AGROCLIMATOLOGY RESEARCH AT THE ICRISAT SAHELIAN CENTER

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Abstract: Agroclimatology research at the ICRISAT Sahelian Center (ISC) is an integral part of the Resource Management Program (RMP). It is mainly concerned with resource assessment and environmental effects on biological processes. The two basic research approaches include: Macroclimatic Analysis or Strategic Planning Studies and Microclimatic Analysis or Tactical Studies. These two approaches are illustrated in the paper with suitable examples. Major activities undertaken in the strategic planning studies are rainfall analyses, soil-climatic zonation, water balance simulation, temperature analyses, and research on climate change. The analyses provide agronomically-relevant information for land use planning, choice of crop/cropping system and resource allocation. Our analysis of daily rainfall data in West Africa showed that the onset of rains is much more variable than the ending of rains. Based on our analysis of the length and frequencies of dry spells for 150 locations in the Sudano-Sahelian zone of West Africa, we demonstrated that dry spells from emergence to panicle initiation and during grain filling of cereal crops last longer than during panicle initiation to flowering. These results may be applied in several areas including agronomy, physiology and plant breeding. We also analyzed daily rainfall data for 21 locations in Niger for significant pointers regarding climate change, and discussed the implications of these changes for agriculture. In the area of tactical studies, we emphasized research on Conditional Cropping Systems (CCS), multilocational water balance studies, measurement and prediction of variations in evaporative losses from soil in millet based cropping systems, measurement of energy balance and evaporation over bare soil and fallow bushland, quantifying wind erosion and its effects on crop production, and climate and population dynamics of the pearl millet earhead caterpillar. Research on CCS from 1989 to 1991 clearly showed that it is possible to grow a relay crop of millet/cowpea during years with an early onset of rains, where the second crop of cowpea is grown for hay. This concept is currently being applied in on-farm projects conducted by the national programmes in West Africa. Our water balance studies at four locations from 1984-87 in Niger showed that applying a limited quantity of phosphorus to sandy soils results in 2-3 fold increases in water use efficiency and grain yield. Studies on the measurement and prediction of evaporation from low density millet crops that were conducted in collaboration with the Institute of Hydrology showed that evaporation from the soil surface constitutes a significant water loss and that up to 36% of the seasonal rainfall could be lost through direct soil evaporation. Porometry and lysimetry techniques were used to separate soil and plant evaporation. In studies conducted over two contrasting land surfaces, fallow bushland and bare soil, we showed that evaporation from bush vegetation changed little compared to the large change in evaporation observed over the bare soil. Wind erosion, especially during the early part of the rainy season, is one of the major constraints to crop cultivation in the Sahelian zone. We have initiated a multidisciplinary research effort to quantify the physical processes involved in wind erosion, assess damage to crops, evaluate management techniques to minimize the damage and to screen varieties. Some of the recent research results in this area are discussed.

Résumé: La recherche agroclimatique au Centre Sahélien de l'ICRISAT fait partie intégrante du Programme de gestion des ressources et porte essentiellement sur l'évaluation des ressources et les effets de l'environnement sur les processus biologiques. Les deux voies de la recherche sont axées sur l'analyse macroclimatique d'une part - ou études stratégiques de planification - et une analyse microclimatique - ou études tactiques - d'autre part. La première approche comporte comme activités essentielles: l'analyse de précipitations, le zonage pédoclimatique, la simulation du bilan hydrique, les analyses de température et la recherche sur les changements climatiques. Ces analyses procurent les données pertinentes du point de vue agronomique permettant de planifier l'utilisation des terres, le choix des systèmes de cultures et l'affectation des ressources. Notre analyse des pluies quotidiennes en Afrique de l'ouest a montré que la variabilité des précipitations est bien plus grande au début qu'à la fin des pluies. Nous avons pu démontrer, sur la base des relevés de durée et de fréquence des périodes de sécheresse pour 150 sites dans la zone sudano-sahélienne de l'Afrique de l'ouest, que ces périodes sont plus longues de la levée des semis aux stades de formation des panicules et de remplissage des grains que du stade de la formation des panicules à celui de la floraison. Les applications de ces résultats sont nombreuses, notamment en agronomie, physiologie et sélection des plants. Nous avons aussi analysé les données pluviométriques quotidiennes sur 24 sites au Niger afin d'identifier les indicateurs significatifs de changements climatiques et entrepris d'en analyser les conséquences pour l'agriculture. Dans la deuxième approche, celle des études tactiques, nous mettons l'accent sur les systèmes de cultures sous conditions, les études multilocales de bilan hydrique, la mesure et les prévisions des variations des pertes dues à l'évaporation du sol dans les systèmes de cultures basés sur le mil, les mesures de bilan énergétique et de l'évaporation sur le sol nu et jachère arbustive, la quantification de l'érosion éolienne et ses effets sur la production agricole ainsi que sur la dynamique climat-population de chenilles de l'épi du mil (*Pennisetum glaucum*). Les recherches entreprises sur les systèmes dits de "cultures sous conditions" de 1989 à 1991 ont clairement montré qu'il est possible, lorsque les pluies commencent tôt, de cultiver mil et niébé en alternance en destinant le niébé à servir de foin. C'est le concept courramment appliqué dans les projets-pilote conduits sur les champs des paysans par les Programmes Nationaux en Afrique de l'ouest. Nos études de bilan hydrique sur 4 sites au Niger de 1984 à 1987 ont montré qu'on doublait, voire, triplait l'efficacité d'utilisation de l'eau et les rendements par l'apport d'une petite quantité de phosphore sur sols sableux. Les études menées en collaboration avec l'Institut d'Hydrologie sur la mesure et la prévision de l'évaporation des cultures de mil clairsemées ont montré que l'évapotranspiration à la surface du sol représente une perte significative d'eau et qu'on pouvait relever jusqu'à 36% de perte de pluies saisonnières, due à cette évaporation directe du sol. Les évaporations du sol et de la plante ont pu être mesurées séparément grâce aux techniques de porométrie et lysimétrie. Enfin, les mesures effectuées sur deux types de relief contrastés, jachère arbustive et sol nu, ont montré que les taux d'évaporation et les bilans énergétiques étaient très différents d'un site à l'autre. L'érosion éolienne, notamment au début de la saison des pluies, est l'une des contraintes majeures à l'agriculture en zone sahélienne. Nous avons entamé des recherches multidisciplinaires pour chiffrer les processus physiques qui interviennent dans cette érosion, évaluer les dégâts causés aux cultures ainsi que les techniques de gestion permettant de limiter ces dégâts et, enfin, pour cribler des variétés prometteuses. Nous présentons en conclusion quelques résultats récents de ces activités.

