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Agro-Climatic Assessment (Description and Analysis) of Madiama Commune in Mopti Region, Mali (West Africa)

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AGRO-CLIMATIC ASSESSMENT (DESCRIPTION AND ANALYSIS) OF MADIAMA COMMUNE IN MOPTI REGION, MALI (WEST AFRICA)

INTRODUCTION:

The commune of Madiama is about 25 kilometers from Djenné (capital of the admistrative Circle) and 120 kilometers southernmost of Mopti (capital of the 5th Region of Mali). It lies between 13° 45 N to 13° 52 N, and 4° 22 W to 4° 30 W. It is part of the Niger Delta region and located in the northern part of the republic of Mali. The commune, which comprises 11 villages, has a total land area of 16970 hectares (169.7 square kilometers), or about 66 square miles. Madiama village, which is in the central part of the commune, is the commune seat. The population of the commune was about 7,000 inhabitants in 1999 with a density average of about 41 inhabitants per km^2.

Like in other areas of the West African semi-arid Sahel region, the climatic conditions in Madiama commune are unique and characterized by an extreme combination of monomodal and erratic rainfall with high radiation loads and temperatures during the growing season which influence annual crops and pastures potential because of the continuous and high evaporative demand from the atmosphere. Also, these conditions lead to very difficult conditions for perennial plants and negatively impact the length of the growing cycle for annual crops leading to low yields and frequent crop failures (O. Badini et al., 1997).

An understanding of the intimate relationship between the weather and agricultural production systems, especially the complexities associated with the variability and distribution of rainfall in term of drought risks and yield fluctuations is an essential element in improving crop production and agricultural planning. For example, the amount, distribution and reliability of rainfall, the duration of the growing season, the potential evapo-transpiration rates, and the variability in the soil and its physical potential to hold water are features that need to be investigated.

To understand and characterize the agro-climatic conditions in Madiama, first, the physiogeography of the area as well as the general climatic patterns of the Sahel region influencing the local climate of Madiama are introduced. Then, local rainfall amounts and variability are described and assessed through the analysis of long-term (30 years at least) annual, monthly, seasonal and decadal (every ten-day) totals. Through the probability analysis of the rainfall carried out on a decadal basis, the seasonality of rainfall and its reliability are described. Also, temperature, potential evapotranspiration, and length of growing season have been analyzed. Finally, the application of this agro-climatic analysis to crop suitability analysis as well as crop improvement and planning useful to Madiama and the region are introduced.

I. AGRO-ECOLOGICAL CHARACTERISTICS

Physiogeography and Soils

As in the rest of Mali, the commune of Madiama has a monotonous relief, which is mainly flat with low plateaus and basins, and a mean altitude of 279 m. It is part of the inland Niger delta and influenced partly by the Bani River (an affluent of the Niger), which is on its western side toward the city of Djenné. The soils in the commune range widely in texture, natural drainage, and other characteristics. A morpho-pedological study conducted recently (O. Badini and L. Dioni, 2001) has identified a total of eight major soil units on a land area of 16,970 hectares for the commune (Figure 1 – Soil Map). They range from hydromorphic flood plains from the west side near the Bani River to plateaus and some rock outcrops on the east side.

On a transect running west to east, we find the hydromorphic Flood Plains (*unit Ci*) with gleyey and pseudogley hydromorphic soils (USDA *Aqualfs*) which represent 6.20 percent of the commune. They are followed by hydromorphic Alluvial Levees or Sand Banks (*unit Tr*) making about 6.6 percent. The Soils of this unit are *Psammaquents* or French Sols minéraux bruts d'apport alluvial. The third unit is represented by Old Levees and Alluvial Terraces (*unit t1*). They have silty and loamy material and represent about 13.5 percent of the commune. The Old Alluvial Plains and Terraces (*unit Ca*) represent 6,6 percent of the commune. The soil type is *Plinthic Haplustalfs* or French sols hydromorphes à tendance vertique avec nodule calcaire. They are followed by Hydromorphic Loamy Plains (*unit Cl*) on 20.1 percent of the land. The commune is dominated by the plains of sandy to loamy materials (*unit t2*), which cover about 36.8 percent of the commune. The soils are tropical ferruginous soils (or USDA *Ultic Haplustalfs*). The two last units found mostly on the east side of the commune are Land underlain by laterite (*unit Vi*) representing 5.5 percent with *Aridic Cuirastals* as soil type and ironstone plateau (*unit Bk*) with *Cambic Cuirorthids* soils representing 4.7 percent of the commune.

Generally the soils of the commune are poor in nutrients elements. Baseline values have been derived that show very low values for total Nitrogen (less than 0.1 percent in all soils), very low values for Organic Carbon content (0.08 to 0.5 percent) and deficient Phosphorus content (2.5 to 8 ppm). The soils range from strongly acid (pH 4.2) in the hydromorphic flood plains to slightly acid (pH 6.2) in the loamy and sandy plains.

Agro-ecological Zones

The agro-ecological zone is defined here as an homogeneous geographic entity on the standpoint of its climate, geology, geomorphology, soil and vegetation. In Mali, the PIRT project (1983) has identified 49 agro-ecological zones and 14 natural regions (Makan Fofana et al., 1997). Madiama commune is part of the north Soudanian or south Sahelian Bio-climatic zone. Most of the commune is located in the inland Niger Delta region, but its extreme east stretches to the Bandiagara-Hombori Plateau (Cf. Carte du Zonage Agro-écologique du Mali, PIRT 1986). Therefore, from east to west of the commune, one finds the following agro-ecological zones: The Bas-Plateau Bobo, the Moyen-Bani Niger, and the Delta Vif.

The Bas-Plateau Bobo:

A higher relief characterizes this zone, with indurated laterite in some areas and soils on cuirasse and rock outcrops on non-arable lands (Unite Bk on the map). The arable lands have loamy sand (soil unit t2), sandy clay loam (soil units ca, t1) textures or laterite clay (soil unit Vi). The vegetal cover is diverse and its ligneous component is dominated by *Pterocarpus erinaceus, Combretum glutinosum, Terminalia spp., Daniella oliveri, Parkia biglobosa* and *Aformosia laxiflora*. The herbaceous stratum is mainly composed of Andropogon *gayanus, Schizachyrium exile, Andropogon pseudapricus and Loudetia togoensis*. The forage potential is average. The main crop is millet. However, sorghum can be planted in lower lands. In this zone are found intermittent streams and rivers. Underground water is only found at great depth.

The Moyen Bani-Niger:

Beside the hydromorphic lands, soils with slightly sandy texture and average natural fertility characterize this zone. The main ligneous plants are *Acacia albida, Acacia seyal, Pterocarpus lucens, Piliostigma reticulatum, Combretum glutinosum, and Pterocarpus erinaceus*. The herbaceous strata are diverse and dominated by *Cenchrus biflorus, Loudetia togoensis, Pennisetum pedicellatum, Andropogon Gayanus* in non-inundated areas and *Vetiveria nigritina, Panicum anabaptistum* in the often-flooded zone. The forage potential is very high. Rice cultivation is possible on low flooding lands and sorghum is cultivated on higher lands. Underground water is at shallow depth.

The Delta Vif:
In the commune, the Delta Vif is represented by the floodplains of the Bani River (an affluent of the Niger). These lands are part of the lacustrian zone seasonally flooded by the rising waters from the Bani. In this part of the commune are found the flood plains (Ci), making about 6.2 percent of the commune. The type of vegetation found in this zone is function of the length and patterns of flooding. On the soils where floodwaters remain longer, are found some vivacious herbaceous such as *Echinocloa stagnina* (Bourgou[1]), *Oryza longistaminata, Mimosa pigra, Voscia cuspidata.* On the soils with shorter duration of floodwaters, are found *Vetivera nigritana, Eragrostis barterii, Panicum anabaptistum,* and ligneous species such as *Mitragyna inermis, Piliostigma reticulatum.* The forage (pastures) potential is very high. The receding floodwaters permit the cultivation of rice. The underground water is at shallow depth in this zone.

II. GENERAL CLIMATIC CHARACTERISTICS

1. Brief Climatic History

Like all the earth's regions, the Sahel has been subjected to repeated climatic fluctuations throughout its history. Cold, warm, dry, and moist periods have altered the face of the region many times. Figure 2 illustrates the fluctuations that have taken place over the last 18,000 years (K. M. Leisinger and K. Schmidt, 1995). Approximately

[1] The term bourgou (bourgoutières), derived from the Peul word bourgou meaning forage, refers to the deep basins of the Active Delta that produce a lush (rich) pasture as the flood waters recede. These flood retreat pastures (pâturages de décrue) become the focal point for transhumant herds during the dry season.

20,000 years ago the Sahara expanded southward into the current Sahel zone (including the study area) during a pronounced dry period. Rivers dried up, vegetation died out, and sand dunes were formed. About 15,000 years ago climatic conditions began to improve. Moist tropical air masses advanced far to the north during the summer months, bringing a considerable increase in rainfall.

