rainy season for all Burkinabè regions are strongly positive and significant, many reaching ≥ 99% significance levels (Table 4.25*b*). The only exceptions occur for peanuts in HB and soybeans in Ca, which record non-significant negative coefficients. The dominance of significant positive coefficients for both onset and cessation implies that the Burkinabè crops are more exposed to late onset and late cessation dates, ranging from normal (average) to longer rainy seasons. This situation indicates that crop yields increase with the length of the rainy seasons. Thus, accurate seasonal forecasts could help avoid the replanting of crop seeds, benefiting crop yields. In Burkina Faso too, the overall occurrence of strongly positive and significant correlation coefficients for Center (e.g., millet), East (e.g., sorghum), Haut-Bassin (e.g., maize), and Mouhoun (e.g., maize) suggest the great influence of rainfall on agriculture in these agricultural regions. Therefore, the four dominant crop regions of this country are highly vulnerable to low rainfall (see Tables 4.25*a*,*b*).

Unlike for Mali and Burkina Faso, the negative signs dominate the correlations between rainfall and end-of-season raw crop yields for Côte d'Ivoire, except when crop yields are correlated to the onset and cessation dates of the rainy seasons (Tables 4.26*a*-*c*). In Tables 4.26*a*,*b*, crops correlate most strongly and significantly with rainfall for the individual months of March (1 significant positive coefficient and 11 significant negative coefficients), May-June (2 significant positive and 14 significant negative, 7 significant positive and 5 significant negative, respectively), and September-November (4 significant positive and 20 significant negative, 5 significant positive and 15 significant negative, 3 significant positive and 15 significant negative, respectively), as well as with the March-

June-centered rainy season (5 significant positive and 10 significant negative), October-November-centered rainy season (6 significant positive and 18 significant negative), May-October-centered rainy season (3 significant positive and 12 significant negative), and March-November-centered rainy season (4 significant positive and 16 significant negative), and the annual totals (5 significant positive and 16 significant negative), with some correlation coefficients reaching ≥ 99% significance levels. The exceptions occur for the correlations between end-of-season crop yields and rainfall for the specific months of April (5 significant positive and no significant negative), July (6 significant positive and 1 significant negative), August (5 significant positive and 2 significant negative), and the July-September-centered rainy season (3 significant positive and 3 significant negative), which each registered less than 8 positive/negative significant coefficients.

Further, the correlation coefficients between crop yields and the onset and cessation dates of the March-June-centered rainy season (onset: 29 significant positive for late onset and 6 significant negative for early onset; cessation: 28 significant positive for late cessation and 8 significant negative for early cessation), July-September-centered rainy season (onset: 4 significant positive for late onset and no significant negative; cessation: 4 significant positive for late cessation and no significant negative), and October-November-centered rainy season (onset: 28 significant positive for late onset and 6 significant negative for early onset; cessation: 24 significant positive for late cessation and 5 significant negative for early cessation) in Côte d'Ivoire are strongly positive and significant, many reaching ≥ 99% significance levels (Table 4.26*c*). Like in Burkina Faso, the dominance of significant positive correlation coefficients for both onset and cessation (for all three Ivorian rainy seasons) implies that the Ivorian crops are also more subject to both late onset and late cessation, ranging from average to longer rainy seasons, which are indicative of crop yields increasing with the length of the rainy seasons. However, Côte d'Ivoire registers few cases of early onset (negative signs) and late cessation (positive signs) such as for cocoa in CWb and for coffee and plantain in CEb and Sb, as well as cases of late onset (positive signs) and early cessation (negative signs) such as for rice in Cb, CEb, Sb, and yams in Cb, where crop yields are remarkable.

Overall, crop yields for the four dominant Ivorian agricultural regions (Center, Central-west, South, and West) register more strongly negative and significant coefficients with rainfall for individual rainy season months, overall rainy seasons, and annual rainfall totals, and more strongly positive/negative and significant correlation coefficients with rainfall for both onset and cessation dates. These correlations support that these regions being prime crop regions receive probably more fertilizers and pesticides for both cash and staple crops. These regions are also located in the rainiest part of Côte d'Ivoire; they therefore may be vulnerable to too much rainfall (see Tables 4.26*a-c*).

4.3.3 Concluding Remarks

Analyses of Central West African crop data identified 12 dominant agricultural regions (Koulikoro, Kayes, Sikasso, Segou for Mali; Center, East, Haut-Bassin, Mouhoun for Burkina Faso; Center, Central-west, South, West for Côte d'Ivoire) and eight major crops (cotton, peanuts, millet, sorghum for Mali/Burkina Faso; cocoa, coffee, maize, plantain for Côte d'Ivoire). This revealed that cereals and subsistence crops (especially millet and sorghum) are more important for the northern regions (Soudano-Sahelian), while starch crops, root plants, and cash crops (especially plantain, yams, cocoa, and coffee) dominate the southern regions (Gulf of Guinea Coast). The study of regression-based trends of crop parameters investigated the extent to which crop acreage, production, and yields were related for the overall study periods or subperiods. The relationship of production to acreage (positive) is more apparent than the relationship of yields to acreage, which suggests that in spite of some improvement in farming practices (e.g., fertilizer and pesticide uses, mechanization), crop productions in Mali, Burkina Faso, and Côte d'Ivoire are more a function of acreage increase than yield increase.

Moreover, the analyses of crop yields in Central West Africa show variations from one year to another as well as from one crop to another. Both staple and cash crops show strong variations that are related to rainfall variations. Thus, correlation analyses of rainfall (for several measures) versus end-of-season crop yields reveal that both raw and detrended crop series seem to correlate strongly, positively, and significantly with rainfall, particularly for staple crops in spite of some weaker positive and more negative correlations, particularly for cash crops (especially cotton). The presence of significant positive coefficients indicates that in many cases, increased rainfall leads to increased crop yields across the study area. Therefore, lack of water is the primary constraint to crop growth, especially in drought-prone areas such as north Mali and extreme north Burkina Faso. The weaker positive and more negative correlations (particularly raw staple and cash crops in Côte d'Ivoire) could be due to the fact that crop production in Central West Africa has incorporated some adaptative or gradually improving cropping practices that might counterbalance the effects of rainfall decrease (e.g., Dancett, 1978; Glantz, 1994; Camberlin and Diop, 1999). Further, the inference can be made that too much rain/flooding (through drowned crops) could have played a role in the negative correlations, as well as the impacts of reduced solar irradiance, physical damage, and increased incidence of pests and diseases. Additionally onset and cessation dates of the rainy seasons show more strongly positive and significant correlations with raw crop yields (especially in Burkina Faso and Côte d'Ivoire) than the rainy season months, overall rainy seasons, and annual rainfall indices/totals. This situation shows that shorter (early onset and early cessation, negative coefficients) and longer (late onset and late cessation, positive coefficients) rainy seasons have equally occurred in Mali, while average to longer (late onset and late cessation, positive coefficients) rainy seasons have prevailed in Burkina Faso and Côte d'Ivoire.

Considering the fact that variability in rains has impacts on variability in raw and detrended crop yields, one should wonder about their consequences for the Central West African society and economy. The next chapter addresses these socioeconomic matters and examines the implications of rainfall/crop yield relationships -- how yields could improve under either favorable or unfavorable rainfall amounts. Furthermore, the descriptions of the agroclimatologic histories in Central West Africa, as well as policy responses (colonial to recent decade environmental policies) to ensure accurate seasonal climate forecast (importance of rainfall variability in policy writing) and thus reduce food insecurity are also analyzed in Chapter 5.

CHAPTER 5

SOCIOECONOMIC DEVELOPMENT AND MPLICATIONS FOR RAINFALL VARIABILITY/CROP YIELD RELATIONSHIPS AND ADAPTATIONS

5.1 Implications for Socioeconomic Development

Social and economic impacts of rainfall variability and crop yield variations are critical in determining the economic aspects of Central West Africa. Variations in both rainfall and crop yields are connected to the society and economy via a combination of agricultural and food security responses. Developed for this study, Figure 5.1 shows a relational chart between rainfall, crop yields, society, economy, and sustainable development.

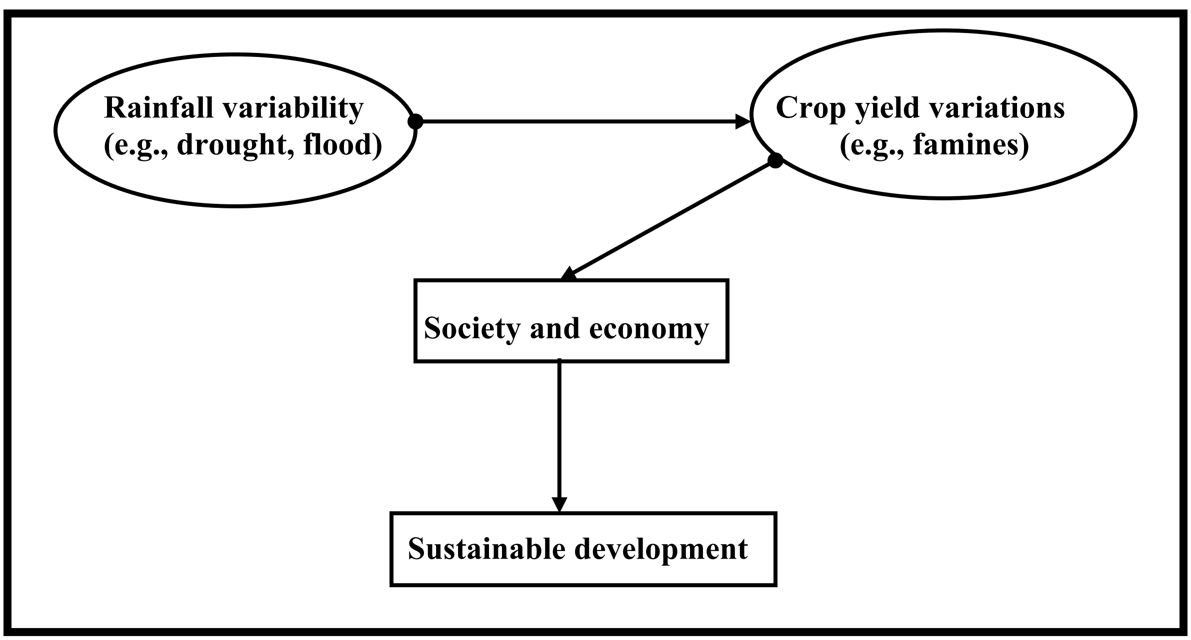


Figure 5.1: Rainfall variability/crop yield relationships and sustainable development (developed for this study).