Agroclimatology research at the ICRISAT Sahelian Center (ISC) is an integral part of the Resource Management Program (RMP). The primary objective of RMP is to develop production systems that match material from ICRISAT's crop improvement programmes to the physical and social environments prevailing in the West African semi-arid tropics (ICRISAT, 1987). In this context, "matching" means attempting to maximize production without sacrificing yield stability from year to year and without squandering irreplaceable resources such as top soil and groundwater reserves. There are marked differences in rainfall, soils and other agroecological factors between different climatic zones in West Africa, as well as in the socio-economic environments. Such varied environments require the development of a range of solutions and general concepts for resource management.

The need for a more efficient and effective system of natural resource management is greatest in West Africa, since this is the only region of the world where the *per capita* food production has declined over the past two decades, while the ratio of food imports to total food consumption has increased. Several factors are responsible for the low agricultural productivity in West Africa. However, the most important are climatic: the low and highly variable rainfall and the high demand for water imposed by the high temperatures and radiation throughout the year. These factors cause great variability in yearly crop yields. Total crop failures occurred in many parts of West Africa from 1968 to 1973. The demand for food far exceeded the limited productivity associated with traditional agricultural methods during such dry years. Even more serious is the apparent degradation of soils and vegetation. Hence there is an urgent need to develop new technologies in resource management that maximize the efficient use of the limited climatic and soil resources for achieving greater yield stability, while protecting the productivity of the region's fragile soils.

THE AGROCLIMATIC RESEARCH APPROACH AT ISC

Developing an improved crop-production technology requires a more complete and quantitative understanding of the temporal and spatial variation of natural resources, and of the nature and degree of their influence on crop growth and productivity. Hence agroclimatology research in RMP is mainly concerned with resource assessment and environmental effects on biological processes. The two basic research approaches are:

a) the assessment of the available natural resources to enable long-term development planning or crop diversification. This approach could be termed Macroclimatic Analysis or Strategic Planning Studies.

b) the monitoring of short-term variations in crop growth and development due to intraseasonal variations in weather during the growing season to facilitate operational decisions. This approach is termed Microclimatic Analysis or Tactical Approach.

The foregoing approaches are illustrated hereafter by suitable examples. Since West Africa has distinct and varied bioclimatic zones, one question that could be asked is whether the strategies suggested are applicable globally. It should be emphasized that all area-specific questions should be examined thoroughly before drawing conclusions. A careful analysis of traditional systems can yield valuable information about climatic hazards and constraints.

MACROCLIMATIC ANALYSES OR STRATEGIC PLANNING STUDIES

Macroclimatic Analyses or Strategic Planning Studies are mainly concerned with evaluating natural resources from the agronomic point of view, on a regional and national scale. The collection and classification of soil, water and climatic resources provide a data base that may be used for designing appropriate strategies for their exploitation. Analyses are made of rainfall probabilities, drought frequencies and probabilities, rainfall events such as the onset and end of the rains, temperature probabilities and simple water balance.

Rainfall analyses

An analysis of historical rainfall data can be used in assessing cropping potential and evaluating cropping risks. In our climatic data base for West Africa, we have focused initially on collecting long-term daily rainfall data for a large number of locations. This was necessitated by the fact that the use of monthly averages to describe seasonal regimes is often suspect, not only because moisture availability over a short period of even 10 days is critical but also the onset and end of season -- either average or individual years -- do not coincide with calendar months. Our first report on the rainfall climatology of a SAT region was on Niger (Sivakumar *et al.*, 1979), followed later by reports on Mali (Sivakumar *et al.*, 1984) and Burkina Faso (Sivakumar and Faustin, 1987). Some of the major aspects of the rainfall analysis are described hereafter.

Understanding rainfall variability: Persistent droughts during the 1970s and 1980s focused a great deal of attention on the rainfall variability in West Africa, which should be understood in its temporal and spatial dimensions.

Temporal variability: Temporal or time-dependent variations in rainfall are quite common in West Africa and can be represented at three time scales: annual, monthly, and daily. The coefficient of variation (CV) of annual rainfall is between 15-30%. For example, the variation in mean annual rainfall at Banfora in Burkina Faso (Figure 1) over the last 64 years is about 25%. Although the mean annual rainfall at Banfora (represented by the horizontal line in the figure) is 1148 mm, since 1968 rainfall has been below normal; in 1983 it was only 480 mm. The variability in the monthly rainfall is larger since the rainfall is usually limited to the summer months i.e., May to October. Aridity prevails during the rest of the year and is most pronounced from December to February. There are major differences between the maximum, average and minimum monthly rainfall. Mean rainfall is always higher than the median.

Rainfall variability is greatest in comparisons between specific days. Generalized characteristics of daily rainfall for four locations in the Sudano-Sahelian zone (Table 1) show that number of rainy days, as well as the average rainfall per rainy day, increase from May and reach the maximum by August. Differences in the average duration between the rainy days of different locations show that at Hambori and Niamey, the risk to crop establishment in June is higher. At Kolda, where the rains begin late, the duration between the rainy days in May is similar to that at Hambori.

Table 1. Generalized daily rainfall characteristics for four locations in the Sudano-Sahelian zone

RD = Number of rainy days; RRD = Rain (mm) per Rainy Day; DRD = Duration between rainy days

	May			Jun			Jul			Aug			Sep			Oct			Annual	
Station	RD	RRD	DRD	RD	RRD	DRD	RD	RRD	DRD	RD	RRD	DRD	RD	RRD	DRD	RD	RRD	DRD	RD	RRD
Hamb.	2	5.0	20.1	5	8.4	9.1	10	11.7	14 1	11	14.1		7	9.6	4.6	2	6.5	19.1	38	9.1
Niam.	4	8.8	11.5	7	11.0	5.3	10	14.2	2.8	13	15.0	1.8	8	11.0	4.1	2	8.0	18.6	44	11.7
Ouaga	6	12.8	3.2	9	12.4	2.1	12	15.5	1.3	16	16.0	1.9	12	11.9	11.1	4	8.8	28.0	63	11.9
Kolda	2	9.0	18.7	9	14.4	3.4	15	16.8	1.5	19	18.3	1.3	16	17.9	1.4	8	14.4	6.0	69	15.2

Spatial variability: Rainfall in the semi-arid regions is characterized by high spatial variability (Sharon, 1974; Jackson, 1977). Spatial variability, using monthly means for West Africa, has been studied by Nicholson (1980) who used correlations between individual stations to derive rainfall anomaly types. A systematic network of rain gauges is not often available to monitor the spatial variability of single rain storms in West Africa. We installed 17 rain gauges on a 400 m grid over 500 ha at the research center at ISC in order to study this aspect. Data from the rain gauges were plotted after each rainstorm, and maps were made showing the spatial variability of rainfall. On 22 July 1986, 21.2 mm of rainfall was recorded at the meteorological observatory. However, over the ISC farm, rainfall ranged from 34 mm in the northwest corner to 8.9 mm in the southeast corner (Figure 2).