This favorable climate lasted for about 5,000 years (about 8000-3000 BC). The Sahara desert receded to small, isolated areas in northern Africa. An enormous drainage network came into existence in the regions south of the Sahara. Rivers deposited sediments over broad areas such as in inland delta region of the Niger, where land use today is based on extensive irrigation. Previous arid, desolate areas came to life again, and the tropical rain forest advanced far to the north. Sand dunes were gradually covered with vegetation and sand masses no longer migrated southward. Red, fertile tropical soils were formed in areas where it is virtually impossible for soils to be formed today due to aridity. Humankind is still profiting today from the favorable climatic conditions of that time; soils that were formed then continue to benefit present-day agriculture.

After this relatively "wet" period, the climate once again worsened. Precipitation became highly variable and the amount of rainfall dropped considerably, causing lakes, river systems, and rain forests to recede and leading to a renewed advance of the desert. Today climatic history still determines to a considerable extent the potential for agriculture in the Sahel. In many areas, people live in an environment that took many thousands years to develop. If these areas continue to be degraded, they will probably not recover under today's arid conditions.

2. General atmospheric circulation

The general meteorological situation of the Sahel in West Africa is greatly influenced by global wind circulation, which determines periods of rain and aridity in the region. Two zones of pressure in general may influence the basic climatic pattern over the Sahel and the tropics. Belts of high pressure in the subtropics surround a low-pressure belt along the equator. The equatorial low-pressure belt corresponds to mass of moist air with continual low pressure, affected by rising movements, which cool the air. This cooling causes saturation, condensation, and cloud formation resulting in heavy rains that maintains high levels of humidity in the equatorial zone (Trewartha, 1968).

Near the 30th parallel on each side of the Equator are masses of tropical air (hot and dry) producing the prevailing winds (also called easterlies or trade winds). Three permanent centers of high pressure or anticyclones influence the region. These are the Azores anticyclones over the Atlantic Ocean, the Saharan anticyclone over North Africa (Lybia-Soudan) and the third one called the Southern Hemisphere anticyclone over South Atlantic around Saint-Helena. The equatorial low-pressure center attracts the prevailing winds of the high-pressure zones in the two hemispheres. It is the convergence of the prevailing winds of the two hemispheres near of the zone of Equatorial low pressure that forces the air in the latter to rise. The area of contact between the dry and hot tropical air and humid equatorial air is called the intertropical convergence zone or ITCZ.

In the region, the movement of the low and high-pressure zones and the ITCZ between them regulates climate. In association with the sun's apparent movement, this front advances northward between March 21 and June 21 for the north front and then recedes to the south between June 21 and September 21, and slowly disappears from September 21 to December 21 while the southern ITCZ takes shape as the sun's apparent movement brings it south of the equator (Trewartha 1968; Atlas Jeune Afrique, 1975).

The ITCZ is a zone of rising turbulence and it is its passage above the various regions that brings the rains. In intertropical Africa it is not temperature which determines season but rainfall. The latter follows rather than accompanies the passage of the ITCZ, the lag between the ITCZ and the release of heavy rainfall reaching 200 to 300 km (Cochemé and Franquin, 1967).

2. Season and Weather in Mali

The start of different seasons is linked to the existence of the anticyclones of Azores, Saharan (Lybia-Soudan), and Saint Helena, both on the surface and at high altitude. The movement of the ITCZ is affected by the fluctuations of these anticyclones, their position and elevation. The air masses over the region are controlled by the center of action, the origin, and the different characteristics following the predominance of either of the two air fluxes affecting the region.

The anticyclone of Azores reaches its most active position in July-August; when it is in its most meridional position, the wind blows from north to northeast in the whole of West Africa. In winter (from November to May) the Sahel including Mali is subject to the influence of the dry *east* winds flux called "Harmattan" due to the predominance of the Saharan anticyclone (hot during the day and cool at night). Precipitation is rare. The dry season grows longer toward the northern part of the Sahel. And finally, a period of summer precipitation (with heavy showers) occurs when the anticyclone of Saint-Helena (remaining permanently between the Equator and 20° S) sends a very moist southwest air of oceanic origin, i.e., the monsoon (from the Arabic word *mausin*, a season).

The circulation described above helps to distinguish clearly two distinct seasons and transitional periods (Konaré and Konaté, 1976).

The dry season. During this period the ITCZ is situated between 5° and 10° N in the south of Mali, which is subjected to Harmattan. Its duration varies between 6 and 9 months from south to north. This season is marked by the appearance of dry mist due to the presence of solid particles, which overhang in the air near the ground. During the hot afternoons, small whirlwinds occur near the grounds, perhaps owing to the strong horizontal temperature gradients. Whirling sand and dust, a spectacular phenomenon, can gain in magnitude and transform in sandstorm.

The interseasonal periods. These are neither rainy nor dry months when the ITCZ oscillates between 10° and 15° N and is very active. Unstable clouds that cause sudden showers and sporadic storms, generally during mid or late evening characterize this period. The highest temperatures are registered during this period, and the absence of wind circulation near the ground is observed.

The humid season. It is affected successively by heavy showers and monsoon and is marked by two distinct types of weather.

At the end and beginning of the season, the rains occur as showers accompanied by squalls or "tornadoes" which are very characteristic of the Sahelian region. The squalls are provoked by the dry prevailing winds dropping abruptly to earth and then brusquely rising again, pushed by the mass of humid air. They always move from east to west. They are signaled by violent windstorms followed by torrential rain (which can have disastrous effect) with the temperature dropping 5° to 10° C.

The monsoon factor is the dominant factor in the rainy season. The intertropical front, almost nonexistent, is pushed toward 20° N and half of southern Mali is subjected to the very humid western winds of the Gulf of Guinea. An overcast sky or sometimes dense clouds, causing moderate rainfall or stormy showers, mark this regime, which reaches its maximum intensity during August.

4. Climatic Zone

The study area is part of the South Sahelian zone (below 650 mm isohyets) (Figure 3 – Sahel Zone) with a short rainy season, considerable variability in the rainfall amount and distribution, severe drought due to high evapotranspiration, and high daily and annual temperature. There are no noticeable seasons that can be defined by temperature as in temperate zones. Differences in temperature are greater between day and night than between summer and winter.

The three- to four-month rainy season occurs during the summer from June to September, with rainfall ranging from 400 to 600 mm. However, because of high temperatures and intense solar radiation, much of this precipitation evaporates before it can be used for agriculture. There is sufficient humidity for agriculture for only two to four months during the year, with dry months predominating the rest of the time. However, the climatic characteristics of the commune are somehow different from other parts of the Sahel due to the fact that an important part of the commune lies in the agro-ecological zone of the Central Niger Delta.

5. Hydrology

In the study zone, the flooding follows the start of the rainy season, but the onset date for the rise in the water levels varies from year to year. J. Gallais (1967) has studied the rise regime of the Djenné Delta (Pondori floodplains). The triggering of the water rise in the study area is very slow. The waves of the rising water from the Niger at Ké-Macina take up to two or three weeks before reaching Belentieny and then Sofara. The flooding pattern is slow and gradual.

Due to its location in relation to the Bani River, the commune of Madiama is mainly an intermediary zone lying between the flooding zone (east side) and the ironstone plateau on the west side. Many rivers and streams (Yamé) run through the commune. The most important are the Yamé flowing through Promani-Tatia to the Bani River at Baratou village. Another less important Yamé runs through Kessédougou and Toumadiama. At the extreme south of the commune a third, more or less steep-sided Yamé is found.

III. AGRO-CLIMATIC DESCRIPTION AND ANALYSIS

1. Weather Data Availability

To monitor weather factors, and build a weather database for the commune and the region, an automatic weather station with data logger was installed in Madiama village (seat of the commune) on June 3rd 1999. A weather database comprising hourly and daily weather data on air and soil temperatures (maximum and minimum), relative humidity, total solar radiation (flux and rate), wind speed and total rainfall is available. A network of 10 rain gauges was installed in June 2000 in each of the other 10 villages of the commune. Also, historic daily weather data (solar radiation, rainfall, minimum and maximum temperature) from 1950 to 1999 for Mopti, Djenné and Sofara were obtained from the Meteorological service of the Government of Mali, and compiled for use in the present study and long term simulation modeling and analysis. A ten-year decadal rainfall data for Madiama was also compiled and entered in the computer.
We also have the capability to generate any number of years of weather for simulation modeling studies using CLIMGEN (Campbell, 1990; Stockle, 1996).