Rainfall variability, crop yield change, and sustainable development share a cause-effect link (Afgoni, 1979; Guitteye, 1986). The rainfall vagaries/impacts go far beyond the agricultural sector. Indeed, the high spatially and temporarily variable rainfall in Central West Africa is associated with catastrophes including drought, flood, and weather-related outbreaks of pests as well as plant and animal diseases. These variations in rainfall do not always support secure crop yields, leading to strong pressures on the fragile ecosystem, economy, and society to offset the high population demand and the dangers of food insecurity. Here the environmental and socioeconomic problems should be viewed in relation to the degree of the non-mechanized agricultural techniques that limit crop productivity and damage natural resources such as forests and soils (Ministère du Logement et al., 1996). The negative causes that are generally listed in relation to poor cultivation techniques include: (1) bush fire practices; (2) perpetual addition of new lands; (3) shortening of fallow; (4) clandestine infiltration of farmers, loggers, and poachers into classified forests; (5) forest exploitation (e.g., cutting down timber); and (7) wood/fuel gathering for domestic uses (Turner et al., 1990; FAO/UNDP, 1994; Kini, 1995).

There is a feedback effect between socioeconomic development and the decline of natural resources. People overuse the arable lands extensively to solve their persistent impoverishment, hunger, and economic needs. In the process, they sacrifice future needs over present or short-term requirements (Koli Bi, 1992). Certainly, rainfall variability impacts food availability through its effects on water resources and livestock production (e.g., limited access to grasses) (Albergel et al., 1984; Simpara 1987). This worsens the critical food supply (especially in northern Mali/Burkina Faso) and causes conflicts over the distribution of limited arable lands (e.g. southern and central regions of the three countries), shown through the imbalance between high annual rate of population growth and low rate of food production and available lands. The obligation to feed a rapidly growing population has resulted in expanded cultivated areas, an ever-shortening fallow combined with widespread depletion of forests and soil nutrients (e.g., reduction of arable lands and soil degradation/erosion).

Deforestation and desertification, in turn, perpetuate the poverty level because the pressures place on the environment are too great to satisfy the high population needs, but rather contribute to alter the economy and hamper the social progress through disruption of hydroelectric power generation, life-threatening property damages (e.g., road and rail infrastructure destructions), and serious economic activity disruptions (e.g., increased agricultural unemployment). Consequently there is a massive rural population exodus towards major cities, where people are searching for better life opportunities. As, Tarhule and Lamb (2003, p. 1751) noted, West African "cities…are presently experiencing growth rates of 9-11 percent compared to national population growth rates of 2.7-3.2 percent." Rural exodus is linked to high unemployment as well as to urban delinquency growth, which are main contributory factors to both food and human insecurity (Nicholson, 1981; Vermeer, 1981; Guitteye 1986; Sow, 1987; Koli Bi, 1992).

Sustained agriculture and food security through increased crop productivity and environmental preservation are the ultimate goals of Mali, Burkina Faso, and Côte d'Ivoire. According to Glantz (1994, p. 15), there are two basic ways of increasing crop productivity: (1) crop yield increase and (2) cultivated acreage expansion. Although these two faming methods may be used in conjunction, they are rarely combined in

Central West Africa. The first method involves the implementation of new farming methods such as irrigation, use of optimal mix of improved seeds, fertilizers and pesticides, and matching techniques of appropriate crops with rainfall regimes (e.g., water in right quantities and at the right time). These will improve yields on existing fields; however, a critical shortage of any one of these components may result in crop failure. In contrast, the second method is the perpetual search for new croplands (or expansion of existing fields) caused by high population growth rates and the various pressures put on previously fertile lands. The consequences are the extension of agricultural activities into marginal areas and the acceleration of land degradation processes (e.g., overgrazing). Unfortunately, due to the widespread poverty in the study area and other factors such as poor road conditions, the majority of farmers lacks access to the fertilizers and irrigation techniques used in the first method (increasing crop yields). Hence, the second method in which farming is heavily dependent on the vagaries of rainfall is widely applied in this part of the world. Still, there are strategies to understand the interactions between rainfall and crops; attempts to deal with the rainfall variability are ongoing in these countries, where the main coping method is agroclimatology (FAO et al., 1967; Olufayo et al., 1998). The next section presents strategies applied within each Central West African country to limit the impacts of rainfall variability on crop yields drawing upon agroclimatology.

5.2 Agroclimatologic Histories: Adaptive Strategies

The branch of climatology closely related to agricultural production is agroclimatology (FAO et al., 1967). The natural resource depletion that always is linked to rapid demographic growth, arable land scarcity, and irrigation limitations has need of sustained agriculture for sound social progress and economic development. Therefore, strategies that incorporate agroclimatologic knowledge are needed. Figure 5.2, also developed for this Dissertation, portrays the role of agroclimatology for possibilities of increased crop yields in rain-fed agriculture. Figure 5.2 suggests a projected way to promote crop yields, which is one of the ambitious self-sufficient food security goals of Central West African governments. Thus, this agroclimatologic section investigates how rainfall knowledge is employed to assist farming operations such as planting and harvesting. It first discusses the agroclimatologic (or agrometeorologic) histories of Mali, Burkina Faso, and Côte d'Ivoire, based on information gathered from interviews and local unpublished governmental reports provided by visiting the national weather services of the study area. Then it shows how each country copes with rainfall variability in order to evaluate and guide future research needs, techniques, and applications.

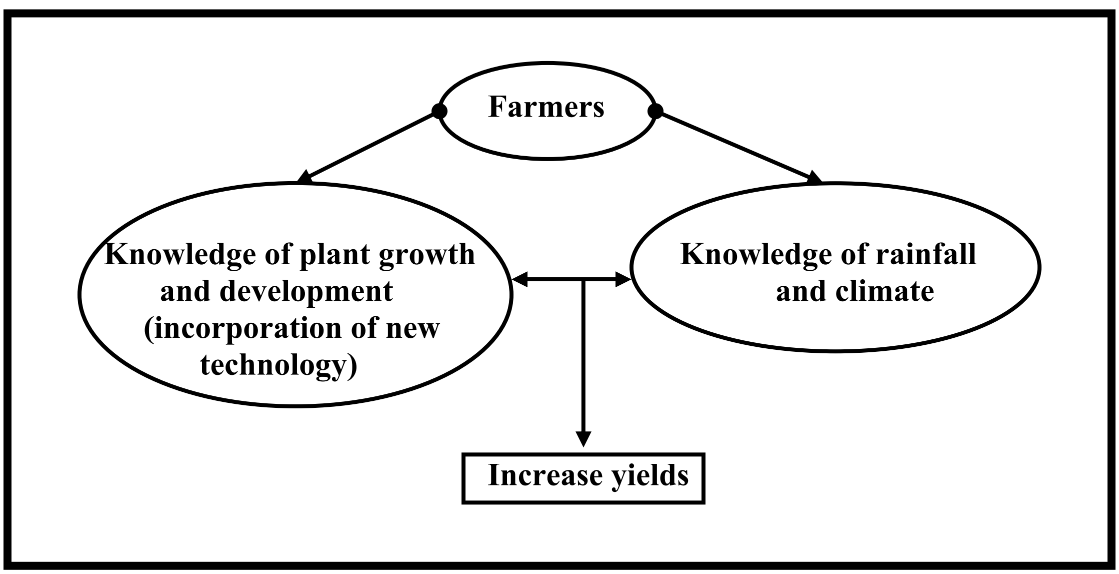


Figure 5.2: Role of agroclimatology in crop yield increase (developed for this study).

5.2.1 Mali

The Malian agrometeorological section, part of Direction de la Météorologie Nationale (DMN), was created within the national weather service in the 1970s during the highly publicized Sahelian drought. Indeed, with the occurrence and persistence of the drought, the farmers lost their ability to effectively use their natural climatic indicators acquired from experiences and observations and needed the use of climatic information to improve agricultural output. The agrometeorological service is subdivided into two subsections: (1) the user operational (or technical) assistance and (2) the agrometeorological experimentation group.

The first subdivision develops and reports climate information bulletins every 10 days. It also broadcasts climate information through proximity radios in all major local languages. The climate information enlightens the farmers and the general public on the important steps of farming activities. For instance, the broadcasts help in the selection of crop varieties, use of improved seeds, and strategies to increase crop yields by avoiding replanting of certain crops due to false start of rains or extended dry spells. The second subdivision, the agrometeorological experimental group, formulates agrometeorological advice about plowing techniques, planting, fertilizer applications, and weeding methods. The instructions also help farmers coordinate the plant-flowering stage (which is more water-demanding) and the rainy season dates when there is likely to be more water. In selected experimental fields, farmers measure the productivity differences between the agrometeorological application fields and the control fields. The agrometeorological division works in collaboration with other services, forming a multidisciplinary team that includes agronomists, soil scientists, and mass media. The goal is to promote self-sufficient food security combined with environmental preservation.

Overall, the Malian practice of agrometeorology registers successes that have boosted the importance and applicability of climatic information. In other words, Mali has responded very well to this agrometeorologic challenge (Tarhule and Lamb, 2003). The successful results also require governmental, non-governmental, and worldwide institutional cooperation and financing. So far the climatic advice is utilized almost everywhere in the country except in the two northernmost dry regions of Tombouctou and Gao because of insufficient funding to develop some dry farming techniques such as irrigation. Thus, the general public in Mali, especially the farmers, relies to a great extent on the rainfall information from the meteorological service to decide on when, what, and how to plant.

5.2.2 Burkina Faso

The Burkinabè DMN created an agrometeorological division in 1975. This section performs three main tasks: (1) data collection (e.g., daily rainfall, temperature, relative humidity, etc.); (2) follow-ups of agricultural campaigns; and (3) preparation of 10-day period reports that summarize climate activities for the country's ten synoptic and twenty agrometeorological stations. In addition, a monthly bulletin is published for the other types of weather stations such as rainfall and climatological stations. The AGRHYMET Center in Niamey (Niger) contributes to the training of the Burkinabè agrometeorologists (like other Sahelian countries). Burkina Faso's agrometeorological division also determines the crop water requirements for different stages of plant growth (e.g., planting, flowering, harvesting) from April to October. However, unlike in Mali, the Burkinabè agrometeorological program lacks extensive experimental fields. So, the Burkina Faso situation is not nearly as strong as in Mali. Indeed, there is also low general public involvement, especially from farmers. Because of low prioritization and financial deficiency, the related agricultural and climatic services neither offer training in the use of climate information to farmers nor check on their farming activities. Furthermore, the agrometeorological division does not undertake the translation of weather forecasts, which are in French, into any of the local languages. Hence, most of the farmers do not rely on climatic information to decide when, what, and how to plant in order to enhance crop productivity.

