International Crops Research Institute for the Semi-Arid Tropics

Review of Soil, Water and Nutrient Management Research in ICRISAT

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Edited by

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INTRODUCTION

M.V.K. Sivakumar

The semi-arid tropics (SAT) are characterized by sparce vegetation and low productivity of traditional rainfed agriculture. Inadequate vegetative cover does not provide sufficient protection against the impact of torrential rainstorms that may occur during the rainy season, resulting in surface runoff, soil erosion and subsequent loss of fertile top soil. As a consequence, the rate of soil degradation in the SAT is alarmingly high. The low and erratic rainfall, high soil and air temperatures, soils with poor native soil fertility, surface crusting and low water holding capacity, and recurrence of water deficits in the crop growing season are some of the main abiotic factors leading to this situation. It is imperative that soil fertility and water be managed effectively and conserved through careful husbandry of natural resources and land-improving investments so that soil quality is improved. Development of improved soil, water and nutrient management (SWNM) practices suitable for varied soil and agroclimatic conditions in the SAT is crucial for ensuring the long-term productivity and sustainability of the farming systems in the dry tropics.

Right from its inception on 5 July 1972 with the adoption of its constitution and the establishment of its governing board, ICRISAT has recognized the importance of SWNM research for the SAT. By the end of 1973 crop season, the following highlights were reported (ICRISAT, 1974):

- The ridge and furrow system effectively manipulated runoff, reduced drainage problems and erosion and increased infiltration.

- Overall rainfall use efficiency was estimated at about 70% on the improved experimental watershed versus 50% for a traditional *rabi* (post-rainy season) cropping system.

- Two years of fertilizer response observations have helped to provide information for designing further experiments involving diverse crops, soils and management systems.

In 1974, the small watershed, a natural catchment and drainage area, was chosen as the focus for study and intervention of SWNM practices. In eight watersheds on black soils, investigations were conducted on different cropping systems and different resource management technologies, from traditional to improved.

The overall research thrust of SWNM research in ICRISAT was focussed on the following areas:

- Quantification of the climatic environment with particular reference to rainfall climatology across the SAT.

- Development of soil and water management systems to ensure optimum soil moisture environment for crop growth, minimize land degradation and restore soil quality.

- Development of improved nutrient management strategies through a better understanding of nitrogen dynamics in semi-arid cropping systems of short and medium duration (90-150 days) that include grain legumes in Asia.

- Development of more effective nutrient management practices with emphasis on phosphorus and nitrogen for the millet- and sorghum-based cropping systems in West Africa.

- Exploitation of beneficial soil fauna and flora for increased crop and soil productivity.

- Assessment of technologies for improved management of soil, water and nutrient resources and identification of adoption constraints, common property issues and degradation and sustainability of agriculture.

- Use of system simulation models to evaluate technology options and for technology transfer to other agroecologies.

In pursuance of the above thrusts, ICRISAT committed considerable resources and funds to SWNM research over the years. Initially, research efforts were oriented to problem solving at the ICRISAT Center in Patancheru and the number of full time nationally recruited staff (NRS), conducting SWNM investigations at ICRISAT, Patancheru increased steadily from 1974 to 1979-80 (Fig. 1). The strength of internationally recruited staff (IRS) grew from one staff member in 1974-76 to 6 by 1982 (Fig. 1). A number of special project staff also came on board during 1979-83. These developments provided a significant staff strength, ranging from 19-21, in the SWNM area during 1979-85.

By 1981, SWNM research of ICRISAT became global with the initiation of full-time research on SWNM aspects at one African location of ICRISAT (Burkina Faso) and the first report on ICRISAT's SWNM research in Africa was published in 1982 (ICRISAT 1982). Around the same time, research work was initiated at the ICRISAT Sahelian Center (ISC) with the appointment of an IFDC soil chemist. ICRISAT core IRS staff with full-time responsibility for SWNM research stayed between 2-3 during 1983-95 (Fig. 2). However, consistent presence of 1-3 staff members from special projects during 1981-95, helped underpin SWNM research at ISC.

Long-term staffing trends in the SWNM area at ICRISAT locations in India and Africa (Fig. 3) show a significant decline in India, from 19 to 12 during 1990-95, much of it in the NRS category (Fig. 1). The IRS staff strength in India was however stable during this period. Total full-time staff involved in SWNM research in India is still higher than the staff strength in Africa (Fig. 3).