2. Rainfall Analysis and Characteristics

2.1. <u>Rainfall Amounts and Distribution</u>

2.1.1. Annual Rainfall

In areas such as the study region where pronounced seasonal patterns of rainfall are influenced by changes in solar energy and pressure patterns (Sivakumar et al., 1984), mean annual rainfall could help provide useful assessment of agricultural potential. The annual rainfalls, the long-term mean and the general rainfall trend in the area of Madiama in the period from 1950 to 2000 are plotted in Figure 4. The annual rainfall in the commune and surrounding area varies considerably from year to year, a very common characteristic in the semi-arid tropics. From 1950 to 2000 such as shown in Figure 4, the mean annual rainfall is 544 mm. The lowest annual rainfall of 274 mm was recorded in 1987 while the highest annual rainfall in the past 51 years was 914 mm, received in 1957. Rainfall variability as a percentage of deviation from the mean of the last 50 years is plotted in Figure 5.

To take into account the change in rainfall patterns since the droughts of the 1970's in the Sahel region, the period 1950 to 2000 was divided into 1950-69 and 1970-00, and annual averages were computed for the two periods, i.e., 1950-69 (Figure 6), and 1970-00 (Figure 7). Figures 4 and 5 show that years of above average and below-average rainfall tend to come in clusters as seen throughout the Sahel. The annual rainfall during 1950-69 was consistently above the long-term average of 544 mm. During this period, only two to three years had below average rainfall with percentage deviations from the mean only around 10% (Figure 5). During the last 30 years starting around 1970, most of the years were below this same average of 544 mm. During this period, more than 70% of the years had below average long-term rainfall with percentage deviation from the mean reaching 50% in some cases (e.g. 1987).

The average rainfall for the period 1950-69 (Figure 6) was 636 mm compared to an average of 482 mm (Figure 7) for the period 1970-2000. The average rainfall loss between the two periods is around 154 mm. A trend of declining rainfall over the last three decades is therefore evident (Figure 4). The consequences for this drop in rainfall amount are the increased aridity and limiting water availability for rainfed crops, more risks for crop failure, and diminishing pastures. These same constraints caused by the drop in rainfall are common for the many parts of the Sahel region since the droughts of the 1970's.

These data show that analysis based on the records of the most recent 30 years is more reliable for characterizing the rainfall patterns of the study zone. Therefore, we will use the period (1970-2000) for the assessment of agro-climate in the study site and possibly elsewhere in the region.

2.1.2. Seasonal Rainfall

Due to the seasonal movement of the ITCZ that regulates the rainfall pattern, precipitation in Madiama and in the Sahel region in general is monomodal. Intermittent rains start in May and become regular in July. It causes widespread rainfall and local rainstorms. The beginning and the end of the rainy season may be distinguished from the peak period in August by the more violent, short but heavy rainstorms, and gust of winds. In the beginning of the rainy season, the impact of this rainfall and the runoff that results from it erode the soil, already made bare by the lack of residue cover due to human and animal activities (bush fire, grazing, different uses).

Based on the occurrence of 10 mm of rainfall in two consecutives decades (Sivakumar et al., 1984 & 1987), the rainfall data during the year were divided into dry season (probabilities less than 16%), prerainy or postrainy season (probabilities from 16% to 45%), and rainy season (probabilities exceeding 46%). Rainfall received across the area during the rainy season is about 425 mm representing 88% of the annual total. This figure is as in most of the semi-arid areas in the Sahel where over 80% of annual rainfall is received during a short rainy season covering 3 to 5 months (Sivakumar et al., 1987). This pattern emphasizes the monomodal nature of the rainfall in the region.

2.2. Rainfall Variability Analysis

As shown in the previous section, limiting water availability is one of the main constraints to rainfed crop production in Madiama and the region. But even more critical for agriculture than the actual amount of rainfall or change of seasons is rainfall variability. The mean annual rainfall patterns show a large standard deviation and a high coefficient of variation (CV). For the last 31 years, the mean annual rainfall of 482 mm has a Standard Deviation (variance) of 140 mm and a Coefficient of Variation (CV) of 29 per cent. Proper to the whole region, the ITCZ moves irregularly, thus making precipitation variable. Annual variations more than 50 percent can occur, depending on how far this zone of converging air masses advances to the north. This is why rainfall becomes less certain toward the Sahara.

To assess the mean monthly rainfall variability in the area, rainfall along with the standard deviation, coefficient of variation (CV), maximum and minimum rainfall, and the range of rainfall recorded each month have been computed from the daily rainfall data from 1970 to 2000. The results of this analysis are presented in Table 1. The monthly rainfall distribution is shown in Figure 8. The maximum rainfall is received in July and August representing 58 % of total annual rainfall. The monthly rainfall varies from year to year. As shown in Table 1, the CV of monthly rainfall is very large during the dry,

prehumid and posthumid periods. During the rainy season the CVs are, as can be expected lower, with July and August recording the lowest CV (42.7 and 43.7 percent respectively).

Compared to the wetter zones in West Africa, rainfall in July and August shows a pronounced peak in the Madiama area. In this Sahelian zone, which is under the influence of the northernmost movement of the ITCZ, low rainfall is received in all months except in July (125 ± 53 mm) and August (155 ± 68 mm). The wide variability in rainfall is characteristic of the whole Sahel region and represents a main agro-climatic constraint to crop production.

3. Probability Estimates and Reliability Analysis of Rainfall

Rainfall data in the form of simple arithmetic averages provide a broad description for generalized application. The annual, seasonal, and monthly rainfall patterns in the Madiama area described above present an average picture of water availability but averages conceal interyear fluctuations. For example, the quantity of rainfall received over a period of time at a particular location gives a general indication of its sufficiency for crop needs, but the survival of a crop depends upon the reliability of receiving a specific amount of rainfall for a short period. Knowledge of rainfall estimates in a given geographical region enables the development of suitable strategies for agricultural planning and implementation (Sivakumar et al., 1984). Agronomists and agricultural engineers to plan water management for crop production and design water collection and storage systems often use frequency analysis of rainfall records. The idea is that the past gives a clue about what to expect in the future.

In the probability analysis of the monthly rainfall data for the last 31 years in Djenné-Madiama area, the probability of a given monthly precipitation for a given number of years out of 10 was computed and the results are presented in Table 1. Rainfall in June can be expected to be at least 12 mm 9 years out of 10 and 83 mm only one year out of 10.

A decadal reliability analysis was done from the daily rainfall of the last 31 years starting in 1970. Rainfall in each period for each year was added up resulting in a table of 10-day totals for 36 periods in each of the recorded years. The data was then arranged in order of magnitude and then, the lower quartile (rainfall exceeded in 3 out of 4 years or 75%), median (2 out of 4 years or 50%) and the upper quartile (in 1 out 4 years or 25%) were computed. These three statistics representing confidence limits for 10-day rainfall have been plotted to represent trends throughout the year (Figure 9). Also, an estimate of potential evapotranspiration (PET), computed from the model CropSyst, was superimposed on the graph, which allows an examination of periods of adequate rainfall and risk periods.

Diagram such as Figure 9 helps in the understanding of current cropping systems and the design of new ones. When the median rainfall exceeds PET, crops will not suffer water stress. This corresponds for example, to the period from July 29 to September 1 in Madiama area. If the lower quartile falls below 0.5*PET, crops will probably suffer if they are at full leaf canopy or at a sensitive stage of growth. This corresponds to the period after the first decade of September for Madiama. Upper quartile values greatly in excess of 2 PET indicate the possibility of flooding in lowland sites, and waterlogging and accelerated soil erosion on upland sites. Fungal diseases or spoilage of ripening crops may also occur at times of excessive rainfall (Muisaers and al., 1997).

In the monomodal rainfall regime of Madiama (Fig. 9), median rainfall rises to a peak around August 8 and then falls rapidly. Double (sequential) cropping of unirrigated uplands is not possible in such a situation. Reliable rainfall for germination and establishment can be expected beginning July 9 and will exceed the crop's requirement until September 17. Crops are not likely to suffer water stress between July 29 and September 1.

3. Temperature Analysis

After rainfall, temperature is the most important climatic variable for crops. Temperature variation is much less localized than rainfall. The temperature of the environment is mainly a manifestation of the radiation and energy balance. Because of uniformly high radiation levels throughout the year, the study area as well as the whole Sahelian zone has a warm environment that is seasonally modified by changes in water regimes and surface conditions.

In the zone, the diurnal and annual variations in temperature are more marked than in wetter Sudanian zones such as Sikasso in the south. Two hot seasons could be distinguished: the first from September to October and the second from March to June separated by a cool season from November to February. The diurnal variation in Temperature is higher (*15°-20°*C) during the dry season than reached during the rainy season (*8°-10°*C). The mean maximum air temperatures are very high during the hot, dry season (March to May) reaching up *42°C*, while during the rainy season they vary between *32°* and *35°C*. The minimum air temperatures are lower during the cool season and increase progressively to 27 oC during May, and vary between 23 and 25° *C* during the rainy season. Table 2 gives details of Temperature patterns for the Madiama area.