5.2.3 Côte d'Ivoire

In Côte d'Ivoire, an agrometeorological division was created in 1978 within the SOciété de Développement et d'EXploitation Aéronautique aéroportuaire et Météorologique (SODEXAM), the Ivorian national weather service. From 1978 to 1987, this section did not work directly with the farmers but only through agriculturally related services such as the Agence Nationale d'Appui au Dévelopment Rural (ANADER) that supervise farming activities. Due to the language barrier (more than 70% of the farmers do not speak French, the sole official language), the climatic information (especially rainfall and temperature) is transmitted every 10 days to the farmers through designated local agricultural services. Since 1987, these 10-day climate reports have been less technical to enhance the use of rainfall information by many users. Still, the general public, in particular farmers, do not fully relate to climate information (or even bother to obtain it), which is not mass disseminated and explained in the local languages. Generally speaking, since Côte d'Ivoire did not experience the Sahelian drought as severely as Mali and Burkina Faso, agrroclimatologists and farmers in this country are not well responsive to the agroclimatologic challenge.

Unlike in Mali, the utilization of agroclimatologic information in Burkina Faso and Côte d'Ivoire still needs much improvement to assist crop productivity. These countries need to make greater use of rainfall variability information (e.g., seasonal climate forecasts, use of historical and current rainfall information) to increase agricultural output. Since 1998, annual West African seasonal climate forecast workshops have been held; fortunately these have included Abidjan (Côte d'Ivoire, 1998) and Ouagadougou (Burkina Faso, 2000), where some progress is needed in agroclimatologic application (see Chapter 2, Section 2.2.3). Despite rudimentary technology and low human resource capacity as well as needs for greater applications of historical climate information and use of year-to-date information, efforts should be made to implement the recommendations of the workshops, which focus on the need for consideration of rainfall variability in setting agricultural goals to enhance crop yields and improve the future of agroclimatology (Olufayo et al., 1998).

The overall description of Central West African agroclimatology is an important contribution of this Dissertation because the agroclimatologic histories in Mali, Burkina Faso, and Côte d'Ivoire have never been published. In the next section, the study focuses on the fairly disparate unpublished reports, published governmental documents, and a very few literature on the state of colonial to recent environmental policies in order to reveal the use of rainfall variability in the drafting and practicability of governmental decisions in crop productivity. This section also examines the impacts of environmental policies on crop yields, especially during inconsistent years between rainfall and yields.

5.3 Relative Importance of the Governmental Decision-Making Processes in Agricultural Productivity

As shown in Chapter 4 (Section 4.3), rainfall strongly influences crop yields in Central West Africa in spite of some inconsistent years (weaker positive and negative correlations). Thus, the present section explores how crop productivity and agricultural change may be related to other factors such as human decisions in policy implementations. Indeed, with the worldwide interest in environment and development, establishment of environmental policies, concern, and awareness have increased remarkably. For Central West Africa, inquiries into natural resource utilization versus preservation began with the 1972 Stockholm meeting when the United Nations Environmental Program (UNEP) was created, and have been rising since the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro (Brazil) in June 1992.

Beginning in 1994, the search for socioecologic equilibrium has become a priority in Mali, Burkina Faso, and Côte d'Ivoire, with the creations of ministries of environment, and several related environmental services (e.g., national environmental action plans). These environmental organizations in collaboration with ministries of agriculture support agricultural production and its counterpart, natural resource preservation. Through observations, diagnoses, and analyses of environmental problems, these institutions elaborate policies toward improvement in the uses of Central West African natural resources. The implementation of environmental policies is through collaborative efforts from decision-makers (e.g., politicians, people involved in marketing or investing environmental decisions), scientists, and resource users such as farmers and hydrologists (Ministère de l'environnement et du tourism, 1994a,b; Ministère de l'environnement, 1997).

It is important to mention, however, that Central West African society has been concerned with ecological problems since at least colonial times (e.g., Ibo, 1993; Leonard and Ibo, 1993; Pouchepadass, 1993). The societal and economic decision-making processes in traditional Africa were based on a thorough knowledge of social, demographic, economic, and physical environment factors, as well as on their complex interactions (Kaboré, 1998). This knowledge was acquired through experience and observation, and transmitted from one generation to another. There was almost perfect socio-ecologic equilibrium in this traditional society, which has been disrupted at the beginning of colonial times. Thus, efficient policies now require a synthesis interface between modern cultures, the heritage of Western civilization (i.e., colonization), and African traditional values.

Recent and persistent conflicts between population growth and available resources in this portion of Subsaharan West Africa are apparent through interpretation of historical sources compiled in Ibo (1993), Leonard and Ibo (1993), and Pouchepadass (1993). Indeed, the consequence of prior management of resources helps in understanding the current environmental concerns and problems as well as the actual ecological policies. Here, the past refers essentially to the colonial times; even though there is relatively little documented and dated information, this previous era is important in the administrative and political structure of Mali, Burkina Faso, and Côte d'Ivoire today. Their national boundaries and modern definitions are imprints of the French colonization referred to as Afrique Occidentale Française (AOF), which was created in 1895, reorganized in 1904, and lasted until 1960, when the three countries obtained their independence from France. Since that time, the independent (modern and transformed) Subsaharan West African society has been experiencing an environmental breakdown. The interactions between human activities and the environment have several detrimental consequences demonstrated by the spread of poverty, the systematic clearing of the landscape (e.g., forests, trees), and the exploitative/abusive use of water resources and soils. The environmental impacts vary from one country to another as a function of the resources that have been overused (e.g., forests/deforestation, soil degradation/desertification).

In this Chapter, environmental diagnostics and policies from colonial times to recent decades are reviewed in relation to rainfall variability and crop yields. Themes such as soil degradation, deforestation, agricultural change, and rainfall variability (e.g., droughts and flood) are relevant to policies directed toward improving crop yields and boosting socioeconomic development. The aim is to consider how crop variation may be related to environmental policies. In addition, this section draws on unpublished reports and recent literature to advocate policies to: (1) restore and preserve natural resources as well as encourage rational uses; (2) satisfy population growth and its increasing needs; and (3) mitigate impacts of rainfall variation for sustained agricultural output as well as socioeconomic developments. These environmental policy discussions focusing on Mali, Burkina Faso, and Côte d'Ivoire are mainly based on interviews, unpublished governmental reports, and the following six published documents: Ibo (1993), Leonard and Ibo (1993), Pouchepadass (1993), Ministère de l'environnement et du tourism (1994a,b), Ministère de l'environnement (1997), and Kaboré (1998).

5.3.1 Mali

Based on interviews and reviewed unpublished governmental documents as well as Ministère de l'environnement (1997), the Malian documentation of environmental concerns is relatively recent (i.e., since independence) compared to those of Burkina Faso and Côte d'Ivoire (since colonial times; presented later in Sections 5.3.2 and 5.3.3). Since 1960, Mali has been very sensitive to and interested in its environment and natural resources. The equilibrium of the environment is particularly fragile in areas that suffer frequent and severe alterations in their biotopes (small areas with uniform environments occupied by communities of organisms). Mali belongs to these unstable zones due to its high rainfall variability, annual population growth of 2.97%, annual cultivated land increase of 4.7%, and farming system mainly based on extensive rain-fed agriculture and bush fire techniques (http://www.worldbank.org, 2002). Understanding of the post-1960 actions and policies for natural resource restorations requires a focus on historical nature protection. As mentioned earlier, Malian environmental policy lacks documentation and date references from the former French colony of Soudan, which took the name of Mali in 1960 to express its new identity. Since then, the country has experienced and dated four successive environment-planning periods. Yet was only in the late 1990s that Mali's environmental resolutions began to clearly include rational uses of resources as well as awareness of sustainable socioeconomic development. Figure 5.3 summarizes the different periods of the Malian environmental policies that are further reviewed after the chart.

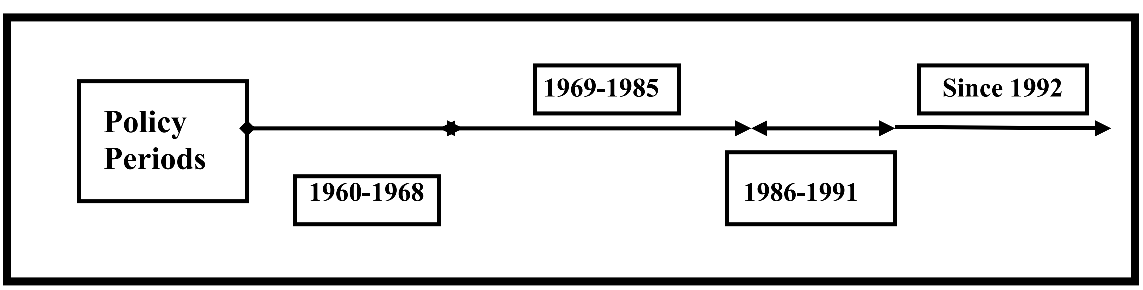


Figure 5.3: Delimitation periods of environmental policies in Mali (see text for sources).

- From **1960 to 1968** (according to unpublished government documents), the environment policies were centralized in government hands and drawn initially for a five-year period (1960-65), but lasted three more years. These policies focused on natural resource preservation, especially of flora and fauna. During this period, the government through the municipality, entirely conceived, elaborated, supervised, and controlled environmental planning.

- From **1969 to 1985** (unpublished government documents), the policies were more localized with the introduction of the concept of regions. Indeed, Mali was subdivided into seven administrative regions (note that these regions are the same agricultural regions delineated in Fig. 3.3 and discussed throughout this Dissertation), with the capital city, Bamako, established as its own district. Again, a five-year execution period was still the target, but this duration was not followed because of the 1970s and 1980s Sahelian drought, during which Mali encountered an economic crisis with a severe decrease of its GNP per capita (i.e., from about $800 US to less than $300 US over 1970-1980), which resulted in an unbalanced macro-economy. Thus, the Malian government started to take into account environmental concerns by expanding actions against desertification in the 1974-1978 plans. Since 1982, a structural adjustment program with a more liberalized capitalist economy has been applied (as opposed to the socialist or communist approach before then). Environmental management and desertification controls were contemplated and enacted as national priority tasks. The authorities encouraged further population involvement and less governmental intervention in economic production sectors. For the natural resources and land degradation remediation, the state adopted in 1985 a desertification control plan, namely the Plan National De Lutte Contre la Désertification (PNLCD), which intensified numerous national/regional resource management initiatives.

- From **1986 to 1991** (unpublished government documents), the policies registered smoother decentralized planning with more flexible investments because the approach continued to emphasize the regional-based efforts. The turning point political events in 1991 (i.e., civilian rebellions, military response or coup d'état, and ultimately installation of a more democratic government) enhanced this regionalization process. Each Malian region gained its own juridical recognition and became in charge of its local or regional economic development.