Analysis of the data collected during 1986 and 1987 showed that the average relative variability of individual rainstorms, defined as the percentage deviation from the mean, varied from 2 to 62%, while the variability over the rainy season was 17% (Sivakumar and Hatfield, 1990). Storm volume showed a large influence on the correlation decay with distance. Point rainfall measurements were better correlated with the network average rainfall than with the rainfall recorded at the meteorological station.

Persistency and extreme magnitude of variability: The rainfall variability discussed in the foregoing leads to instability in the traditional mean figures for crop production. The recent drought in the Sahel is not unique. Annual rainfall deviations from the mean at Niamey for the past 80 years (Figure 3) indicate that droughts occurred between 1910 and 1920, 1940 and 1950, 1968 and 1973, and 1976 and 1984. The 1950s were generally wet (Sivakumar, 1986a). Severe, extended droughts are a recurrent feature in the region's climatology (Nicholson, 1982) but the 1960-80 drought around Niamey was unique in its persistence. Rainfall deviations 20-40% below the mean were common. Nicholson (1981) showed that in 1950, rainfall all over West Africa was above normal, even up to 250% above normal in some locations. However in 1970, rainfall was below normal throughout the region.

Geographical patterns of rainfall variability: Rainfall fluctuations are associated with a preferred geographical pattern. For example, the reduction in the mean annual rainfall in Niger after 1969 (Figure 4) is characteristic of the entire country (Sivakumar, 1989). This figure uses pre- and post-1969 averages to examine the effect of the post-1969 droughts on the long-term rainfall averages. The southward movement of rainfall isohyets after 1969 was evidence of the severity of droughts facing the country. Around 16° N, the region that received an average annual rainfall of 550 mm before 1969 received only 400 mm after 1969. These patterns indicate that abnormal rainfall conditions are nearly continental in scale.

Rainfall probabilities: Decadal precipitation totals for a long period of time are available for numerous locations in the Sudano-Sahelian zone and could be analyzed by fitting the most appropriate mathematical function to rainfall data, when computing the probabilities of receiving a certain amount of rainfall e.g., 10, 20, 30 mm etc. Markov chain models for precipitation analysis, introduced by Gabriel and Neumann (1962) are widely used. Applications of these models in agricultural planning has been discussed by Stern and Coe (1982).

Probabilities of receiving rainfall of 10 mm or more during each decade (Figure 5) for Hambori, Niamey, Ouagadougou and Kolda clearly show the differences in the onset of rains from north to south. Rainfall probabilities could be used effectively to show the seasonal progression of rainfall dependability (defined as 75% probability by Hargreaves, 1974), thereby providing a useful means to differentiate locations. At Hambori, the probabilities do not reach the dependable level of 75% probability until after decade 19, while at Ouagadougou, located further south, this occurs 40 days earlier by decade 15. However, such large differences in probabilities between these two locations are not observed towards the end of the season.

Date of onset of rains and length of growing season: In West Africa, the date of the first rains is important in planning agricultural operations, particularly sowing. Several studies (Stanton and Cammack 1953, de Geus 1970, Jones and Stockinger 1972, Kassam and Andrews 1975) showed that early establishment of crops results in higher yields.

Sivakumar (1988) computed the dates of the first and last rains and the length of the growing season for each year from the data base for 58 locations in the Sudano-Sahelian zone. A highly significant relationship was observed between the date of the onset of the rains and the length of the growing season across the southern Sahelian zone from which the potential length of the growing season can be assessed with reference to the date of the onset of the rains. The early onset of rains, relative to the computed mean date of the onset for a given location, results in a longer growing season. This is illustrated in Table 2 for Niamey, Niger (data base 1904-1984).

Table 2. Probabilities of growing season length exceeding specified durations for variable onset of rains for Niamey, Niger

Date of onset of rains	Length of gro 75	95	115	135
24 May	100	99	48	1
2 June	100	87	11	0
12 June	99	48	1	0
22 June	87	11	0	0
2 July	48	1	0	0

The average date of the onset of rains at Niamey is computed as 12 June, and the average length of the growing season is 94 days. However, if the onset of rains occurs 20 days early ie., by 24 May, there is a 43% probability that the growing season will exceed 115 days. On the other hand, if the rains are delayed until the beginning of July, there is only a 2% probability that the growing season will exceed 95 days.

Empirical analysis of dry spells for agricultural applications in West Africa: Recurring droughts and decreased agricultural productivity in West Africa during the last two decades emphasize the need for a clearer understanding of the length of dry spells, and their frequencies and probabilities (Sivakumar, 1991a). The simplest calculations of dry spells for general applications involves computing the probabilities of maximum and conditional dry spells exceeding a user-specified threshold value from a given calendar date. Table 3 shows the probabilities of dry spells exceeding seven, 10 and 15 days within the following 30 days starting from the first day of each decade of the year at Niamey, Niger. Data are presented from the beginning of May to the beginning of October, the period during which rains are received at Niamey. These data provide a quick overview of the drought risks during the year. For example, the risk of a long dry spell before 1 June is still quite high and exceeds 70%. The probabilities of both the maximum and conditional dry spells exceeding 10 days are above 70% from the middle of September, which suggests that standing crops after that time will face increasingly greater risks of water shortage.

Table 3. Probability (%) of maximum and conditional dry spells exceeding indicated lengths within 30 days after a starting date at Niamey, Niger

Starting date	Maximum dry spell (days)			Conditional dry spell* (days)		
	>7	>10	>15	>7	>10	>15
1 May	100	100	83	100	93	57
11 May	97	93	70	93	80	59
21 May	97	83	60	87	70	50
1 June	87	67	53	80	43	23
11 June	70	43	23	63	27	7
21 June	53	27	10	50	13	0
1 July	53	20	7	43	13	3
11 July	43	10	3	33	10	3
21 July	33	17	3	23	7	0
1 August	30	7	0	27	7	0
11 August	47	10	0	43	3	0
21 August	57	13	0	57	13	0
1 Sept.	80	23	13	77	20	13
11 Sept.	97	70	43	97	67	40
21 Sept.	100	93	70	100	90	63
1 Oct.	100	97	97	97	97	93

* Calculation of dry spell conditional on the previous day before the start of the period under consideration being rainy.

It is important to consider the different periods that follow the sowing of a crop for more precise applications in agriculture, since sowing dates in the semi-arid West African regions vary from year to year. Assuming that the computed date for the beginning of rains each year is also the date of sowing, the length of dry spells (or days until the next day with rainfall greater than a threshold value) at different probability levels can be computed for consecutive 10-day periods from sowing (Sivakumar, 1991b). A plot of the lengths of dry spell at different rainfall thresholds and two probability levels for Ouagadougou (mean annual rainfall 792 mm), Burkina Faso is shown in Figure 6. One significant feature that emerges from the data in Figure 6 is the pronounced drop in the drought risk (or the waiting period for rainfall) from 20 DAS to 60 DAS. This is more evident at the 90% probability level

(Figure 6b) than at the 50% probability level (Figure 6a). Assuming that a pearl millet variety of 90 days maturity duration comes to the stage of panicle initiation within 20 days after sowing (DAS) and to flowering by 50-60 DAS, the implication is that dry spells from the stage of emergence to panicle initiation last longer than those during panicle initiation to flowering. The length of dry spells increases with time after 100 DAS.