5. Potential Evapo-Transpiration (PET)

Although the rainfall amount and distribution at two locations could be similar, the water requirements of crops at these locations could be different if the atmospheric demands for water between those locations are different. Potential Evapotranspiration (PET) gives the idea of a potential demand for water at a given location. At Madiama the mean annual rainfall is 482 mm and the mean PET is 2151 mm (**Table 2**). Average daily PET values during the dry season were 7 mm and about 5mm during the rainy season.

6. Length of the Growing Season (LGS)

Viewed in terms of water availability for plants (crops and pastures) and based on the balance between Precipitation (P) and Potential Evapotranspiration (PET), the seasonal rainfall occurrences as well as the growing period in the commune and surrounding areas can be classified into a preparatory period (P ≥ 0.1 PET) (Cochemé and Franquin, 1967, a first intermediary period or prehumid period (P ≥ 0.5 PET), a wet

season or humid period (P ≥ PET) and a second intermediary period or posthumid period (P ≥ 0.5 PET). This is followed by a dry season. The duration of the rainy season as well as the length of the growing period depends on the depth and characteristics of these classes. Results are presented in Table 2.

6.1. Preparatory Period

The point where the rainfall equals 1/10 of PET defines the beginning of the preparatory period, which ends with the beginning of the first intermediary period (P = 1/2 PET). The preparatory period can be utilized for preparation of the soil and early sowing of crops resistant to drought in the seedling stage (Cochemé and Franquin, 1967). At Madiama, this period starts in the third decade of May and ends in the first decade of July. It has a variable duration of 31 ± 19 days.

6.2. Rainy Saison and Growing Period

The growing season is described as the period during which the soil moisture coming from precipitation is freely available to the crop or plant cover. To enable quantitative assessment of the growing period, the following working definition is used. The growing period is the period (in days) during a year when precipitation exceeds half the potential evapotranspiration, plus a period required to evapotranspire an assumed 100 mm of water from excess precipitation (FAO, 1978). A normal growing period must exhibit a humid period, i.e. a period with an excess of precipitation over potential evapotranspiration.

6.2.1. Beginning of the growing period (and rainy season)

The determination of the beginning of the growing period is based on the start of the rainy season (same as start of prehumid period). This period is taken as the time when precipitation equals half potential evapotranspiration (P = 0.5 PET). The reliability of rainfall during the early rains is increased at that threshold, and this period, "a false start of rains" damageable to young seedlings, is eliminated. Additionally, this premise takes into account the fact that the amount of moisture required to sustain germinating crops is much below the full rate of evapotranspiration and during crop emergence it approximates 0.3 PET.

Considering this definition, the best time for planting in Madiama area would be approximately in the first decade of July with a variable duration of 30 ± 18 days. Compared to localities such as Sikasso (south of Mali) where the growing period starts early in May, the short moist period in the Madiama area explains the predominance of crops such as millet and short-duration sorghum.

6.2.2. Humid Period

A normal growing period is defined as one with a period when there is an excess of precipitation over PET, i.e. a humid period. Such a period not only meets the full evapotranspiration demands of crops at a complete or maximum canopy cover, but also replenishes the moisture deficit of the soil profile and avoids water stress. Based on the normal long-term average, this period corresponds to the period July 19 to August 28 in Madiama area. The total length of this period is 34 ± 20 days in the Madiama area.

6.2.3. End of rains and rainy season

During the post humid period, precipitation is again less than PET and crops begin to draw upon water stored in the soil. Subsequently, the frequency and amount of the rainfall decreases sharply and rainfall deficit increases (Figure 9). This results in a marked alteration of the environment and triggers pronounced changes in physiological responses of crops. Under such conditions and in the absence of soil moisture reserves, crops are forced to mature when precipitation is equal or less than 0.5 PET. The time, when P = 0.5 PET in the post humid period is taken as the end of rains and rainy season.

The total rainy season (or total length of growing period permitted by rainfall alone) in Madiama area is about 84 days with a coefficient of variation of 30%. This corresponds to the 3rd decade of September (Up to the end of September). Importance of soil water conservation can be stressed here to allow a longer growth cycle for crops so that they are not forced to mature with very low productivity.

6.2.4. End of growing period

The growing period for most crops continues beyond the rainy season and, to a greater or lesser extent, crops often mature on moisture reserves stored in the soil profile. Soil moisture storage must be therefore considered in defining the Length of Growing Period. However, the amount of soil moisture stored in the soil profile, and available to a crop, varies with the depth of the soil profile, the soil's physical characteristics, the rooting pattern of the crop and other factors. Furthermore, changes in soil moisture reserve lead to changes in the actual evapotranspiration rate. The soil data bank we are building will be used to evaluate this assumption and permit a more exact estimation of the total growing period. The characterization of the weather will help in the selection of cropping systems and varieties suited to the climate.

For the purpose of the present evaluations, at the end of the posthumid period, a general figure of 100 mm water is assumed to be available to crops. Accordingly, the time taken to evapotranspire 100 mm of storage water has been added to the duration of the rainy season, to set the end of the growing period. The choice of 100 mm is based on experimental evidence from East and West Africa (FAO, 1978), which indicates that the crops of the study can utilize stored moisture in the range of 75 – 125 mm, by the time of harvest. Accordingly, in the case of our study area, the growing period can be extended by 18 days considering the moisture availability from water stored in the soil. Thus, the average length of growing period can be extended to 102 ± 25 days.

Table 3 shows the growing cycle length for a number of local crops and the number of years out of 10 when the growing period can be expected to exceed a given length. For example, for a millet variety such as *sagnori* with a growing cycle estimated at 87 days, only in 6 years out of 10 (that the growing period can be expected to be long enough for this crop variety. With a sorghum cultivars such as *Toroniou* (with a growth cycle of 107 days) only in 4 years out of 10 that the growing period can be long enough to accommodate the growth pattern of this crop in Madiama. Such analysis is useful in

characterizing the agro-climatic suitability of crops in a given environment. Should the aridification of the Sahel continue at the present trend, we could expect more crop cultivars to be unsuitable to their present environment.

Actual length of growing period will depend on soil and crop types. In a future study, the soil data bank related to the map units in Fig.1 will be used to evaluate this assumption and permit a more exact estimation of the total growing period in the study area.

7. <u>Applications of the Assessment</u>:

The present contribution is a preliminary analysis that account for some of the methods that can be used to characterize the agro-climatic environment of crops and other plants. Rainfall variability analysis insights such as presented here, can be adapted to the small farmer based food productions systems. It can also help the development of suitable strategies in West Africa and elsewhere for crop improvement and planning.

Decision-makers can use frequency and reliability analysis of rainfall records to plan water management for crop production and design water collection storage systems. The most important applications of decadal rainfall probabilities are in the decisions concerning planting dates of crop, the length of the rainy season and the dependability of rainfall and moisture availability at different locations. The expected quantity of rainfall and the degree of certainty with which this rainfall occurs are crucial factors in farm decision-making. As in other parts of West Africa, timely planting and the associated primary cultivation is key to good crop establishment and successful crop performance in Madiama and in the semi-arid tropics in general.

Also, in order to relate cropping patterns to rainfall, the length of the growing season is particularly important. Knowledge of agro-climatic characteristics such as the length of the growing period could help in the choice of the appropriate crops/crop cultivars whose normal growth cycle (from sowing to physiological maturity) duration matches the available length of the growing period. Dates of beginning of the preparatory, humid, and moist periods computed for different locations also help in deciding the possible timing of different field operations.

Climatic zonation such as permitted by the procedures used here is useful for suggesting region-specific crop planning and is important for the transfer of adaptable soil-water and crop-management technology. Regional differences in precipitation probabilities should aid the process of determining areas most suitable for successful crop production. It can also be used to assess the optimum times for various agricultural operations.

CONCLUSION

The major constraint limiting the time available for rainfed crop production is availability of water. Providing water for food production in the Sahelian zone of Africa still remains an urgent need, and approaches are needed to assess crop/climate relationships, provide a rational basis for land resource assessment and for planning efficient exploitation of climatic resources for agriculture.

Although many other factors such as the socioeconomic situation of the farmer and the market demands play an important role in agricultural planning at local and regional levels, agro-climatic analysis where the available growing period is compared with the phenology of the crop and the climatic risks to crop production are delineated could help assess the potential for successful crop production. In addition to the parameters of rainfall variability and reliability, PET and temperature described in the present study, the variability in the soil and its physical potential to hold water are features that need to be included in the determination of land suitability for crops and other plants.

Future contribution will use modeling tools such as CropSyst to integrate other factors such as soil type, crop varieties and management. Soil-water balance modeling will be carried out using daily rainfall, temperature and radiation as input to the model to better characterize the water use and loss as well as the length of growing cycles permitted by the different soil types in the study area. Such an approach, which integrates agro-climate and soils constraints, will provide a rational basis for land resource assessment and for planning efficient exploitation of climatic resources for agriculture and other natural resources. Further work is also needed to regionalize the analysis. Data from other environments and stations should be included in the analysis by accounting for effects of elevation, latitude, longitude, etc.