- From **1992 to present** (data compilation began in 1992 and was published as Ministère de l'environnement, 1997), the remnants of the earlier centralized environment policy system were completely abandoned for a successful regionalized system, though resource degradation processes were and are still going on. After parliamentary ratifications of numerous environmental policies and initiations of several national, regional, and local seminars/consultations, Mali adopted an environmental action plan with an emphasis on desertification control in 1994. This plan is referred to as Plan National d'Action Environmentale/ Programme d'Action National pour la mise en oeuvre de la Convention Internationale de lutte contre la Désertification (PNAE/PAN-CID); its work is conducted by a permanent secretary, a consultant committee, and inter-ministry committees comprising environmental experts, national/international consultants, technical assistants, and ministries dealing with environmental matters (e.g., ministries of rural development, public health, industry, hydraulics, and energy). The context, diagnosis, elaboration, execution, and recommendations of the PNAE/PAN-CID were finally written and published in 1997 (Ministère de l'environnement, 1997). The main goal was to integrate environmental preservation and rational use of resources for sustainable socioeconomic developments. Mali's environmental action plans today retain nine programs that are pursued through several projects:

1. The national territory management program via the Programme National d'Aménagement du Territoire (PNAT) seeks the acquisition of proper tools for sustained management of the environment and the resources;

2. The natural resource management program through the Programme National De Gestion des Ressources Naturelles (PNGRN) plans to reverse and/or eliminate the resource degradation and desertification trends for sustainable social and economic developments;

3. The water resource control program or the Programme National de maîtrise des Ressources en Eau (PNRE) promotes easy access to drinkable water (e.g., clean or running water), appropriate management control (e.g., eradication of polluted water), widespread usage (e.g., agricultural and domestic uses), and continuous utilization;

4. The population living condition improvement program via the Programme National d'Amélioration du Cadre de Vie (PNACV) contributes to the maintenance of life quality and improvement of the peoples' existing situations;

5. The new and renewable energy development program through the Programme National de développement des ressources en Énergie Nouvelles et Renouvelables (PNENR) intends to satisfy energy needs through uses of non-traditional energy sources (e.g., solar energy) instead of the sole consumption of wood fuel;

6. The environmental information program or the Programme National de Gestion des Informations sur l'Environnement (PNGIE) focuses on gathering all reliable environmental information/data and making it accessible to all potential users for better management and care;

7. The environmental information, education, and communication program via the Programme National d'Information, d'Éducation, et de Communication environnementale (PNIEC) contributes to peoples' behavioral changes toward resource uses. It also encourages population involvement toward desertification and land degradation controls as well as preservation of the environment;

8. The follow-up and execution program of environment conventions (international and national) through the Programme National de suivi des CONventions (PNCON) insures the cohesion and execution of all environmental preservation and related fields ratified conventions; and

9. The desertification control and environmental preservation program or the Programme National de Recherche sur la lutte contre la désertification et

la protection de l'environnement (PNR) promotes the functioning of environmental protection research.

Overall, in Mali, the policies and laws drawn in the 1960s were conceptualized without public input or consultation. Because they were too general, the applicability of these environmental policies was not a success at regional and local levels. These policies are often referred to as first generation laws and were updated and reinforced in 1969 with the occurrence of the Sahelian drought. The 1969-1985 policies are referred to as second generation laws and further emphasize the restoration and preservation of natural resources as well as desertification control. Here, there were implementations of fines for policy violations (e.g., clandestine infiltration of farmers, loggers, and poachers into protected zones). In spite of policy reinforcement and improvement, the applicability of second generation laws was a failure as evidenced by insufficient local population participation and the continual elaboration of new policies. The late 1980s to the early 1990s policies, or the third generation laws, were less authoritarian and more flexible, and they promoted improved environmental techniques at more local to regional levels. They also encouraged input and involvement from local populations. Since 1995, Mali has renewed and refined all of its earlier environmental concerns and policies (e.g., desertification control). This contributes to better responses to the needs of local population by adapting environment planning to regionalization procedures. The period 1992-1997 registered a global funding increase (grants) for environment protection with the endorsement of the United Nations desertification programs, Convention des Nations Unies sur la lutte Contre la Désertification (CCD). Currently, Mali also plans to create a national environmental fund (Ministère de l'environnement, 1997).

Thus, Malian environmental policies always have followed ratifications of regional and international environmental preservation agreements and participation of non-governmental organizations. The plans went from a centralized focus to regional interests, but all of them followed the same goals promoting rural environment development. Five points were raised: (1) self-sufficient food security; (2) accessibility to potable water resources in both rural and urban settings; (3) control of the desertification phenomenon; (4) development of animal resources; and (5) reduction in the isolation of the northern regions of the country.

Among the nine environmental programs of the last policy period summarized above, only the first four programs are relevant to this study -- the problems of sustained resource management, resource degradation/desertification, agricultural water utilization, and socioeconomic development. Thus, acreage, production, and yields for major cash (cotton and peanuts) and staple crops (millet and sorghum) were compared in Chapter 4 (Fig. 4.17*a*, top two rows and Table 4. 17*a*) to suggest that in Malian, smallest and largest values are more distinct for cash crops, especially cotton. The cash crops display both exponential (e.g., cotton) and linear (e.g., peanuts) increasing trends for acreage and production during the overall study period or subperiod, while their yields decreased. All crop parameters dropped below the long-term mean in 1989, 1993 for cotton and in 1968, 1993 for peanuts. Millet and sorghum also increased linearly for acreage and production during the overall study period or subperiod, while their yields decreased. The crop parameters also dropped below the long-term mean in 1987, 1992, 1995, and 1997 for millet, while production and yields decreased in 1990 and 1992 for sorghum despite increased acreage. It is interesting to focus on how crop yield data in Mali relate to the peak events in the Malian environmental policies that have already been presented above. Due to the lack of complete crop data before 1966, only the last three policy periods (i.e., 1969-1985, 1986-1991, and 1992 to present) are considered in terms of their impacts on crop data and variations:

1. The **1969** policy subdivided the country into regions, which explains why the agricultural data collected for Mali are aggregated at a regional level after this year. However, the economic consequences of the beginning of the Sahelian drought in the late 1960s disrupted the gathering of crop records from 1968 onward, a problem that persisted until to 1984 (see Tables 3.6*a* and 3.7*a*);

2. The **1974-1978** policies focused on actions against desertification during the midst of the Sahelian drought. Therefore, crop data were not a priority and complete figures were not collected (see Tables 3.6*a* and 3.7*a*);

3. The **1982** policy concerned itself wholly with structural adjustment plans, so complete crop data were still missing (see Tables 3.6*a* and 3.7*a*);

4. The **1985** policy focused on the PNLCD, an improved desertification control program in order to reverse the trends of decreasing crop yields (data collection of which had been reinstated), which fortunately registered a slight increase in spite of the persistent Sahelian drought (see Fig. 4.17*a*, top two rows);

5. The **1991** policy coincided with the installation of a democratic government. For the cash crops, acreage and production increased/yields decreased in this year, and inversely, for staple crops, yields and production increased/acreage decreased

in 1991 (see Fig. 4.17*a*, top two rows). This situation emphasized a self-sufficient food security program, in which the government prioritized the need for more inputs (such as fertilizers) to increase the yields of staple crops; and

6. The **1992-1997** policies led to seminars and implementation of the PNAE/PAN-CID. However, yields decreased, while acreage and production increased during 1994-97 (see Fig. 4.17*a*, top two rows) for all crops. The staple crops of millet and sorghum, which are the foundation of the country, should have been more sensitive to policy implementation than do the cash crops because they are the basis of Malian self-sufficient food security goal.

In conclusion, the Malian environmental policies show the 1960s as a time of regionalization, which structured all subsequent crop records. The 1970s through the mid-1980s focused more on adapting to the Sahelian drought than on tracking crop parameters of acreage, production, and yields. After the mid-1980s, a renewed interest in self-sufficient food security has brought with it a focus on data collection and improved agricultural policy-making that was implemented to the extent of attempting to boost staple crops.

5.3.2 Burkina Faso

A review of primary and secondary environmental literatures (unpublished governmental documents; Ministère de l'environnement et du tourism, 1994a; Kaboré, 1998) reveals that concerns and policies for the preservation of the environment in Burkina Faso can be traced all the way to 1935. The policies have evolved in four different phases: 1935-1973, 1974-1978, 1979-1993, and post-1994. Figure 5.4 reviews the Burkinabè environmental policies that are further explored after the chart.

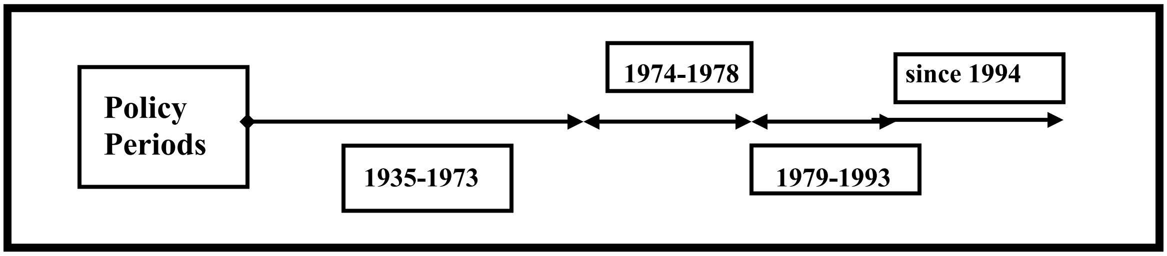


Figure 5.4: Delimitation periods of environmental policies in Burkina Faso (see text for sources).

- From **1935 to 1973** (according to unpublished government documents), the policies primarily focused on the protection and classification of forests. These policies were established during the colonial times, persisted during and after independence (in 1960), and remained until the early 1970s. Few land areas were brought under cultivation because of the belief that nature would regenerate itself if humanity did not alter natural productivity. Therefore, during this period, there were more protected areas than cultivated lands. However, with the occurrence and persistence of the Sahelian drought since 1968, which also coincided with a rapid population increase reaching a 2.64% growth rate in 2002 (http://www.worldbank.org, 2002), new attitudes were adopted toward the resource protection policies that the people had never respected. The policies were reinforced with introductions of fines and penalties against violators (i.e., farmers, loggers, poachers) of protected areas. Also, during the beginning drought period, decision-makers encouraged public participation in the establishment of the policies.

- From **1974 to 1978** (unpublished government documents; Kaboré, 1998), the policies centered on reforestation conducted through the ambitious program of creating industrial plantations (the area size was not rigorously documented). The forest ecosystem destruction was mitigated by replacing the degraded vegetation with planted wood and by minimizing or eliminating the pressure on trees while still providing wood fuel to the population. Unfortunately, the reforestation project was not achieved because it was undertaken with a mindset that (human-induced) deforestation and (partly climate-induced, partly human-induced) desertification were sporadic phenomena. Further, these forest plantation programs were too costly (e.g., around $500 US per hectare) and started without any practical population involvement (Kaboré, 1998). Finally, even though the few industrial plantations actually developed were located in rural lands, the output (e.g., timber, wood/fuel) was mainly intended for urban population domestic uses.