Data on the lengths of dry spells could also be used as a guide for breeding varieties that have maturity durations that fit the climatic characteristics of different locations. An example of this application is shown in Figure 7 for Niamey, Niger (mean annual rainfall 560 mm), Kaolack, Senegal (800 mm), Ouagadougou, Burkina Faso (830 mm) and Bougouni, Mali (1260 mm). The length of dry spells in Niamey increases with time after 90 DAS. Kaolack and Ouagadougou, with nearly similar mean annual rainfall, show some differences in the lengths of dry spells. Dry spells become progressively longer after 90 DAS at Kaolack and after 120 DAS in Ouagadougou. Breeding strategies should be oriented towards maturity at 80 days for Niamey, 90 days for Kaolack, 110 days for Ouagadougou and 140 days for Bougouni.

Sivakumar (1991b) presented the length of dry spells and their frequencies for 150 locations in West Africa. An analysis of drought frequencies showed that the frequencies of the lowest dry spell range of < 5 days increase asymptotically with increasing annual rainfall; with dry spells exceeding 20 days, the frequencies decrease sharply with increasing mean annual rainfall.

Soil-climatic zonation for setting research priorities

Rainfall and PE data indicate that with regard to rainfed agriculture, the Sudano-Sahelian zone cannot be treated as one homogenous zone. Research strategies for any given crop must take account of both climatic variability and very different soil types. Questions also remain about the criteria used in the selection of research sites for regional programmes, the representation of contrasting environments in regional networking and the assessment of the national research programmes' needs for strengthening research in important climatic zones.

Sivakumar (1986b) has developed a soil climatic zonation for West Africa that superimposes the growing season lengths on the Soils Map of Africa (UNESCO 1977) in order to answer some of the foregoing questions. Soil-climatic zones in the Sudano-Sahelian zone are prioritized and shown in Table 4.

The water balance approach

The real-time rainfall data collected through the large network of rain gauges in the Sudano-Sahelian zone have not been adequately exploited in estimating available soil moisture for crop growth. Several water balance models with varying flexibilities of input data requirements, computer processing time and output data features are currently available and should be used to determine the available water contents of soils during the growing season using real-time weather data. A comparison of these data with crop water requirements at different growth stages should facilitate the choice of a suitable crop or cropping system for a given location. Examples of the use of this approach have been given by Virmani *et al.* (1978) and Sivakumar and Faustin (1987).

Table 4. Soil-climatic zones, their approximate extent and priority ranking in the Sudano-Sahelian zone

Soil type	Length of growing season (days)	Approximate extent of ranking ('000 ha)	Percentage of total area	Priority ranking
Luvisols	100-150	32 010	24.0	1
Arenosols	60-100	29 973	22.5	2
Luvisols	60-100	10 268	7.7	3
Vertisols	100-150	5 455	4.1	4
Vertisols	60-100	4 030	3.0	5
Regosols	100-150	12 200	9.1	6
Regosols	60-100	7 473	5.6	7
Nitosols	100-150	2 855	2.1	8
Fluvisols	100-150	3 920	2.29	9
Fluvisols	60-100	2 538	1.9	10
Arenosols	100-150	2 250	1.7	11
Planosols	60-100	2 443	1.8	12
Cambisols	60-100	1 758	1.3	13
Cambisols	100-150	813	0.6	14

Temperature analyses

Air temperatures in the Sudano-Sahelian zone are usually higher because of the high radiation load. Temperatures increase and rainfall decreases from south to north. We have used the data for 64 stations in the Sudano-Sahelian zone to show mean monthly and annual maximum and minimum air temperature patterns. The cumulative frequency distribution patterns of minimum and maximum air temperatures for the whole year and for the rainy season is shown in Figure 8. For the Sudano-Sahelian zone as a whole, annual as well as rainy season minimum temperature ranges are small in comparison with the maximum temperature ranges (Sivakumar, 1989). When compared with the annual means, the minimum temperatures for the rainy season are about 2 to 2.5°C higher while maximum temperatures are lower.

Mean temperatures for the rainy season could be misleading because for certain crop growth phases the air temperatures are in fact much higher. Cumulative frequency distribution of minimum and maximum air temperatures at the time of sowing (May-June) and harvesting (Sept-Oct) show (Figure 9) that mean maximum temperatures at the time of sowing can exceed 40°C. Probabilities of maximum air temperatures exceeding defined thresholds have been reported for Mali (Sivakumar *et al.*, 1984) and Burkina Faso (Sivakumar and Faustin 1987).

Research on climatic changes

Over the past two decades, recurrent droughts and associated famines in West Africa have caused ample concern in the international community as to whether long-term agricultural production could be sustained in this region. One of the basic questions related to this aspect is the continuity of the rainfall decline that has been observed thus far. We have analyzed the long-term daily rainfall data for Niger to ascertain the degree of climate change, if any, that has occurred (Sivakumar, 1991c).

Rainfall in Niger is unimodal and over 80% of the annual rainfall is received in three months i.e., July, August and September. In order to verify the correspondence between rainfall patterns during these three months and the annual rainfall, moving averages for Filingue, Niger (mean annual rainfall: 430 mm) have been plotted (Figure 10). The rainfall pattern in August follows that of the annual rainfall (r= 0.90) more closely than in July (r=0.67) and September (r=0.71).

Analysis of rainfall events and the rainy season: The analysis of monthly rainfall totals does not provide sufficient information on the question of the timing of rainfall and whether it is adequate enough to satisfy crop water requirements. Hence, long-term daily rainfall data for the 21 locations in Niger were analyzed for the periods 1945-64 and 1965-88 for the following events and their standard deviations: the date of the onset of rains, the date of the ending of rains and the length of the growing season

Variations in the average dates of the beginning and end of the rains and the length of the growing season for the two periods for the selected locations in Niger are shown in Table 5. The data show that after 1965, the onset of rains was delayed at most of the stations with the exception of Agadez, Birni N'Konni, Gaya and Tanout. The result of the delayed onset and early ending of rains at most of the stations is the reduced length of the growing season by 5-20 days across different locations in Niger after 1965. Also, the standard deviation of the onset and ending of rains as well as the length of the growing season has increased for the period after 1965. The implication is that cropping has become increasingly risky.