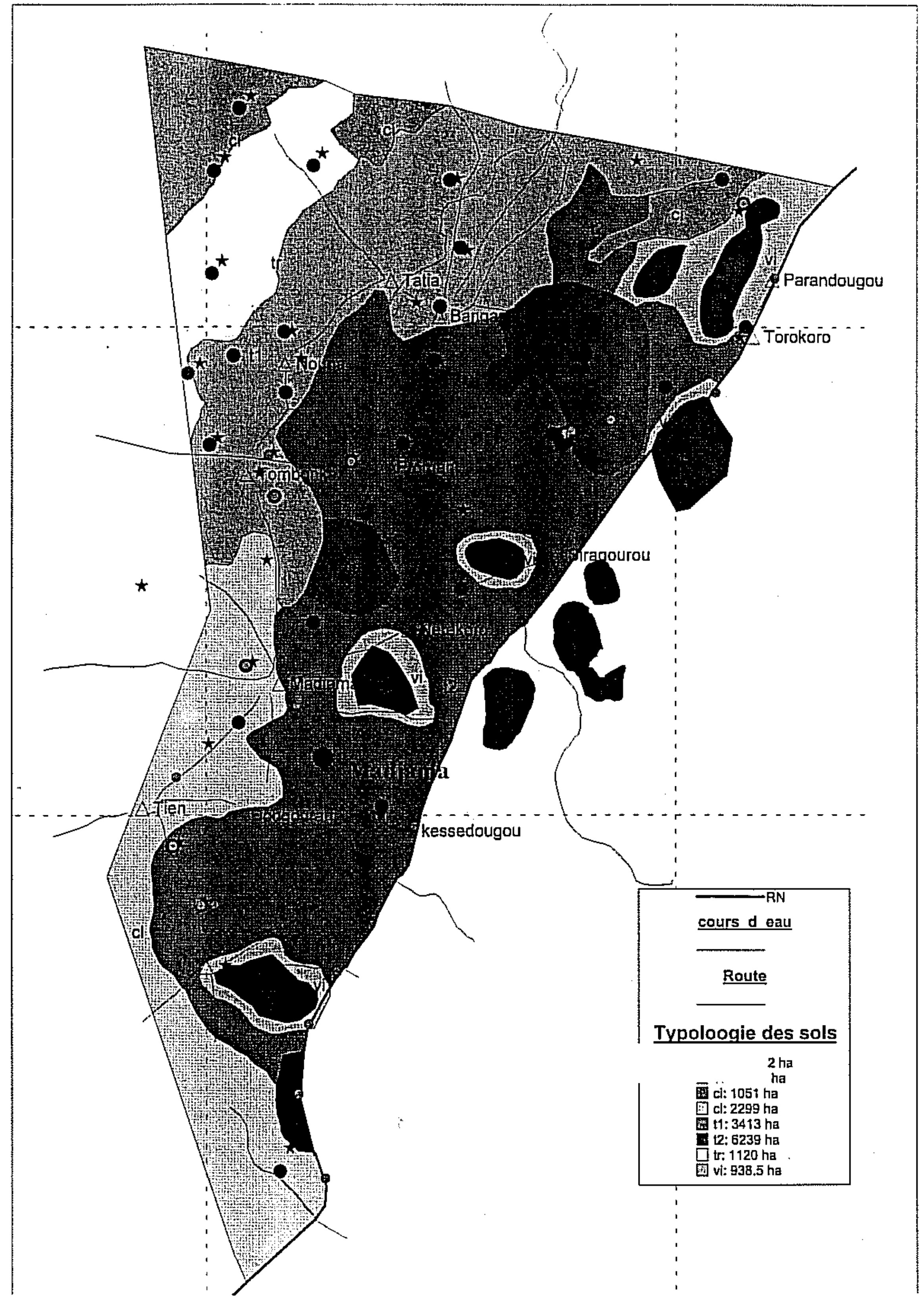
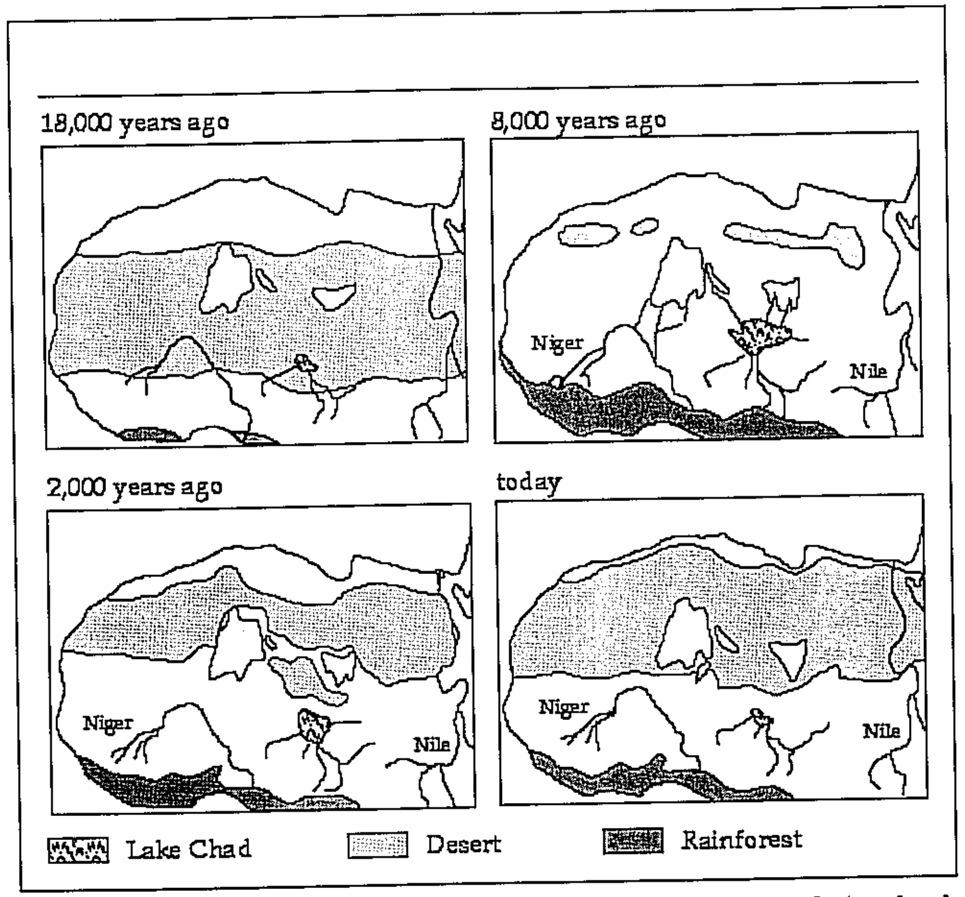
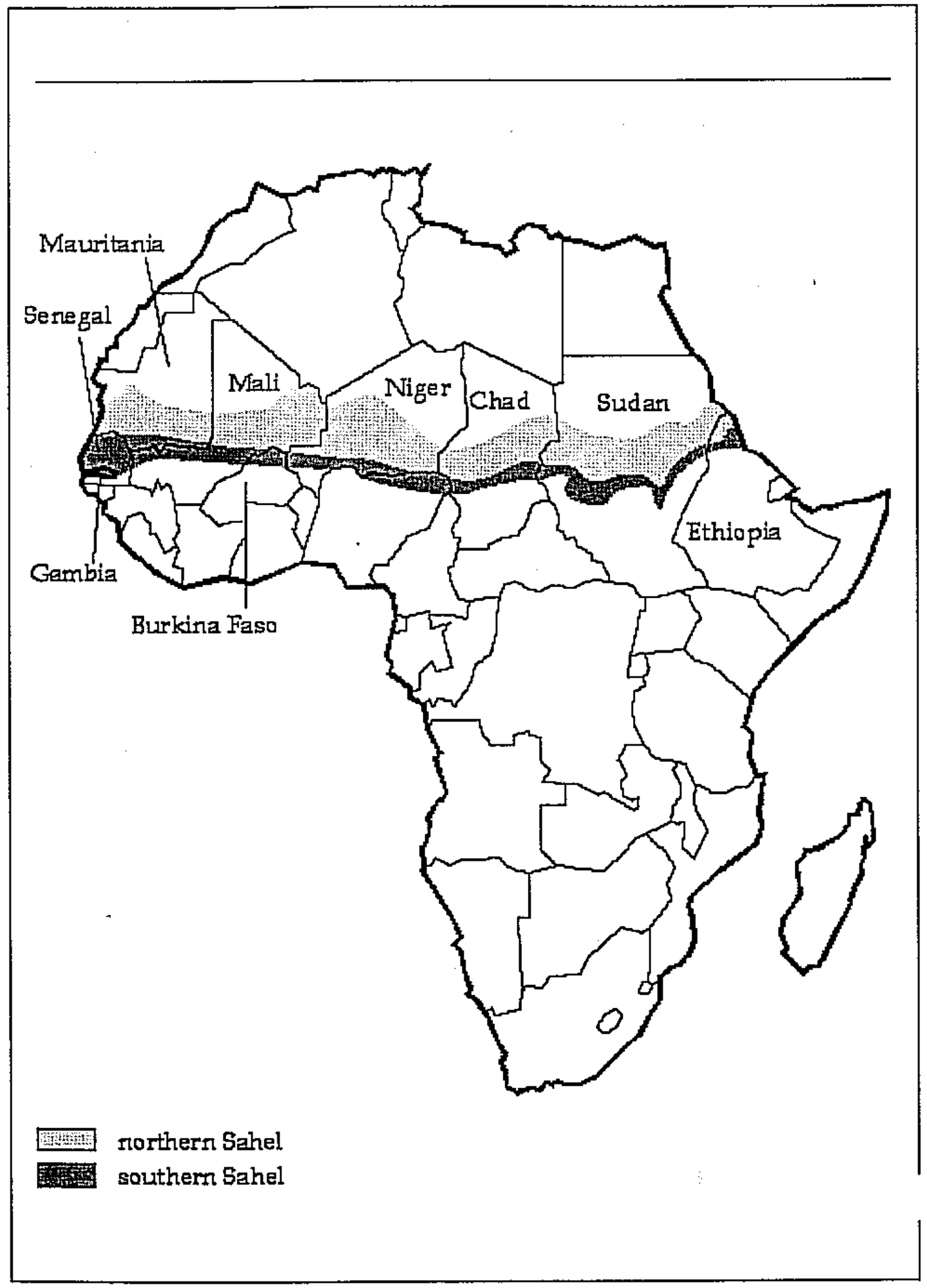