- From **1979 to 1993** (unpublished government documents; Kaboré, 1998), the policies focused on the emerging rural forestry program that was completed in 1986. The program involved the population in desertification control programs through afforestation via the Plan National de Lutte Contre la Désertification (PNLCD). Yet years later, especially after the Rio de Janeiro environmental conference in 1992, the PNLCD was regarded as a failure. Indeed, the land/soil degradation processes were not eliminated or altered and, further, the program did not emphasize socioeconomic development. Therefore, newer environmental problems were identified and policies were defined and adopted. This led to the writing of Burkina Faso’s national environment action plan, referred to as the Plan d’Action National pour l’Environnement (PANE), in April 1994.

- From **1994 to present** (data compilation began in 1992 and was published as Ministère de l'environnement et du tourism, 1994a), the policies have centered on the implementation of the PANE, the objectives of which are to arrive at a socio-ecologic equilibrium involving both a sustainable environment and socioeconomic development. The aims of the PANE include: (a) diagnosis and control of environmental pressures; (b) resource regeneration and biodiversity protection; (c) improvement of the socioeconomic status of the population; and (d) sustainable development. The PANE is conducted through the following five human and biophysical environment programs, in which the first three are classified as major programs, while the last two are considered as minor ones:

    1. Management of natural resources (e.g., classified forests, lakes, and mines) program, or the Programme Cadre pour la Gestion des Patrimoines Nationaux (PCGPN). The PCGPN's goals include: (a) deforestation and desertification control; (b) water resource preservation; (c) biodiversity (e.g., flora/fauna) protection; and (d) rational use of natural resources (e.g., soils, water, and forests) that satisfies the needs of the growing population;

    2. Management of rural land with more involvement from the local population via the Programme Cadre de Gestion des Terroirs (PCGT). This program aims to reorganize Burkina Faso into administrative regions. The PCGT intends to enhance the rural community responsibilities (management/participation) and revise the texts/laws related to the rational uses of natural resources, distributions, and land ownership security;

3. Improvement of rural/urban living conditions through an appropriate investment program, the Programme Cadre d'Amélioration du Cadre de Vie (PCACV). The purpose of this program is to motivate and strengthen individual and collective rural/urban population management for a safe and sound environment and to induce adaptive infrastructure investments;

4. Development of human and technological environmental competency program through education, training, research, and conveyance of opportune attitudes toward the environment, or the Programme de Développement des Compétences en Environnement (PDCE). The PDCE program mobilizes the abilities of human resources and the capabilities of improved and adapted technologies; and

5. Management of environmental information program includes database, experiences, and knowledge, referred to as the Programme National de Gestion de l'Information sur le Milieu (PNGIM). This program is concerned with better systems of data collection, treatment, analysis, and diffusion of information.

In addition, a governmental council, or the COnseil NAtional pour la GEStion de l'Environnement (CONAGESE) controls the PANE program, the main role of which is to integrate environmental concerns, local cultures, and socioeconomic developments. The CONAGESE aims to fulfill the following four tasks: (a) create and enhance collaborative efforts between scientists, institutes, and ministries that work on natural resource management or related fields (e.g., agriculture, water resources, rural development); (b) coordinate all of the different environmental management or related actions; (c) encourage the involvement of the population in environmental projects/policies; and (d) endorse the applicability of environmental policies and legislation.

Overall, in Burkina Faso, the local people viewed policies from colonial times to the first thirteen years of the country's independence (i.e., 1935-73) as authoritarian or repressive laws. These policies were regarded as a continuation of colonial domination, rather than environmental preservation, because most of the protected areas were guarded. Though these policies had some advantages of keeping resources relatively safe and intact, it was difficult for the public to respect them, especially after the occurrence of the Sahelian drought. Indeed, with the rapid degradation of authorized (unclassified) lands due to increased population, there was an urgent need for new croplands. Hence, the government had to readjust the entire natural resource preservation policy in 1974. However, the 1974-1978 policies did not clearly emphasize the improvement of agricultural output. Accordingly, the main goals of the 1979-1993 policies were the reconstruction of destroyed ecosystems and the protection of the remnant of classified forests. These objectives also encountered the increasing need for arable lands. Therefore, the 1979-1993 policies also failed. In the last policy period (1994 to present), the CONAGESE elaborates, supervises, and coordinates natural resource management strategies and actions. These tasks occur in domains such as: (a) desertification control; (b) forests, fauna, and fishing (e.g., satisfying fuel wood and plant/animal protein needs, while preserving the biodiversity); and (c) water resources (i.e., knowledge of availability and priority uses).

From Burkina Faso's colonial times to its recent policies, the PANE programs (i.e., 1994-present) are those most pertinent to this Dissertation. However, only the first and third PANE policy programs are significantly applicable to this study's agricultural and socioeconomic aspects as this research is interested in policies that enhance crop output and lead to sustainable socioeconomic development. Thus, the trends of crop acreage, production, and yields (see Fig. 4.17*a*, bottom two rows and Table 4.17*a* in Chapter 4) for the Burkinabè cash and staple are compared to related policy periods.

Since the crop data start in 1970, comparative analysis takes into consideration all of the policies. A summary of the graphs in Chapter 4 (Fig. 4. 17*a*, bottom two rows) shows that cotton, peanuts, millet, and sorghum show strong variations, with all of their parameters recording smaller values from 1970 to the mid-1980s and larger values thereafter. Cotton registered exponential and linear trends for acreage and production, while its yields decreased. Peanuts and the staple crops of millet and sorghum recorded linear increases for all crop parameters. The cash crops of cotton and peanuts decreased in 1977 and 1980 with additional decreases in 1992-93, 1995 for cotton and 1984, 1987, 1991 for peanuts. Both millet and sorghum declined in 1971, 1987, 1990, and 1997, with additional decreases in 1992, 1995 for millet and 1980 for sorghum. Like Mali, it is interesting to compare peak environmental policy events to crop variations in Burkina Faso:

1. The **1970** policy of forest classifications provided less lands for agriculture; therefore, decreased acreage caused decreases in production and yields for all crops with values smaller than the long-term mean values (Fig. 4. 17*a*, bottom two rows);

2. The **1974-1978** policy focused on industrial plantations, which coincided with the latter part of the most severe period of Sahelian drought during the 1970s. The staple crops were missing the years 1974-75, while acreage, production, and yields either increased or decreased, simultaneously, but in smaller value ranges for the cash crops (Fig. 4. 17*a*, bottom two rows);

3. The **1986** policy centered on the PNLCD, a rural forestry program to alleviate the impacts of desertification (reducing soil degradation and erosion). Thus, crop yields increased accordingly, especially for cotton, peanuts, and sorghum; and

4. The **post-1994** policy centered on the PANE program. Since 1994, each crop registered a unique trend: cotton (acreage and production increased, while yields decreased), peanuts and sorghum (acreage increased, while production and yields decreased), and millet (all parameters decreased; see Fig. 4. 17*a*, bottom two rows).

During the peak events of policy periods, each of the Burkinabè cash and staple crops showed a changed pattern; therefore, it is obvious that agriculture is implicitly related to environmental policies. Even though the outcome shows that the policies put more emphasis on environmental protection/preservation than on increasing crop yields, each policy event impacted both staple and cash crops. However, the PNLCD and PANE programs, which cover most of the crop data years, do not identify clearly the role of environmental policies in meeting the country's self-sufficient food security goals.

5.3.3 Côte d'Ivoire

Ibo (1993), Leonard and Ibo (1993), Pouchepadass (1993), and Ministère de l'environnement et du tourism (1994b) revealed that Côte d'Ivoire has always been concerned with environmental protection. However, since colonial times, the Ivorian economy has mainly been based on the exploitation of forests and their numerous agricultural uses (e.g., timber, coffee, and cocoa). The protection of vegetative cover, the key environmental element, always has been of great concern, and the forestry policies can be subdivided into three main phases: (1) from 1900 to 1959 (during colonial times); (2) from 1960 to 1993 (after independence); and (3) from 1994 to present (following the influence of the Rio de Janeiro conference in 1992). Figure 5.5 summarizes the different periods of the Ivorian environmental policies that are also further discussed after the chart.

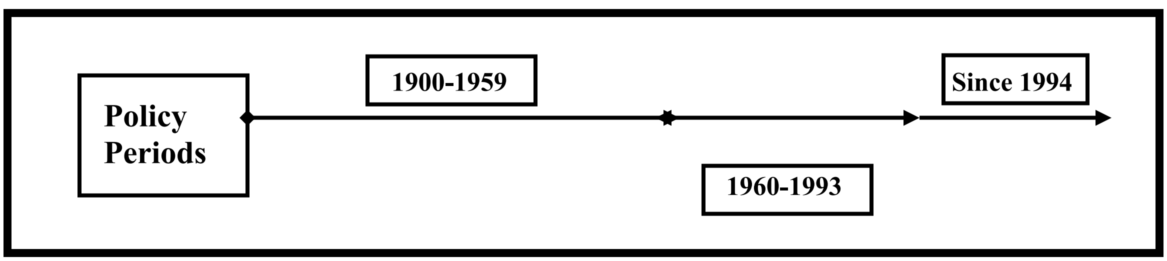


Figure 5.5: Delimitation periods of environmental policies in Côte d'Ivoire (see text for sources).

- From **1900 to 1959** (Ibo, 1993; Leonard and Ibo, 1993; Pouchepadass, 1993), the policies promoted large forest classifications and preservations under the French colonial administration. The 1900 forest legislation confirmed the French governor's absolute control over the classified lands and even on the future uses of those lands that were already exploited. In fact, this law considered the public domain as the exclusive property of France, and such "protection" rules were applied to several areas in the southwestern and northeastern portions of the country. In 1912, there was the creation of a forestry service headed by a French governmental water and forest service administrator, who controlled and regularized all of the classified forests. Theoretically, the forest classification was viewed as preservation of biodiversity and fauna species, but in fact the lands were reserved for the future use of the colonial administration (as evidenced by the inheritance/legacy of colonial plantations). In policy applications, areas around the classified forests were usually left inaccessible to prevent any illegal penetration by the local people (especially farmers, loggers, and poachers) without the colonial administration's permission or control. This forest legislation was modified in 1935 to a forest code that was used even after the country's independence (1960) from France, lasting until the year 1965 (i.e., next policy period). The forest code defined four types of exploitation: (1) state or local government control; (2) temporary non-governmental exploitation permit; (3) cutting down trees for sale or exploitation for sale purpose; and (4) cutting down trees for local exploitation for domestic consumption. The environmental legislation also included the control of hunting activities and the creation of a forest institute in 1940, the Ecole Forestière de l'AOF.