A comparison of the different rainfall parameters for two time periods (1945-64 and 1965-88) for August is shown in Table 6. In order to assess the significance of change in the rainfall parameters between the two periods, a Student t-test was carried out and the level of significance was indicated where applicable. All the stations with the exception of Gaya showed a significant decline in total rainfall in August. Nine of the 12 locations studied also registered a significant decline in the number of rainy days in August. Implications of these changes for agriculture in Niger were discussed by Sivakumar (1991c).

MICROCLIMATIC ANALYSIS OR TACTICAL STUDIES

The strategic studies discussed in the foregoing are mainly concerned with long-term crop planning. However, within-season variations in weather elements have a profound effect on crop growth and yield. A wealth of meteorological information is currently available on a real-time basis to users and the availability of high speed computers should make it feasible to provide easy access to this information on a regional basis. This information could be used to advise on operational decisions at the farm level to maintain crop yields. Such tactical decision-making is based on sound knowledge of the effect of variations in weather elements and the current management practices at the field scale on crop growth, development and yield. This requires an understanding of the physical and physiological processes governing crop growth. In principle, microclimatic studies could address a variety of issues at different scales ranging from field crops and individual plants to single leaves. Our studies are conducted at the field scale with the primary objective of providing information for operational decision-making and for using data to develop simple models for field applications.

Table 5. Variation in the average dates of beginning and ending of rains and the length of the growing season for two periods at selected locations in Niger (s.d. = Standard deviation)

Location	Period	Beg. of rains		End of rains		Length growing season	
		Avg. date	s.d.	Avg. date	s.d.	Avg.(days)	s.d.
Agadez	1945-64	27 July	21.7	5 Sept	10.5	41	21.9
	1965-88	22 July	21.9	24 Aug	12.1	33	22.1
Birni	1945-64	10 June	20.8	2 Oct	9.5	115	21.0
N'Konni	1965-88	6 June	18.2	22 Sept	10.4	109	21.7
Gaya	1945-64	2 June	13.1	8 Oct	11.0	129	20.1
	1965-88	26 May	11.9	2 Oct	8.9	130	17.6
Maine	1945-64	2 July	19.6	20 Sept	14.5	81	23.5
Soroa	1965-88	4 July	21.3	11 Sept	17.9	70	29.4
Maradi	1945-64	10 June	18.9	29 Sept	12.5	111	24.6
	1965-88	24 June	16.0	19 Sept	13.0	87	18.4
N Guigmi	1945-64	19 July	17.5	3 Sept	9.8	47	19.4
	1965-88	26 July	17.0	1 Sept	11.9	38	21.8
Niamey	1945-64	7 June	16.7	28 Sept	10.3	114	17.6
	1965-88	9 June	18.1	24 Sept	15.3	108	22.9
Tahoua	1945-64	23 June	20.8	29 Sept	12.0	98	22.4
	1965-88	29 June	24.2	15 Sept	16.8	79	25.8
Tillabery	1945-64	25 June	18.7	30 Sept	12.4	97	24.1
	1965-88	28 June	24.2	15 Sept	14.7	79	23.6

Table 6. Comparison of different rainfall parameters for two time periods for different locations in Niger during the month of August

	Rainfall		Rainy Days		Rain/rainy day (mm)		Duration between rainy days	
Location	1945-64	1965-88	1945-64	1965-88	1945-64	1965-88	1945-64	1965-88
Agadez	99.6	43.8**	11.9	8.0	8.4	5.5	2.6	5.5
B. N'Konni	241.7	154.8**	15.7	13.4*	15.4	11.6	1.4	1.9
Gaya	264.1	229.0	13.3	16.4*	19.9	14.0	1.7	1.5
Maine Soroa	190.6	132.2*	14.1	11.7*	13.5	11.3	1.7	2.8
Maradi	257.8	162.9**	15.9	13.7*	16.2	11.9	1.4	1.9
N'Guigmi	149.6	93.0*	11.1	8.9*	13.5	10.5	2.9	4.6
Niamey	221.2	160.4**	15.9	13.2*	13.9	12.2	1.3	2.0
Tahoua	160.4	115.6**	15.4	12.1**	10.4	9.6	1.3	2.2
Tillabery	227.7	121.0**	15.0	12.0**	15.2	10.1	1.6	2.3

* Difference between the two time periods significant at 5% level
** Difference between the two time periods significant at 1% level

Research on conditional cropping systems

Our analysis of the relationship between the date of onset of rains and the length of the growing season, which was described earlier, suggests that agricultural planning in the Sahelian region should be formulated from the alternatives that can be offered to the farmer, based on the onset of rains (Sivakumar, 1988). It is essential to match the maturity duration of the crop species/variety to the probable season length to ensure yield stability at the farm level. We have developed a computer program that calculates the probable season length from the date of onset of first rains at a given location. In view of the differing growing season lengths that result from the different dates of onset of rains, we have developed the concept of "Conditional Cropping Systems (CCS)" where the choice of a cropping system in a given year is conditioned by the onset of rains. For example, at Niamey, the recommended CCS is millet/cowpea relay crop with early rains, millet with normal rains and cowpea with late rains. The objective here is to maximize the production during good years by exploiting the long growing season and minimize the effects of drought by making the most efficient use of the scarce rainfall if a short season length occurs.

We tested this concept of CCS in field studies conducted at ISC from 1986-1991. Data on soil water profiles showed that at the time of millet harvest in the CCS treatment, profile soil water was adequate to establish a second crop of cowpea for hay (Sivakumar, 1990). This enables efficient exploitation of soil moisture. In addition, the combined water use of the two crops, millet and cowpea was much higher. Results of this study suggested that it is possible to establish a second rainfed crop of cowpea for hay where the farmers traditionally grow only millet (Sivakumar, 1990) by tailoring management tactics to weather conditions in years with early onset of rains. Our studies also suggested that in years with late onset of rains, growing season length for millet production is likely to be much shorter, resulting in lower levels of dry matter production and yield.

Multilocational water balance studies

We know that the physical processes of soil water flow such as infiltration, redistribution, drainage, evaporation and water uptake by plants are strongly interdependent because they occur sequentially or simultaneously. It is thus necessary to consider field water balance to evaluate the field water cycle as a whole, and the relative magnitude of the various processes comprising it over a period of time. Data on soils, especially on physical and hydraulic properties, are not readily available in West Africa. We have analyzed samples from four different soil profiles in Niger, at Sadore, Dosso and Bengou for physical, chemical and hydraulic properties (Sivakumar *et al.*, 1988). These data show some distinct differences between these soils (Figure 13). Since these three sites were located on a rainfall gradient from 560 mm to 840 mm, they offered a unique opportunity to examine the variations in the components of soil water balance.

We conducted multilocational water balance studies in Niger from 1984-87, in order to understand the variations in crop growth and development with changes in available soil water on the different soil profiles shown in Figure 13. We grew pearl millet at Sadore and Dosso; at Bengou, where the mean annual rainfall is 839 mm, the crops included sole crops of pearl millet, sorghum, maize and groundnut, and intercrops of millet/groundnut and millet/cowpea. We applied N, P and K at 45, 20 and 25 kg ha^{-1} or no fertilizer; bare soil was an additional treatment. We monitored soil moisture at 10-15 day intervals throughout the growing season, and measured dry matter and leaf area index at regular intervals.