Figure 1: Morpho-Pedological Map of Madiama Commune



Source: B. Messerli, Geographic Institute of the University of Berne, Switzerland

Figure 2: Climatic and Environmental History in the Sahel and Northern Africa in the last 18000 years



Source: H.G. Mensching, *Desertifikation*. Darmstadt, 1990. p. 55

Figure 3: The Sahel Zone in Africa

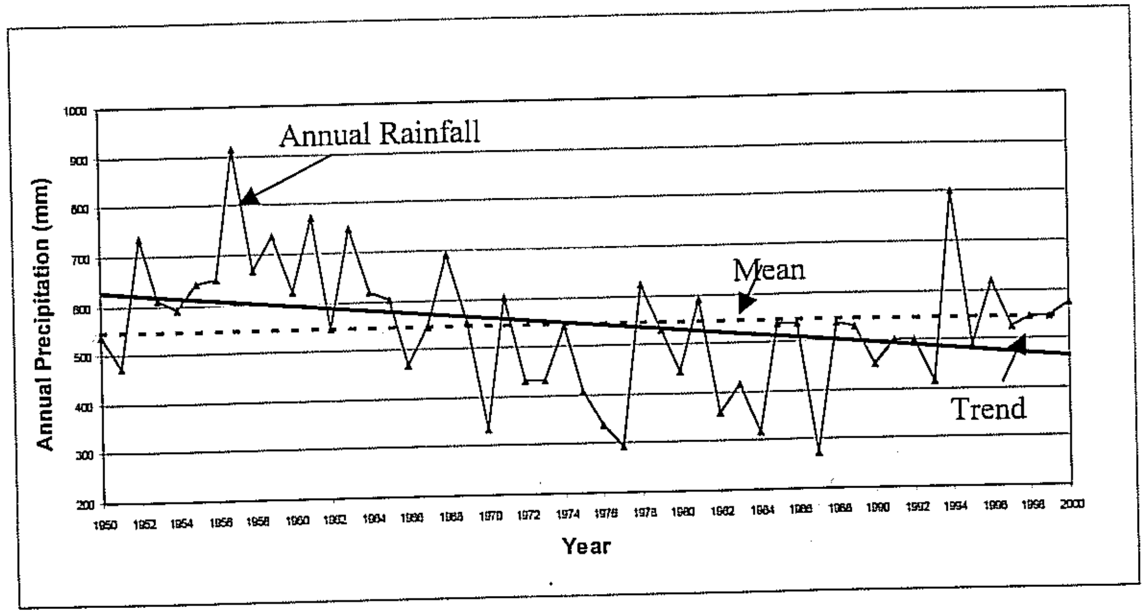


Figure 4: Precipitation Distribution, Mean and Trend from 1950 to 2000 in Djenné-Madiama

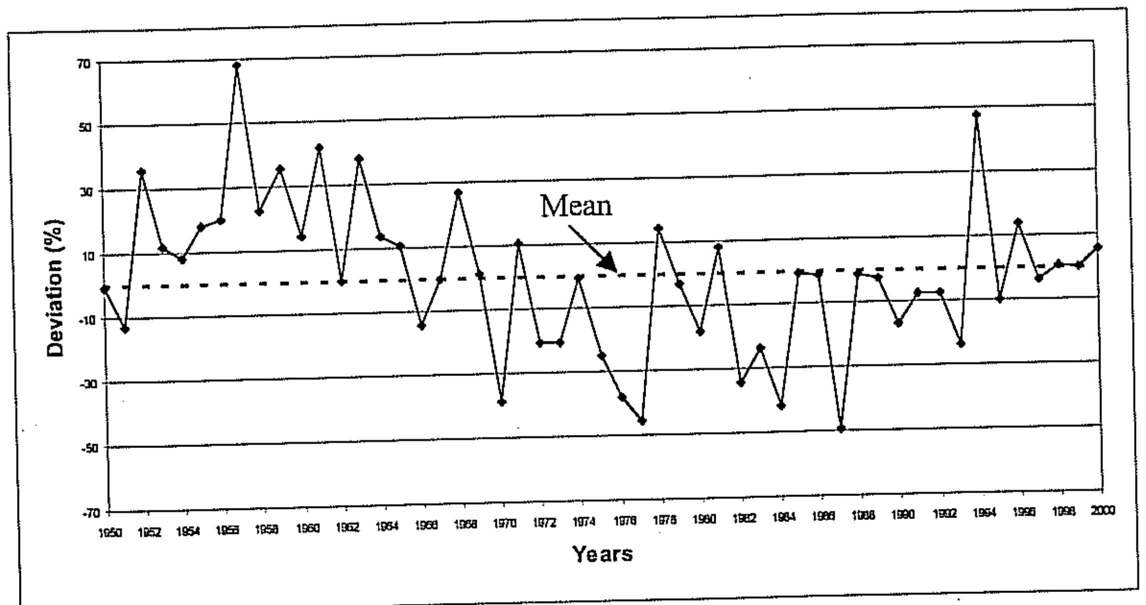


Figure 5: Rainfall Variability as a Percentage of Deviation from the long-term mean (544 mm) for the Study Area