- From **1960 to 1993** (Ibo, 1993; Leonard and Ibo, 1993; Pouchepadass, 1993), the forest was still the major economic source of income. The newly independent country pursued the legacy of the colonial forest protection with some new rules, such as land use and land ownership laws (i.e., the timber exploitation license or the Permis Temporaire d'Exploitation (PTE) and the cash crop, especially coffee and cocoa farming laws) in order to control and regulate all exploited lands. Indeed, influenced by the cash crop inheritance from colonial times, the Ivorian government introduced relatively modern farming technology such as pesticides, fertilizers, and agricultural machinery to assist and enhance cash crop and timber exploitation. The intensive and abusive uses started with the unclassified forests, and thereafter extended to the classified landscapes or the permanent domains of the government (former colonial domains). This agriculture intensification led to a rapid depletion of both the unclassified and formerly classified forests. Therefore, the forest landscape has rapidly diminished from 15 million hectares at the beginning of the 20th century to 12 million hectares in 1960 (at independence) then from 6 million hectares in 1975 to about 2.5 million hectares in 1990 (MAB, 1982; Ministère de l'Agriculture et des Eaux et Forêts, 1984; and Banque Mondiale, 1992). In order to prevent and control further forest depletion, the SOciété d'état pour le DEveloppement des plantations FORestières (SODEFOR) was created in 1966. The role of this national forestry office was to prevent and alleviate/eliminate the land degradation process through stronger reforestation policies, which at that time concerned 300,000 depleted hectares hopefully supplemented every year by at least 10,000 hectares. By the end of the 1980s, the SODEFOR actions were deemed a failure because they were only capable of planting 80,000 hectares compared to the total deforested area, estimated at 500,000 hectares in the same period (end 1980s). So, the government redefined its policies with the creation of environmental ministries aided by international and regional institutions such as the World Bank and the African Development

Bank. The revised/new forest plan is the Plan Directeur Forestier (PDF) program, which targets the period of 1988-2015. SODEFOR is still the executor of this program. It creates a peasant consultation forum via the Commission Paysans-Forêt (CPF) to control the illegal or clandestine occupation of the classified forests, the uses of bush fire practices, and to encourage the participation of the rural population in policy application.

- From **1994 to present** (data compilation began in 1992 and was published as Ministère de l'environnement et du tourism, 1994b), the Ivorian environmental context, diagnosis, and strategies were presented in the 1994 Plan National d'Action pour l'Environnement-Côte d'Ivoire (PNAE-CI) report, which was the first widely publicized environmental action plan book, also referred to as the livre blanc de l'environnement or white book. The PNAE-CI is headed by the Prime Minister and coordinated by the Ministry of the Environment and Tourism (then one department, now divided into two separate ministries). The ministries supervise the regional/departmental commissions, composed of both national and international interdisciplinary consultants. Governmental and international institutions, such as the World Bank, fund (through grants/loans) the PNAE-CI, which focuses on the following eight major programs:

  1. The objectives of the agriculture and natural resource maintenance (e.g., forest, soil, biodiversity protection) program are to enhance food security and to create a sustained agricultural development combined with a preserved forest landscape;

2. The industry, energy, transportation, and tourism (e.g., pollution, nuisance, waste control) program aims to eliminate any form of industrial nuisances through rational mining extraction, control of energy demand, and development of renewal energies (e.g., solar energy);

3. The urban environment degradation program seeks to control the urbanization rate and planning, the eradication of precarious habitations and improvement of living conditions (e.g., access to running water), and the refinement of town councils (i.e., management that integrates population accountability and collectivity participation);

4. The population growth, poverty, and health department programs control the increased pressure on resources and degradation of the environment;

5. The lack of a national environmental information and follow-up system of integrated environmental, social, and economic policy gave rise to a program that involves data gathering, treatment, and diffusion of information to the public;

6. The education, training, and research programs are considered emergency tasks for a global and integrated environmental policy (e.g., environmental awareness of rural women, qualified educational materials);

7. The community participants, the judiciary, and institutional programs are intended to focus unclear projects and to avoid overlapping skills; and

8. The program that addresses sector-based policies, structural adjustment, poverty, and environmental planning aims to enhance each activity sector research.

Overall, in Côte d'Ivoire, the colonial resource protections (1900-1959) were more for retaining forests for future colonial administration use than for resource preservation. Indeed, the cash crop and timber exploitation practices (mainly by the colonial administration) soon overcome intense domain classification in the late 1940s. Cash crop and timber induced more pressure on natural resources (especially, forests) than staple crop cultivation practiced by local population. In other words, cash crop/timber exploitations (inherited from colonial times) were essentially speculative and therefore, were more destructive than staple crop farming, which imposes more rational uses (e.g., less acreage is used since it is usually confined to family activities). Consequently, the colonial policy of natural resource protection met opposition of local peoples because they viewed it as unfair (because they were excluded) and another example of the French administration's desire to exploit larger domains and keep most of the lands for itself.

Similarly, deforestation and agricultural expansion (1960-1993) are the results of the increasing preoccupation of the Ivorian government with international cash crop trading (legacy of colonial times) that were promoted and done by both the Ivorian government and Individual Ivorian and foreign (especially French and Burkinabé) speculators. The question is how compatible really are classified forest practices, traditional farming practices, and high economic goals. Is the farmers' required adherence possible if they are both users and protectors of classified landscape? For instance, the bush fire control commission, created with the required support of the farmers, is a failure because the slash and burn practice is the only "efficient and handy" tool of virgin land clearance for most farmers (i.e., because of lack of individual tractors or other forestry and agricultural machinery). The implementation of agro-forestry might have led to interesting results, but once again it was a costly project and without any government grants/loans the local people could not participate efficiently. Now the critical problem is not just to solve the environment and socioeconomic interdependence difficulties, but also to develop rational uses for sustainable development.

After preliminary national and regional seminars, as well as international conferences since 1992 (e.g., the 1992 Rio de Janeiro environment and development conference), in 1994 the Ivorian government created the Conseil National de l'Environnement (CNE, a national environmental counsel) and the PNAE-CI (a national environmental action program). The CNE develops the policies and strategies, and organizes national environmental dialogues between the authorities, professional and scientific institutions, and non-governmental organizations. The PNAE-CI, on the other hand, checks on the policy coherence, controls adequate management tools, and searches for sponsors to fund (grants/loans) projects or programs. The strength and originality of the PNAE-CI (compared to the first two policies: 1900-59 and 1960-93) lie in its subdivisions into regional and local action plans. Each region develops its own environmental questions because a global (or national) action plan may overlook problems dealing with specific regional concerns. Therefore, this Dissertation relates more to the PNAE-CI policies (i.e., 1994 to present), specifically to the first program, and, to a lesser extent, the fourth program. Indeed, these two programs focus on the relationship between agricultural sector improvement and socioeconomic development.

Unfortunately, the dynamism of crop production is induced essentially by acreage expansion (see Chapter 4, Tables 4.17*a*,*b* and 4.18). This has led to increased pressure on the cropland, causing severe damage, as shown by the remarkable soil degradation and depletion of forests, going from 12 to less than 3 million hectares in 30 years (Ministère de l'Agriculture et des Eaux et Forêts, 1984). The socioeconomic perturbations are noticeable in the increased poverty, rapid annual population increase reaching a 2.45% growth rate in 2002, a decreased GDP per capita from US $1,550 in 1965 to US $630 in 1980 and back to US $1,550 in 2001 (http://www.worldbank.org, 2002). Further, the demographic increase explains the fallow shortening, the perpetual addition of new croplands, and the clandestine penetration of farmers, loggers, and poachers into classified forests. In addition, since 1986, the cash crop price crises have worsened the impoverishment of rural populations. The governmental solution is the progressive redeployment into the cultivation of staple crops, the GDP contribution of which increased from 13.6% (1986) to 22.6% (1991), as compared to the cash crops, which declined from 13.5% to 9.6% during the same period (Banque Mondiale, 1992). However, cash crops and cutting down timber still play major roles in the Ivorian economy.

Here also, the trends of acreage, production, and yields of the Ivorian cash/staple crops in Figure 4.17*b* and Table 4.17*a* (see Chapter 4) are compared to environmental policy periods. Figure 4.17*b* demonstrates that in Côte d'Ivoire, the relationships among crop parameters vary from one crop to another and the smaller values are more apparent for coffee and maize, while the larger values are more distinct for cocoa and plantain. The Ivorian crops show a linear increased acreage and production during the overall study period with decreased yields for cocoa and plantain, slightly increased acreage and fluctuating production with decreased yields for coffee, and all parameters increased linearly for maize. Each of the cash crops registered above the long-term mean values in 1988-1998 (particularly for cocoa acreage) and 1960, 1965, 1967, 1970-1972, 1980 (particularly for coffee yields). Maize's yields registered above average values in 1980-1983, 1996-98, while its production increased progressively to reach largest values in 1997-1998. Plantain was above the mean in 1948-50, 1952, 1957, 1996-98 (yields), and in 1975-1980, 1982, 1986 (acreage). Like Mali and Burkina Faso, it is interesting to detect how variations in crop parameters relate to environmental policies. Based on the length of crop records, all of the three policies are considered.

1. The **1900-1959** forest classification policies promoted more classified forest areas than croplands. Colonial forest plantations dominated farming activities in which acreages of cash crops likely increased more linearly than acreages of staple crops (Fig. 4.17*b*). Cash crop yields also increased and this situation was due to a favorable undamaged environment combined with agricultural inputs, such as fertilizers that were used (for mainly cash crops);

2. The **1960-1993** policies pursued the land use and ownership laws and the creation of SODEFOR (1966) in order to control/eliminate the deforestation phenomenon. With the government's economic goals that supported cash crops, the SODEFOR

registered a failure as evidenced by increased acreage of cocoa and coffee to enhance crop productivity (Fig. 4.17*b*); and

3. The **1994 to present** policies focused on the PNAE-CI program. During the same time, only crop production (as opposed to acreage and then calculate yields) was mainly recorded (Tables 3.6*c*, 3.7*c*, and Fig. 4.17*b*). This situation was largely due to the economic crises (i.e., drop of cash crop prices since 1986), which led the government to be more interested in only recording total crop production to monitor its self-sufficient food security goal (i.e., be able to feed an increasing population).

In Côte d'Ivoire, there are clearly increasing acreage for both cash and staple crops since the late 1940s. These confirm that both the colonial administration (France) and the Ivorian independent government have focused more on cash crop cultivation than on resource protection. However, the forest depletion worsened after the independence. Indeed, in 1965, only 6% of the Ivorian territory was cultivated. This percentage almost doubled by 1975 (11%) and reached 23% in 1989. The deforestation rate was around 250,000 hectares a year for the period 1965-1991, which was much greater than the average annual reforestation of 5,000 hectares (Banque Mondiale, 1992). Consequently, the policies did not impede either the increasing population-intensive crop cultivation or the development of large governmental cotton, cocoa, and coffee plantations.