Our data showed that a major consequence of fertilizers use is increased water-use efficiency (Table 7). Early, vigorous growth results in a large ground cover early in the season. This reduces the proportion of water that would be lost through soil evaporation to some extent, thus facilitating an effective and efficient use of rainfall. Our studies also indicated that different cropping possibilities exist under the same climatic regime because of differences in the soil types under consideration and their management.

Measurement and prediction of variations in evaporative losses from soil in millet-based cropping systems

In West Africa, millet is traditionally grown in wide rows and planting densities are very low. In such sparse canopies, evaporative losses from the soil surface constitute a significant proportion of the total water loss. It is essential to have an improved description of the energy balance and evaporation from the sparse canopies to increase the productivity of such traditional cropping systems. We took detailed measurements of the plant, soil and total evaporation in a sparse millet crop in a collaborative project with the Institute of Hydrology (IH), U.K. and the ICRISAT Sahelian Center. Measurement techniques included the use of state of the art eddy correlation devices (The "Hydra") developed at IH, porometry to measure transpiration and use of microlysimeters to measure soil evaporation. Some of the significant results from this study are:

a) Soil evaporation (E_s) constitutes a significant loss in the water balance of sparse vegetation in West Africa. About 36% of the seasonal rainfall of 560 mm could be lost as direct soil evaporation (Wallace *et al.*, 1989a).

b) Immediately following rain, E_s was high, between 2 and 2.5 mm d^{-1} and dropped rapidly until one week later, when it was less than 0.5 mm day^{-1}. Cumulative E_s is linearly related to the square root of time elapsed since the last rainstorm (Wallace *et al.*, 1989b).

c) Leaf conductances were found to be high, up to 12 mm s^{-1} or 480 mmol m^{-2} s^{-1} and varied according to the leaf surface, age and position in the canopy (Wallace *et al.*, 1990a). Canopy conductances are very low and varied both diurnally and seasonally because of the low leaf area index in the sparse canopies.

d) The Hydra can provide routine measurements of evaporation and sensible heat flux to an accuracy of around 10% with experienced installation and operation, (Wallace *et al.*, 1989b).

Table 7. Effects of N, P and K fertilizer on water use (WU), grain yield (Y) and water-use efficiency (WUE) for pearl millet grown at 3 sites in Niger during the 1985 rainy season

Site	Rainfall (mm)	Treatment	WU (mm)	Y (kg ha^{-1})	WUE (kg ha^{-1})
Sadore	543	Fertilizer	382	1570	4.14
		No fertilizer	373	460	1.24
Dosso	583	Fertilizer	400	1700	4.25
		No fertilizer	381	780	2.04
Bengou	711	Fertilizer	476	2230	4.68
		No fertilizer	467	1440	3.08

Measurements of energy balance and evaporation over bare soil and fallow bushland

The widespread deterioration of large areas of savanna in the semi-arid regions of Africa is believed to be associated with the overexploitation of marginal land via the removal of wood and overgrazing (Barrow, 1987). Whatever the cause, the net effect is to degrade the savanna vegetation to the point where sizeable areas of bare soil appear between vegetation. The proportion of bare soil is a measure of the degree of land degradation. Previous modelling studies of the Sahel were based on simple land surface parameterizations and also suffer from a lack of basic data against which they can be calibrated. According to Cunnington and

Rowntree (1986), the rate of evaporation and net radiation have important effects on simulations of the Sahelian climate.

In a collaborative study with the Institute of Hydrology, U.K. (Wallace *et al.*, 1990b), we compared the net radiation and evaporation over two contrasting land surfaces, fallow bushland and bare soil in Niger. Data presented for six days, before and after a large rainstorm, showed that evaporation from the bush vegetation changed little in comparison with the large change in evaporation observed over bare soil (Figure 12). Net radiation over the bush vegetation was 20% greater than that over the bare soil, but only 12% greater than that over the wet bare soil. Over the fallow bushland, before the rainstorm, changes in the net radiation before and after a rain were small. In contrast, over the fallow bare soil, the amount of net radiation used to evaporate water increased from 50% before the rain to 65% afterwards. Our preliminary measurements showed that collection of such data is important to understand the interaction between vegetation and climate, and its implications for land degradation.

Quantifying wind erosion and the effects on crop production

Environmental conditions during crop establishment in low rainfall areas are usually harsh, since rains received at the time of sowing follow a long and hot dry season. When strong winds blow over bare, erodible soils, especially at the beginning of the season, the potential damage includes sand blasting, burying of parts of or whole plants, growth reduction and low survival rates. Plant responses range from delays in emergence, reduced growth and development to the complete death of cultivated crops. These result in sub-optimal plant stands and farmers are often forced to replant their crops.

Although the consequences of repeated wind erosion phenomena at the farm level are well understood, few attempts have previously been made to quantify the amounts of blowing sand. We thus initiated a research project on the quantification of wind erosion and the effects on crop production. This project will involve three areas: monitoring sand storm events which includes collation of data on storm duration, wind direction, wind speed, and sand movement. The sand catch will be analyzed for size fractions and nutrient content. The damage to the seedling growth will be assessed by measurement of leaf area and dry weights on a daily basis.

During the 1990 growing season, we monitored sand movement during wind erosion using sand catchers developed by the USDA wind erosion unit in Big Spring, Texas and examined the effects of sand deposition on the growth, development and yield of millet. During the growing season, the accumulated sand captured at 10 cm above the soil surface reached 1265 g (Figure 11). During the strongest erosion event, 384 g of sand was trapped. This single event covered 40% of all the millet pockets totally. Plants from the pockets covered by sand showed delays in plant development and reduction in the height, leaf number and leaf area index. Average yield from the unaffected plants was nearly twice the average yield from plants whose pockets had been partially covered.

Studies are currently under way to examine the efficacy of agronomic management techniques such as the use of crop residues and wind barriers as protective measures against wind erosion, which should have major potential for application in the Sahelian region.

Climate and population dynamics of the Pearl Millet Earhead Caterpillar (**Raghuva albipunctella** *De Joannis*)

After the droughts of 1968-72, which resulted in severe food shortages, the Sahel received abundant rains which were accompanied by severe pest outbreaks. Pearl millet was devastated by infestations of the earhead caterpillar (*Raghuva albipunctella* De Joannis). During the seventies, when the outbreaks were most severe, Vercambre (1978) reported yield losses of up to 25% in Senegal.