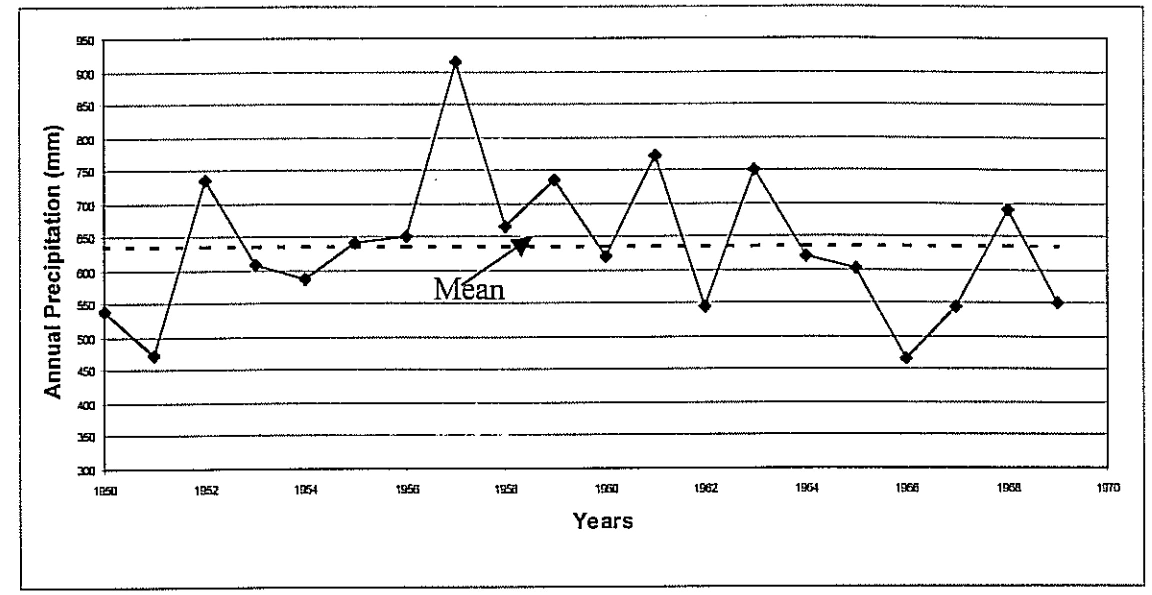


Figure 6: Precipitation Distribution from 1950 to 1969 in Djenné-Madiama

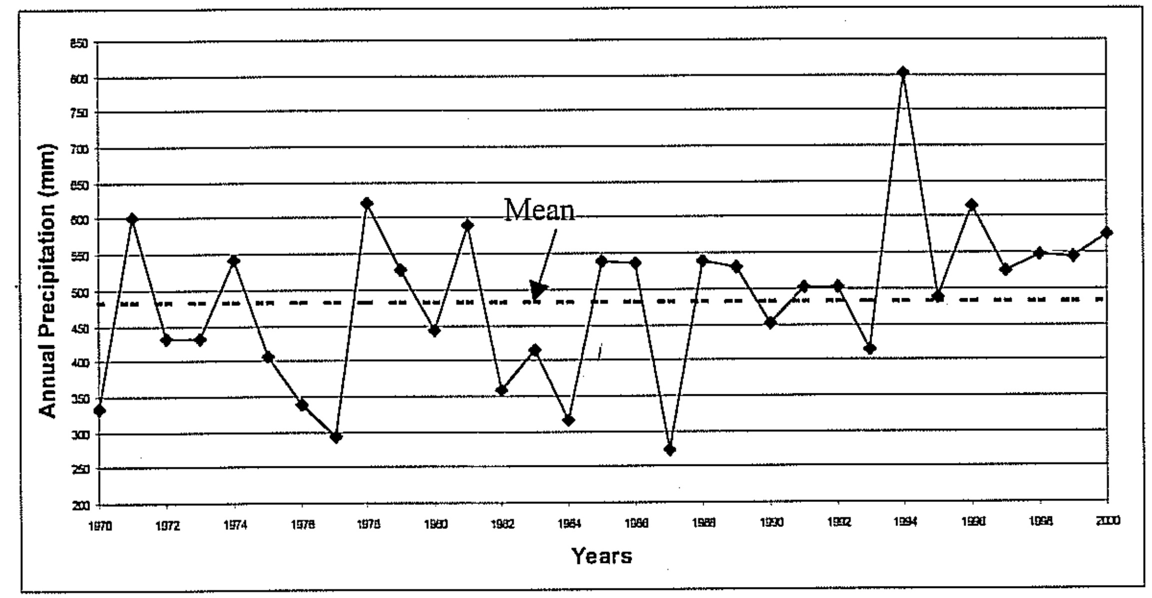


Figure 7: Precipitation Distribution from 1970 to 2000 in Djenné-Madiama

Table 1: Monthly Rainfall Variability and Probability in Djenné-Madiama Zone

	ANALYSIS OF RAINFALL VARIABILITY (1970-00)								RAIN PROBABILITY IN YEARS OUT OF 10								
	N years	NO	Mean	% Total	Max	Min	s	CV (%)	9	8	7	6	5	4	3	2	1
JANUARY	31	28	0.1	0.0	3.5	0.0	0.6	431.5	0	0	0	0	0	0	0	0	0
FEBRUARY	31	30	0.0	0.0	1.0	0.0	0.2	556.8	0	0	0	0	0	0	0	0	0
MARCH	31	27	0.5	0.1	8.2	0.0	1.6	348.6	0	0	0	0	0	0	0	0	2
APRIL	31	18	4.3	0.9	49.5	0.0	10.4	241.3	0	0	0	0	0	0	1	8	18
MAY	31	3	30.6	6.4	152.6	0.0	38.1	124.3	0	1	7	13	17	23	32	58	82
JUNE	31	0	50.5	10.5	111.0	9.0	28.7	56.8	12	16	34	42	50	63	70	76	83
JULY	31	0	124.8	25.9	200.6	30.3	53.3	42.7	38	59	111	116	131	141	162	181	195
AUGUST	31	0	154.7	32.1	336.0	38.9	67.6	43.7	90	104	118	131	134	144	179	209	281
SEPTEMBER	31	0	94.8	19.7	205.6	25.0	44.2	46.6	40	50	72	78	82	96	115	135	161
OCTOBER	31	9	18.6	3.9	95.8	0.0	23.3	125.4	0	0	0	5	12	19	23	32	57
NOVEMBER	31	25	2.8	0.6	61.0	0.0	11.0	394.4	0	0	0	0	0	0	0	2	6
DECEMBER	31	30	0.1	0.0	4.5	0.0	0.8	556.8	0	0	0	0	0	0	0	0	0
TOTAL	31	170	482	100	799	274	140	29	180	230	342	385	426	486	582	701	885

The Headings of the Table are as follows:

N the number of available years of observation for a given month
NO the number of observations with no precipitation
MEAN the arithmetic mean of precipitation over the series of N years expressed in mm
% percentage of total annual rainfall
Max absolute monthly maximum rainfall in the series of observations
Min absolute monthly minimum rainfall in the series of observations
s variance or standard deviation
CV coefficient of variation expressed in percent and representing the quotient of the standard deviation over the average monthly precipitation.

"The rain probability in years out of 10" indicates, in nine columns numbered from 9 to 1, the yearly probability of a given monthly precipitation for a given level expressed in years out of 10 or in percent probabilities.

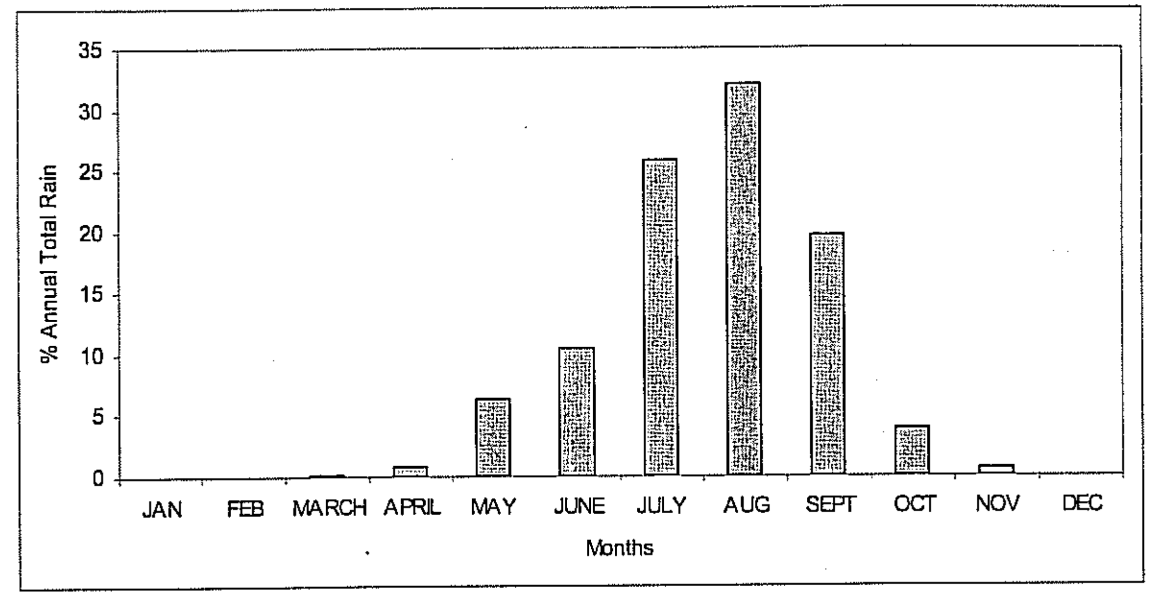


Figure 8: Monthly Rainfall Distribution in Madiama

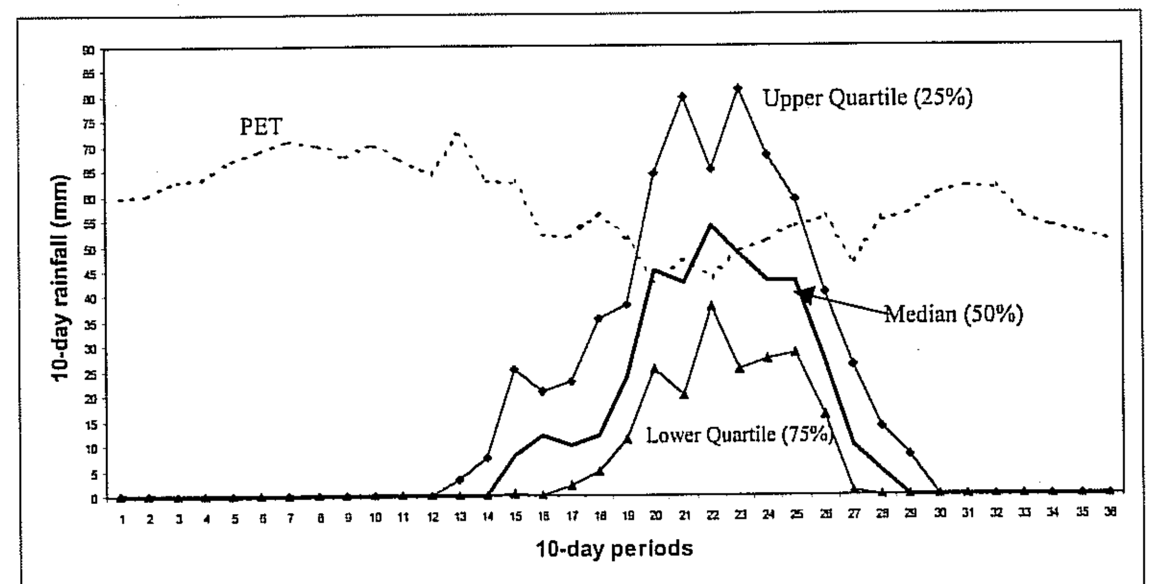


Figure 9: Confidence Interval for 10-day total rainfall and Potential Evapotranspiration (PET)