5.3.4 Summary of the Relationships between Natural Resources and Environmental Policies

Like elsewhere, the environmental problems of Mali, Burkina Faso, and Côte d'Ivoire relate to human activity-based sectors such as forestry, agriculture, water resources, pollution, and waste control. More specifically, in Central West Africa, the concepts involve agriculture, which is the main economic parameter. The concerns about and awareness of the general population involvement in present and future rational farming activities is a valuable aspect. The colonial environmental interests functioned as a satisfaction of the imperialist expansion rather than preservation of natural resources. The resources were protected by a conqueror ideology, which turned them into object of appropriation and speculation. In the process, there were clearances of virgin lands for cultivation or pastoral purposes. During their first years of independence, the governments of Mali, Burkina Faso, and Côte d'Ivoire pursued and/or enhanced the colonial-time policies. Despite some improvement in these policies, independent Central West Africa still experienced an environmental breakdown due to its perpetual search of new croplands and its poor agricultural techniques.

Until the beginning of the 1970s, the national objectives were still to increase crop yields without clear plans to incorporate inputs such as fertilizers and pesticides in order to have higher production over not much increase in acreage, for especially cash crops in Côte d'Ivoire and for staple crops in Mali and Burkina Faso. During the late 1960s and mid-1980s, there was introduction of reforestation practices to overcome the negative impacts of the Sahelian drought combined with abusive use of natural resources resulting from deforestation, desertification, population growth, and cash crop price decline.

However, clear environmental engagement as well as organized diffusion of environmental protection (seminars, workshops, local radios, etc.) in these countries started only in the mid-1990s, with the development of each county's national environmental action plans promoting the rational uses of natural resources, which conclusively contribute to sustainable socioeconomic development. Therefore, the environmental policies were again updated and improved after 1994.

Indeed, the most recent national environment action plans were implemented in 1994 for Burkina Faso and Côte d'Ivoire, and in 1997 for Mali. These action plans are interdisciplinary works incorporating opinions of collaborative sources. Therefore, the importance of these environmental action programs in governmental decision-making processes should be beyond question, since the governments participated in the conceptions and elaboration of the project. Attempts to impose control before the recent action plans were sporadic and somewhat ineffective; now, each country's policies clearly state the challenges to be addressed. For vigorous and sustained socioeconomic growth, the impacts of these irrational resource uses must be resolved and include: (1) collection, treatment, analysis, and storage of a reliable database; (2) population education, training, and involvement in the rational uses and preservation of resources; and (3) improvement of living conditions for both urban and rural peoples. Since Central West Africa is very agriculturally oriented, more emphasis is placed on the last updated environmental policy (1994 to present). Note that 1994-1998 is the overlapping comparative period between crops, rainfall, and policies for all countries. Table 5.1 presents the years spanning 1994-1998 when rainfall indices and crop yields do not share the same patterns of below or above the overall study period mean (extracted from Table 4.19*a*,b in Chapter 4) in order to set up further analyses in relation to the last policy period described above for the tree countries.

Table 5.1: Summary of the temporal relationships between annual rainfall indices and raw/detrended crop time series for Mali, Burkina Faso, and Côte d'Ivoire during 1994-98 (counterpart of bottoms of Tables 4.19*a*,*b*, but for 1994-98). Years of inconsistent rainfall/crop yield relationships are denoted as A (rain is above the mean, yields are below the average national value or long-term average value), B (rain is below the mean, yields are above the average national value or long-term average value), and C (no inconsistent relationships).

RELATIONSHIP		MALI	BURKINA FASO	CÔTE D'IVOIRE
RAINFALL INDICES Versus RAW CROP SERIES	Cotton vs. Rainfall	**A** = 1994,96-97	**A** = 1994 **B** = 1997-98	**A** = 1994-96 **B** = 1997-98
	Maize vs. Rainfall	**A** = 1994-95	**A** = 1995 **B** = 1997-98	**B** = 1997-98
	Rice vs. Rainfall	**C**	**B** = 1997-98	**B** = 1997-98
RAINFALL INDICES Versus DETRENDED CROP SERIES	Cotton vs. Rainfall	**A** = 1994,96-97	**A** = 1994-96 **B** = 1997	**A** = 1994-96 **B** = 1997-98
	Maize vs. Rainfall	**A** = 1994-95	**A** = 1995 **B** = 1997-98	**B** = 1997-98
	Rice vs. Rainfall	**A** = 1994-95,97	**A** = 1994-95 **B** = 1998	**B** = 1997-98
POLICY (1994 to Present)		No obvious relations. Despite above average rainfall, crop yields decreased.	Despite above average rainfall in 1994-96, crop yields decreased. Yields increased in 1997-98 in spite of below the mean rainfall	Despite above average rainfall in 1994-96, crop yields decreased. Yields increased in 1997-98 in spite of below the mean rainfall

As shown in previous analyses (Section 5.3.1-5.3.3) and reinforced in Table 5.1, environmental policies in Central West Africa do coincide with changes in crop yields (as evidenced by isolated years that were singled out). The last policy period was established in 1994 for Burkina Faso and Côte d'Ivoire, and in 1997 for Mali. For Burkina Faso and Côte d'Ivoire, during the first two years (1994-96) of policy implementation, crop yields decreased in spite of above average rainfall. In both countries crop yields increased in 1997-98 despite below the mean rainfall. For Mali, policy was only published in 1997 and crop yields decreased during 1994-1997 in spite of above average rainfall. It is not evident to explain the discrepancy years between rainfall and crop yields using environmental policies because surprisingly, none of the successive environmental policies (from colonial times to present) reflect the participation of climatologists or meteorologists. The few policy references to climate have been implicit and usually linked to variables such as desertification or drought controls. Since these countries are fully aware of the fundamental role of rainfall in rain-fed agriculture (above 80%) in which life revolves around the occurrence or non-occurrence of rainfall, it is therefore a real deficiency not to take into consideration the rainfall variation. With the rainfall variability and crop yield relationships being addressed in this study, recommended policies that deal with rainfall variability and crop yields are presented in Chapter 6.

CHAPTER 6

REMARKS, CONCLUSIONS, AND RECOMMENDATIONS

6.1 Remarks and Conclusions

The environment of Central West Africa reflects how humankind uses it, values it, and disrupts it. Like most developing countries, natural resources have been overused in the study area. This misuse of natural resources has resulted in problems associated with: (a) rainfall variability, (b) agricultural changes, and (c) socioeconomic development. Thus, this study has examined rainfall, agriculture, and socioeconomic aspects in Mali, Burkina Faso, and Côte d'Ivoire during recent decades from 1930 to 1998. The relationships between rainfall and crop yields were analyzed to evaluate the socioeconomic impacts of rainfall variability and agricultural changes for each country.

6.1.1 Rainfall

Rainfall was studied to provide insight into the magnitude of drought or flood conditions in the study area. The conclusions that follow provided the foundation for studying Central West African agriculture and rainfall/crop yield relationships:

1. The final 42 rainfall stations used out of the originally collected data for 101 rainfall stations, were selected from Principal Component Analysis to describe fully the study area rainfall, which is highly variable from one season to another and from one year to another regardless of time-scales (days, months, years, decades);

2. There is a strong south-north rainfall gradient from the Guinea Coast (Côte d'Ivoire with more rain) to the Soudano-Sahel regions (Burkina Faso/Mali with less rain), with an average annual rainfall cycle varying from bimodal (four seasons, two rainy) in the humid south (zone south of 9.3º N) to mono-modal (two seasons, one rainy) in the more arid north (zone north of 9.3º N). This verifies the clear presence of major variations in rainfall trends within the study area;

3. Central West African rainfall experienced a downward trend that started in the late 1950s, but did not produce droughts until the late 1960s, culminating in the low rainfall that led the region to experience large-scale severe drought years such as 1972, 1973, 1983, 1984, and 1990;

4. On the decadal-scale, rainfall ranged from the wet decades of the 1930s, 1950s (especially), and 1960s, to the much drier conditions of the 1940s, 1970s, 1980s, (especially) and 1990s;

5. The study area total number of rain days at different time-scales (monthly, seasonal, annual) demonstrated that the seasonal and annual average rain days have varied throughout the study period (e.g., 25-55 days for the March-June-centered rainy season south of 9.3º N, 20-55 for the July-September-centered rainy season north of 9.3º N, 15-30 for the October-November-centered rainy season south of 9.3º N, and 25-150 annually for entire study region); and

6. The onset of both March-June- and July-September-centered rainy seasons showed a gradual south-north advance of rains across Central West Africa. However, the

cessation of the March-June- and July-September-centered rainy seasons did not show a similar gradual retreat of rains; rather the cessation dates were discontinuous. For the October-November-centered rainy season, non-zonality patterns only occurred in the mountainous and coastal areas of Côte d'Ivoire for the onset and in central-west and southeast for the cessation. The standard deviations of the mean cessation dates were smaller than those of the mean onset dates for all rainy seasons, implying that the withdrawal of the monsoon system is better defined and organized and more rapid in the study area. The onset and cessation dates of the rainy seasons (proxies for rainy season lengths) indicate the magnitude and extent of the start/end of rains and contribute to the wide latitudinal variations in crops.

6.1.2 Agriculture

Agriculture was acknowledged as the major economic activity in Mali, Burkina Faso, and Côte d'Ivoire. These countries have been, are, and for the foreseeable future will remain highly dependent on farming and pastoral activities, especially rain-fed crop cultivation. The analyses showed that:

1. Crop data were used to identify 12 dominant agricultural regions (Koulikoro, Kayes, Sikasso, Segou for Mali; Center, East, Haut-Bassin, Mouhoun for Burkina Faso; Center, Central-west, South, West for Côte d'Ivoire) and eight major crops (cotton, peanuts, millet, sorghum for Mali/Burkina Faso; cocoa, coffee, maize, plantain for Côte d'Ivoire);

2. Cereals and staple crops (especially millet and sorghum) are more important for the northern regions (Soudano-Sahelian), while starch crops, root plants,

and cash crops (especially plantain, yams, cocoa, and coffee) dominate the southern regions (Gulf of Guinea Coast); and

3. Both cash and staple crops showed great variability concerning acreage, production, and yields. Regression-based trends for the overall study period or subperiods revealed that the relationship of production to acreage (positive) is more apparent than the relationship of yields to acreage, suggesting that in spite of some improvement in farming practices (e.g., fertilizer and pesticide uses, mechanization), crop production in Mali, Burkina Faso, and Côte d'Ivoire is more a function of acreage increase than yield increase.