Raghuva diapauses in the pupal stage. The prepupal sixth instar larvae crawl from the panicle, fall to the ground, and penetrate into the soil. Pupation occurs two to three days later. The majority of the pupae are located in the top 10-25 cm soil layer. We monitored the population dynamics of *Raghuva* and studied the relationships between rainfall, soil physical parameters, diapause and subsequent adult emergence during 1983-86 in collaboration with the millet entomology sub-program at ISC (Nwanze and Sivakumar, 1990).

We found the majority of the diapausing pupae (51%) at soil depths of 10-20 cm. The onset and continuity of rains, favourable soil moisture and temperature conditions were key factors in diapause termination, duration of post-diapause development and adult emergence. We established that the number of surviving pupae was closely associated with changes in soil temperature and moisture at different depths from November to May. We also found that moth emergence from the soil usually started 40-50 days after the first 15-25 mm of rain. Our observations indicated that panicle damage is highly dependent upon the date of sowing, crop phenology or maturity cycle and the synchronization between cultivar panicle exsertion and adult moth emergence. These studies stress the importance of knowledge of the physical and biological environments of insect pests and their hosts. They emphasize the need for collection of minimum data sets over several years in order to be able to quantify the major factors required for models of agroecosystems that are essential for designing pest management programmes.

COOPERATION WITH NATIONAL AND REGIONAL PROGRAMMES

Since ISC is a Regional Center, we conduct our research in cooperation with national and regional programmes located in West Africa. We have strong links with the National Meteorological Services of Niger, Burkina Faso, Mali and Senegal in the area of collection and analysis of agroclimatological data. We have supplied historical data, that we computerized, to these national programmes and also assisted them by implementing programmes for data analysis on their computers. We conducted a training workshop in collaboration with WMO for agrometeorologists in West Africa in 1985. Another training workshop on the "Preparation of Practical Agroclimatic Information" for the West African agrometeorologists is scheduled for October 1991. In addition, we have also received agrometeorologists from the Sahelian countries for short periods of six to eight weeks for training in agrometeorological data collection and analysis.

Our collaboration with the National Meteorological Services of Niger extends to several areas such as data collection and analysis, training, and conduct of joint seminars and workshops. We participate regularly in their pilot projects with farmers. We have assisted INRAN (Institut National de Recherche Agronomique du Niger) in monitoring the spatial variability of rainfall at five of their principal research stations in Niger. In addition, we routinely supply them with climatic data from the automatic weather stations at Bengou and Maradi. We recently completed a project describing the soil climatic environments of all the INRAN research locations in Niger and have also trained several students from the University of Niamey and AGRHYMET.

Figure 1. Annual rainfall variation in Banfor, Burkina Faso (mean annual rainfall-1148 mm)

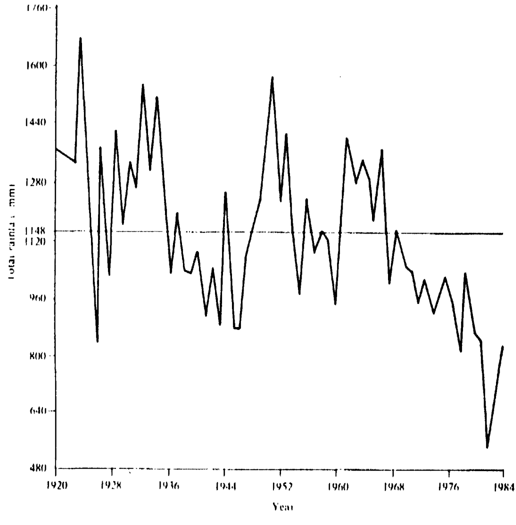


Figure 2. Rainfall variability at ISC, Sadoré, Niger on 22 July 1986 (o = rain gauges)

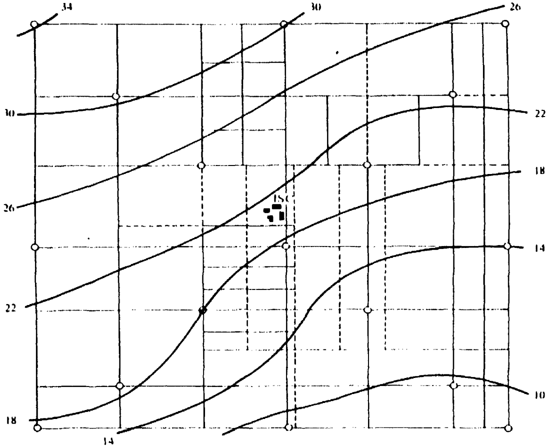


Figure 3. Percentage deviation of annual rainfall at Niamey, Niger

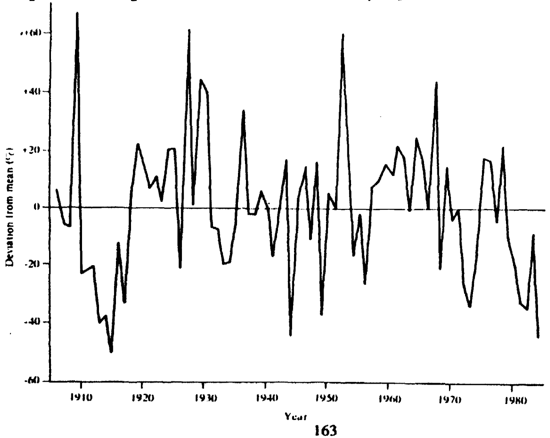


Figure 4. Rainfall isohyets in Niger before and after 1969

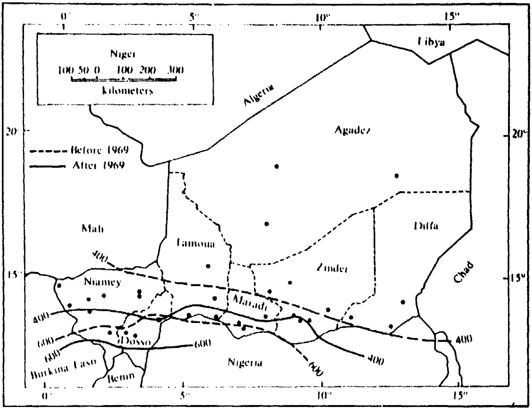


Figure 5. Probability (%) of receiving 10 mm or more rainfall during each decade at four locations in the Sudano-Sahelian zone

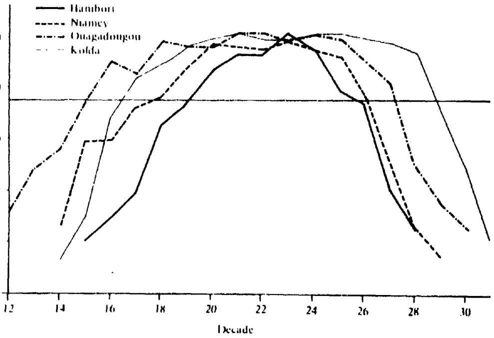


Figure 6. Number of days until next rainfall greater than the threshold values at a) 50% probability and b) 90% probability at Ouagadougou, Burkina Faso