Table 2: Agroclimatological Parameters

COUNTRY: MALI STATION: DJENNE/MADIAMA PERIOD: 1970-2000

LONGITUDE: 4° 22 W LATITUDE: 13° 45 N ELEVATION: 279 m

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
PRECIPITATION (mm)	1.2	0.0	0.5	4.3	30.6	50.5	124.8	154.7	94.8	18.6	2.8	0.1	481.9
TEMP. AVERAGE (°C)	22.9	26.6	29.2	32.0	33.2	31.8	29.3	27.8	28.0	28.9	27.1	23.7	28.3
TEMP. MEAN MAX (°C)	32.2	35.8	38.0	39.6	40.3	38.0	35.0	32.5	32.7	35.0	35.2	31.6	35.5
TEMP. MEAN MIN (°C)	13.6	17.3	20.3	24.3	26.0	25.5	23.5	23.0	23.3	22.8	19.0	15.7	21.2
TEMP. MEAN DAY (°C)	26.3	29.9	32.5	34.7	35.7	34.0	31.3	29.4	29.7	31.0	29.9	26.4	30.9
TEMP. MEAN NIGHT(°C)	19.9	23.5	26.5	29.3	30.6	29.5	27.1	25.9	26.2	26.4	23.8	20.4	25.8
SOIL TEMP. MIN (°C)					34.8	33.0	31.2	29.8	30.9	32.3	30.6	29.8	31.6
SOIL TEMP. MAX (°C)					37.4	36.0	33.8	32.5	34.1	35.5	33.4	27.1	33.7
VAPOUR PRESSURE	7.1	7.2	8.1	10.0	16.5	24.5	27.5	28.3	29.3	26.3	16.0	9.5	17.5
TOTAL RADIATION	385.0	441.0	478.0	503.0	474.0	484.0	463.0	444.0	493.0	464.0	425.0	342.0	449.7
WIND SPEED 2M (m/s)	2.5	2.4	2.6	2.7	2.7	2.7	2.4	2.2	1.8	1.6	1.9	2.3	2.3
EVAPOTRANSP (mm)	169.0	178.0	238.0	247.0	238.0	196.0	157.0	139.0	142.0	147.0	152.0	148.0	2151.0

TYPE OF GROWING SEASON: NORMAL GROWING SEASON (with DRY PERIOD)

DRY DAYS: 263 ± 25 PREPARARTORY DAYS: 31 ± 19

INTERMEDIARY DAYS: 68 ± 20 WET DAYS: 34 ± 20

SEASON BEGINS ON: JUNE 29

BEGIN HUMID ON JULY 29

HUMID PERIOD (34 DAYS) ENDS ON SEPTEMBER 1

END OF SEASON ON SEPTEMBER 21 (TOTAL LENGTH IS 84 ± 25 DAYS)

TOTAL LENGTH OF GROWING SEASON IS 102 ± 25 DAYS

Table 3: Selected Local Crops Growth Cycles and Probabilities of Length of Rainy Season and Growing Period

Crop	Growing Cycle (days)	Yield in 1999 (Kg/ha)
Rice DM16	116	1988
Rice "Riz Blanc"	127	1813
Millet Gaouri	74	680
Millet Sagnori	87	878
Millet Sanio	107	748
Millet Toroniou	77	220
Sorghum M'Bayeri	104	1016
Sorghum M'Bayeri	113	820

Expected Length (days) of Growing Period and Total Rain in Years out of 10

	1	2	3	4	5	6	7	8	9
Rainy season[1]	118	110	101	92	84	75	67	58	50
Growing Period [2]	136	128	119	110	102	93	85	76	68
Total Rain (mm)	654	611	568	525	482	439	396	310	287

[1] Length of rainy season based solely on rainfall

[2] Length of Growing period based on rainfall and a soil water storage of 100 mm.

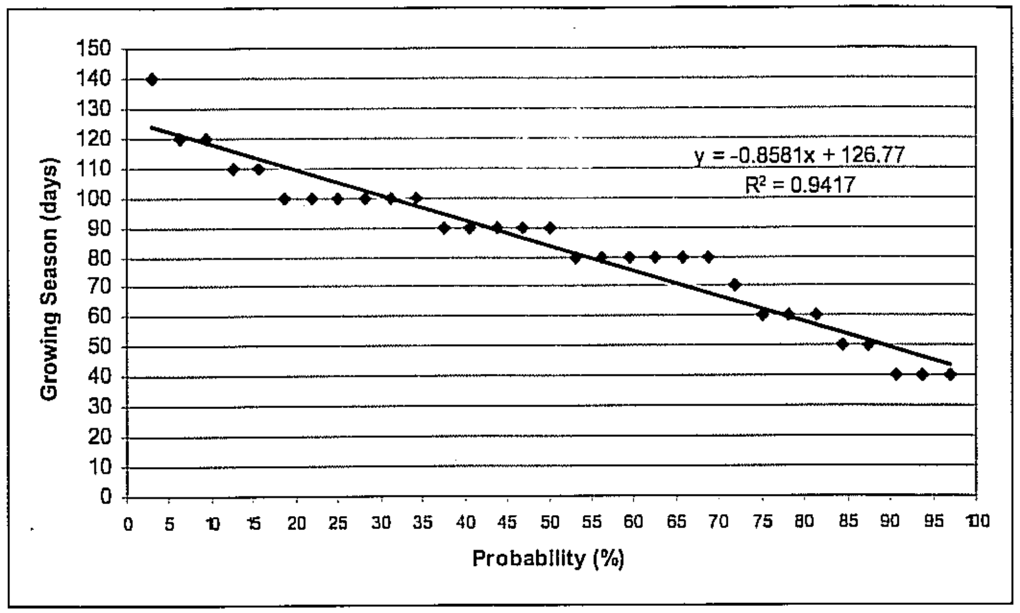


Figure 10: Probability Distribution of Growing Season Length

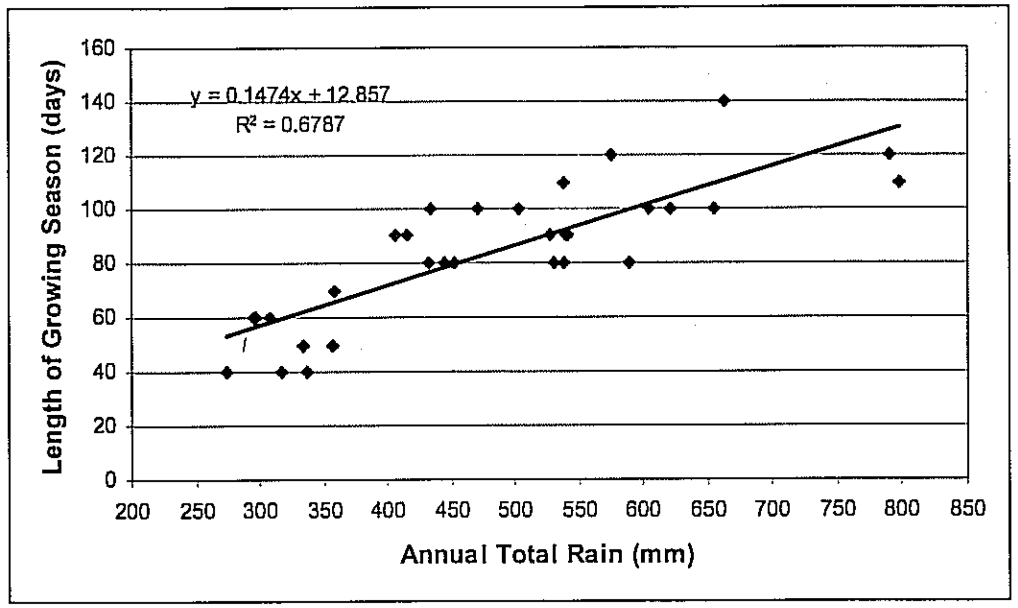


Figure 11. Length of Growing Season vs. Annual Total Rain

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