6.1.3 Rainfall/Crop Yield Relationships

The focus on rainfall variability/crop yield relationships in this Dissertation was highly relevant for Mali, Burkina Faso, and Côte d'Ivoire, because most of their socioeconomic activities (e.g., farming, domestic water consumption, hydroelectric production) are dependent on rainfall. This study suggests that rainfall is an important climatic parameter whose variability alone has several consequences including declines in crop yields. Furthermore, the striking dependence of crops on rainfall reinforces the possibility of indirectly inferring current agricultural forecasts from rainfall forecasts. These subsequent conclusions are made:

1. Demonstrable impacts of Central West African rainfall/crop yield associations are apparent by the degree of variations from one year to another as well as from one crop to another. Both cash and staple crop yields show strong variability that is related to rainfall variability;

2. Correlation analyses of rainfall (for several measures, such as rainy season months, overall rainy seasons, and annual rainfall indices/totals) versus end-of-season crop yields revealed that both raw and detrended crop series correlate strongly, positively, and significantly with rainfall, particularly for staple crops in Mali, in spite of some weaker positive and more negative correlations for Burkina Faso and Côte d'Ivoire, and especially for cash crops (e.g., cotton in all three countries);

3. The presence of significant positive coefficients showed that in many cases, increased rainfall leads to increased crop yields across the study area; thus, lack of water is the primary constraint to crop growth, especially in drought-prone areas such as Mali and northern Burkina Faso. The weaker positive and more negative correlations (particularly raw staple and cash crops in Côte d'Ivoire) likely are due to the incorporation of some adaptative or gradually improving cropping practices that might counterbalance the effects of rainfall decrease. Too much rain/flooding (through drowned crops), reduced solar irradiance, physical damage, and increased incidence of pests and diseases could have also played a role in the weaker positive and more negative correlations in Côte d'Ivoire; and

4. Onset and cessation dates of the rainy seasons showed more strongly positive and significant correlations with raw crop yields (especially in Burkina Faso and Côte d'Ivoire) than the rainy season months, overall rainy seasons, and annual rainfall indices/totals. Early onset and early cessation (both with negative coefficients) as well as late onset and late cessation (both with positive coefficients) dates of rainy seasons have equally occurred in Mali. Late onset and late cessation (both with

positive coefficients) dates of rainy seasons have prevailed in Burkina Faso and Côte d'Ivoire.

6.1.4 Implications for Central West African Socioeconomic Development

The implications for the socioeconomic development of the study area are that both rainfall variations and agricultural change have several impacts on the society and economy that are growing in extent and severity. The indicators are as follows:

1. Rainfall variability/crop yield relationships are important to monitor and understand for Central West African socioeconomic development;

2. Society and economy are sensitive to environmental variations through the effects of rainfall scarcity, food insecurity, and cash crop price crises;

3. Lack of proper knowledge concerning the impacts of rainfall variability on crop yields undermines the drafting of agroclimatological policies and practices in the region even though Mali has responded very well to the agrometeorologic challenge;

4. Rural exoduses (due to widespread depletion of soil nutrients in expanded cultivated areas and deforestation) and their associated social crises in big cities are related to problems such as unemployment increases, juvenile delinquency, and crime rate enhancement;

5. Adaptive strategies to cope with rainfall variability such as agroclimatology (e.g., the Malian experience) could improve crop growth and development as well as planning for rainfall vagaries;

6. Elaboration and implementation of environmental policies (especially agricultural policies) are key ingredients for a sound and sustainable socioeconomic development.

Furthermore, with the repeated environmental calamities (e.g., severe droughts, flooding) in Central West Africa, the international donor community (e.g., World Bank, FAO, USAID) has constantly mobilized substantial resources for emergency food relief. They have assisted in development programs (e.g., experimental field observations in Mali) for the management of the natural resources on which Mali, Burkina Faso, and Côte d'Ivoire depend for their livelihood. Indeed, the current need for such assistance by the international community illustrates the socioeconomic urgency of understanding the relationships between rainfall variability and sustainable agriculture.

6.1.5 Environmental Policies

As shown in Chapter 5, environmental policies in various forms have always existed throughout Central West Africa since colonial times. The first forestry code, written in the early 1900s by the French administration, conferred full power to the colonial authority to manage and regulate the use of all of the natural resources (e.g., forests). The stated objectives were to restore degraded areas (not truly a priority) and to protect the forests against "abusive uses," the latter of which was for the most part intended to apply to the indigenous population. Post-independence Central West Africa initially continued to apply the colonial land laws or, in a few cases, introduced minor reforms usually consisting of adaptations of the colonial laws to the new political statutes. With the recurrent Sahelian droughts since the late 1960s, combined with the depletion of tropical forests, the interface between environmental policies and natural resource uses has constantly preoccupied researchers and development agencies alike. The 1994 to present environmental policies have gained strong support in Mali, Burkina Faso, and Côte d'Ivoire. However, all of the subsequent policies do not strongly address (or address at all) the following issues that now are key to progress:

1. Mass participation is needed to define the role that different interest groups (e.g., rural producers versus urban-based elite or businessmen) are to play in formulating, implementing, and monitoring environmental policies for a better awareness of the relations between resource use and environmental preservation;

2. Involvement of local people is undermined by social and cultural practices, which constrain the input of particular groups such as women and youth;

3. Legal access to land ownership is so complex that it fails to affect rural populations or creates more conflicts (e.g., the ongoing rebellion in Côte d'Ivoire begun in 2002 worsened over land reform). Issues on land tenure also require specific provisions in land laws to counter discrimination against women and young people; and

4. Cooperative organizations have been misused and abused by the governments because the cooperators lack the appropriate technical and managerial skills.

The above key issues strengthen the value of this study, which has greatly enhanced the basis for examining the interrelations of Mali, Burkina Faso, and Côte d'Ivoire rainfall, agriculture, society, and economy. Indeed, these aspects apparently have not been studied all together. This work reinforces the knowledge that the development priorities of Central

West Africa are oriented toward meeting basic human needs, but unfortunately these needs often are met at the expense of natural resources. In summary, the major outcomes of this research are viewed along the following four factors that further enhance the rationale for this Dissertation and attest to its contribution:

1. **Significance**: the lack of environmental equilibrium in Central West Africa calls for a growing number of environmental programs based on focused research. This analysis can contribute to a foundation to achieve sustainable socioeconomic development;

2. **Originality**: this study is the most extensive investigation into the relations among rainfall variability, agricultural parameters (acreage, production, yields), and rainfall/crop yields that has ever been done for Mali, Burkina Faso, and Côte d'Ivoire, covering such a long period of time (1930-1998);

3. **Feasibility**: this Dissertation takes a more practical view of the knowledge of the study area's environment, society, and economy. The fieldwork consisted of visiting Côte d'Ivoire, Burkina Faso, Mali, and Niger, which enriched greatly the research in the following respects: (1) it allowed an efficient gathering of all the available data at each environmental office headquarters; (2) it permitted a classification of all of the needed research data into a single volume, especially for crop data; and (3) it enabled discussions with each country's local environmental scientists and economists in order to formulate a better understanding of the state of research that already has been carried out in each country; and

4. **Benefit**: the Dissertation draws realistic conclusions about each country's rainfall variability, agricultural changes, and socioeconomic development. The research highlights the physical and socioeconomic settings as well as presents the potential resources for a better assessment of the Malian, Burkinabè, and Ivorian realities. This approach provides additional input for the decision-making processes of Central West African governments. Suggestions and implications can lead to additional solutions and policies toward sustained long-term socioeconomic growth in the study area.

6.2 Recommendations for Future Studies

The findings of this study provide important guidance for the management of natural resources in Mali, Burkina Faso, and Côte d'Ivoire, for the understanding of rainfall variability and agricultural change relationships, as well as for the level of sustainable socioeconomic development. However, more studies need to be conducted to amplify the necessity for sound environmental policies. To build on the present research, some areas require further investigations. Thus this Dissertation concludes by recommending the following ten topics for further investigations:

1. Further analyses should focus on and expand applications of regression analysis, a step-forward of the correlation analysis. This method goes beyond measuring the strength of associations between rainfall and crop yields, allowing for forecasts of the impacts of these rainfall/crop yield relationships on the societies and economies of the study area;

2. Development and adaptation of regional simulation models along the same lines as global statistical models (climatological and agricultural) must take into account a sufficiently long period of study to further understand the complicated and dynamic relationships between rainfall and agriculture. Since climatological and agricultural investigation models are usually built on a global-scale, it is necessary to conceive some regional-scale models for more precise and reliable information for Mali, Burkina Faso, and Côte d'Ivoire;

3. Planning and analyses, preferably involving surveys and interviews, must take into account the needs of the study area at three levels: (1) regional level (Central West Africa), (2) national level (each country), and (3) local level (administrative/agricultural regions within each country). Such multilevel application will produce a comprehensive understanding of the balancing between environmental and socioeconomic concerns that must occur;

4. Improvement of the skills of the seasonal rainfall forecasts is a necessity in the study area, where weather scientists should influence decision-makers to consider the impacts of rainfall variability on crops and other activities (e.g., pastoral). The recognition of rainfall variation should be part of environmental planning processes. The existing policies do not completely address -- most of the time they do not even incorporate -- climate variation aspects, especially the rainfall variability, which is an important environmental transformation parameter through disasters such as drought or flooding;

5. Research and policy development need to ensure that rational interpretation of conventional wisdom is taken into account through interactions between local people and their governments. The public should be more involved in conceptualizing and implementing policies. Although noticeable attempts have been made, the participatory approach has always stalled. Since legislation is meant to affect the behavior of the majority of the populations whose livelihood depends heavily on natural resources, consensus or at least involvement of all interested parties is critical and should be sought from the early stages of policy formulation throughout its enactment as legislation and subsequent monitoring and enforcement;

6. Environmental policies and institutional reforms also should stress environmental legislation, promotion of local governance, resource planning, and pricing regulations;

7. Land tenure systems must be strengthened and clarified. Putting natural resource management on a sustainable track requires the establishment of unambiguous and reliable forms of environment resource tenure that shift the balance of power in favor of rural populations;

8. Pre-existing institutions need to foster regional and national synergies or sponsor investigations that encourage existing environmental agencies (e.g., agricultural services, weather offices) to interact, collaborate, and exchange environmental and socioeconomic data;

9. Organizations representing rural producers (e.g., cooperatives) should not be misused or abused by governments to secure cheap agricultural commodities for urban populations. Cooperatives should ensure a more reliable authority system capable of controlling access to the resource base and raising sufficient contributions (labor or financial resources) for productivity-enhancing and sustainable investments. Cooperatives must be free to determine their own lines of business and capital accumulation strategies; and

10. Partnership between environmental scientists and decision-makers must be solid in order to maximize the use of seasonal climate forecasts and rainfall variability information. In fact, the climate information will not only help the evaluation of the needs of all climate users but also will help the government prioritize the environmental research sectors.

The aforementioned recommendations clearly show that a single sector policy approach (e.g., one that does not explicitly address climatology) is not a viable option for natural resource management and sustainable socioeconomic development. Environmental management must respond to and harmonize with the needs and desires of rural people. Therefore, a relatively high political commitment by governments combined with a good deal of effort to involve local populations would allow some breakthroughs in natural resource sustainable uses. Such an enabling environment must simultaneously ensure the socioeconomic attractiveness of the study region. It requires that environmental policies should favor both crop yield improvement and natural resource preservation.

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