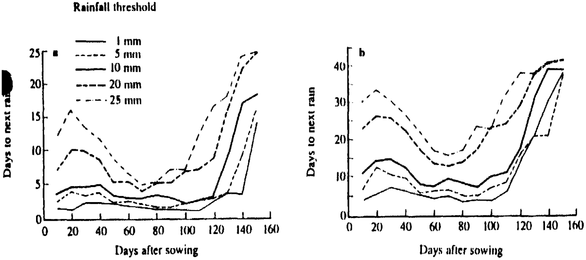


Figure 7. Length of dry spells for 10 mm rainfall threshold at 90% probability for four locations in West Africa

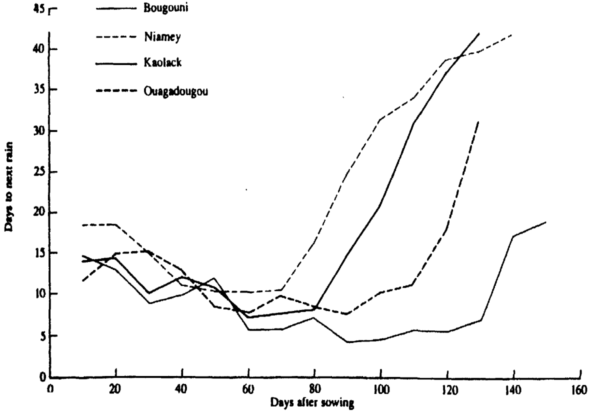


Figure 8. Cumulative frequency distribution of minimum and maximum air temperatures for the whole year and for the rainy season (May-October) in the Sudano-Sahelian zone

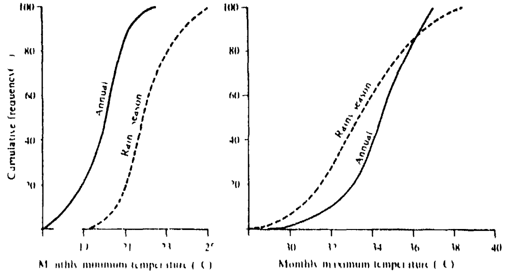


Figure 9. Cumulative frequency distribution of minimum and maximum air temperatures at the time of sowing

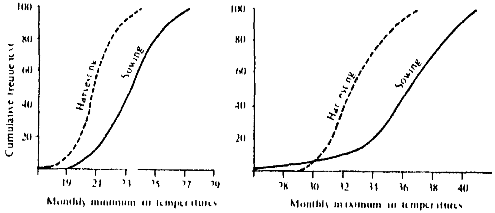


Figure 10. Moving monthly (July, August, September) and annual values of mean rainfall measured at Filingue, Niger

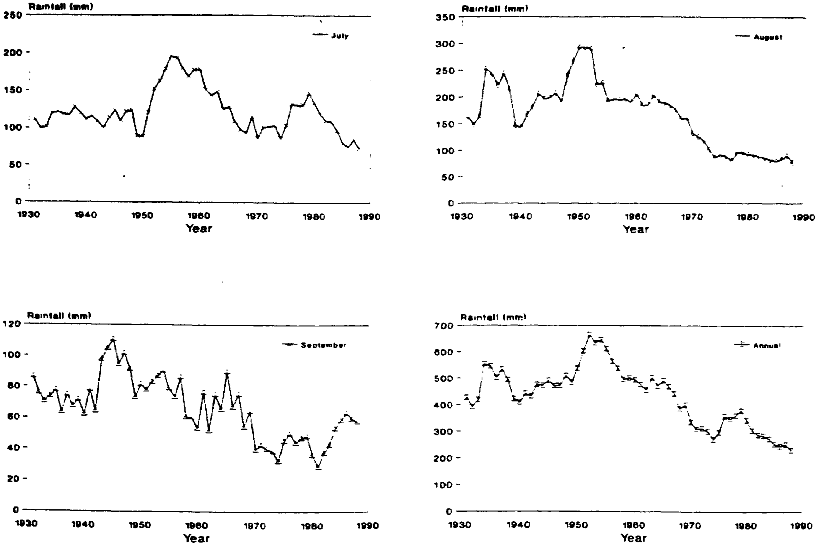


Figure 11 Accumulated sand captured at different heights above the soil surface, ISC Sadore, growing season, 1990

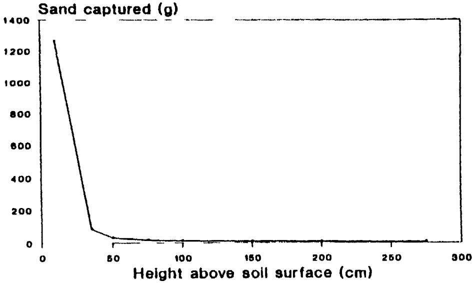


Figure 12 Variation in actual (squares) and potential (circles) evaporation from fallow bushland (●,■) and bare soil (○,□)

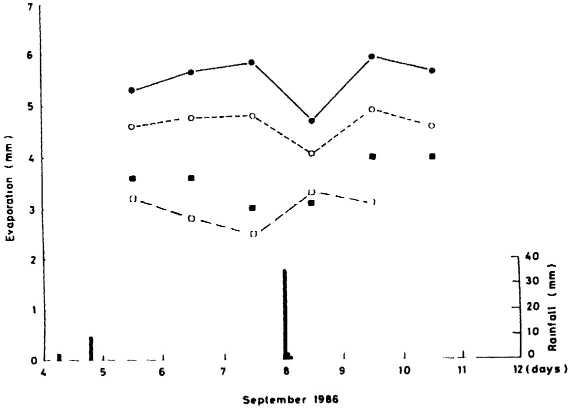
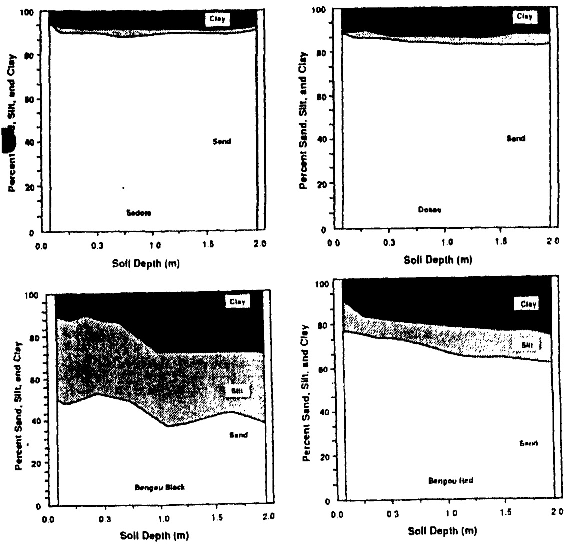


Figure 13. Measured particle size distribution as a function of soil depth for the four soil types



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