In the following pages, we have attempted to provide a review of the SWNM research in ICRISAT. As the previous review of water management research in ICRISAT was carried out in 1982, we have used 1983 as the starting point for this review which covers the period 1983-1995. Fortunately, the Chair (Dr. E.T. Kanemasu) and a panel member (Dr. S.S. Prihar) for the present review were also members of the panel that conducted the review in 1982.

As the emphasis in this review is on the "management" of soil, water and nutrients, we have deliberately excluded "genotype screening" aspects here. However, it is important to mention that the evaluation of genotypes for their response to water and nutrients continues to receive a major attention in ICRISAT. Agronomic management of water and nutrients through strategies such as intercropping, relay cropping, crop rotations, manipulation of plant densities etc., is treated as an integral aspect of all the presentations, wherever appropriate.

We hope that this review, and the companion volume on SWNM research *in print*, provide evidence of productive research carried out at ICRISAT over the past 13 years. We recognize that the current review comes at a very appropriate time. The Greenland Report and the TAC study on Priorities and Strategies for Soil and Water Aspects of Natural Resource Management Research in the CGIAR conclude that promotion of more widespread use of sustainable SWNM management systems requires adoption of new research approaches. A new research paradigm that would permit synthesis of critical technical, institutional and policy aspects to achieve real impact is being called for. It is clear that this is a time of change in direction. This review offers us the opportunity to discuss the major issues involved and we look forward to the future as both a challenge and an exciting opportunity.

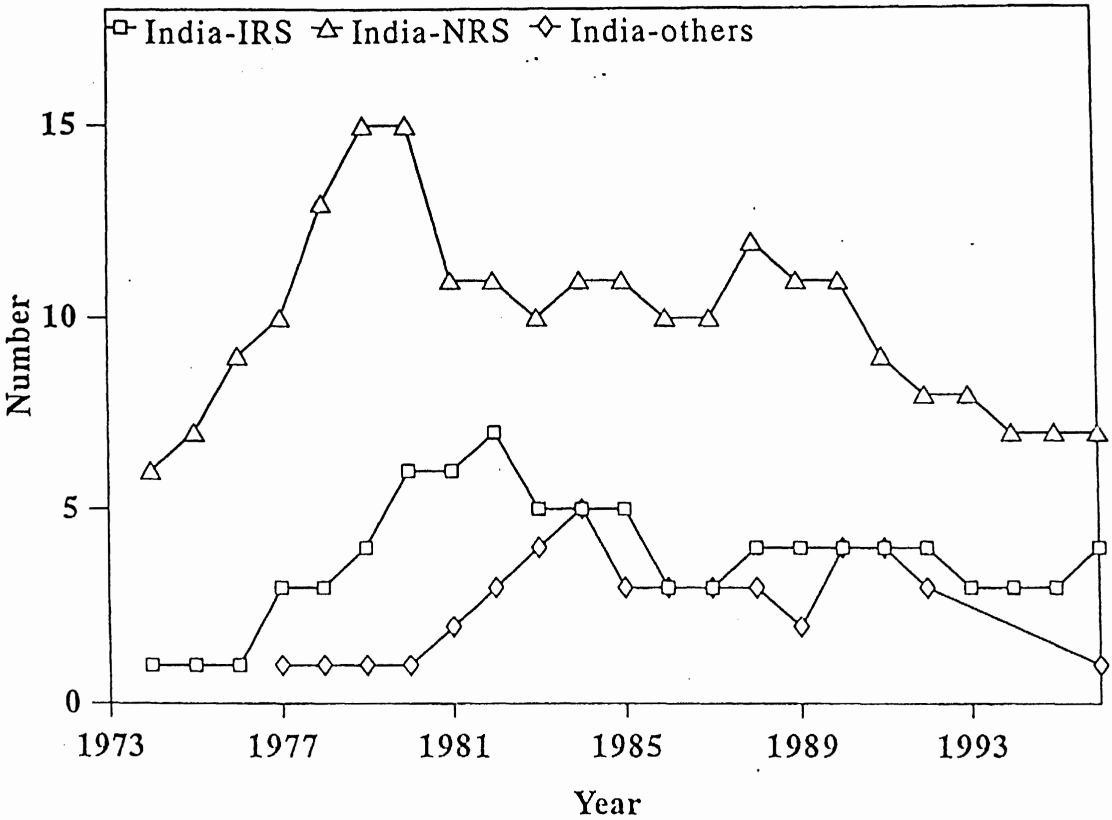

Fig. 1. Number of full time internationally recruited scientists (IRS), nationally recruited scientists (NRS) and scientists of special projects (others) involved in SWNM research at ICRISAT Asia Center, India.

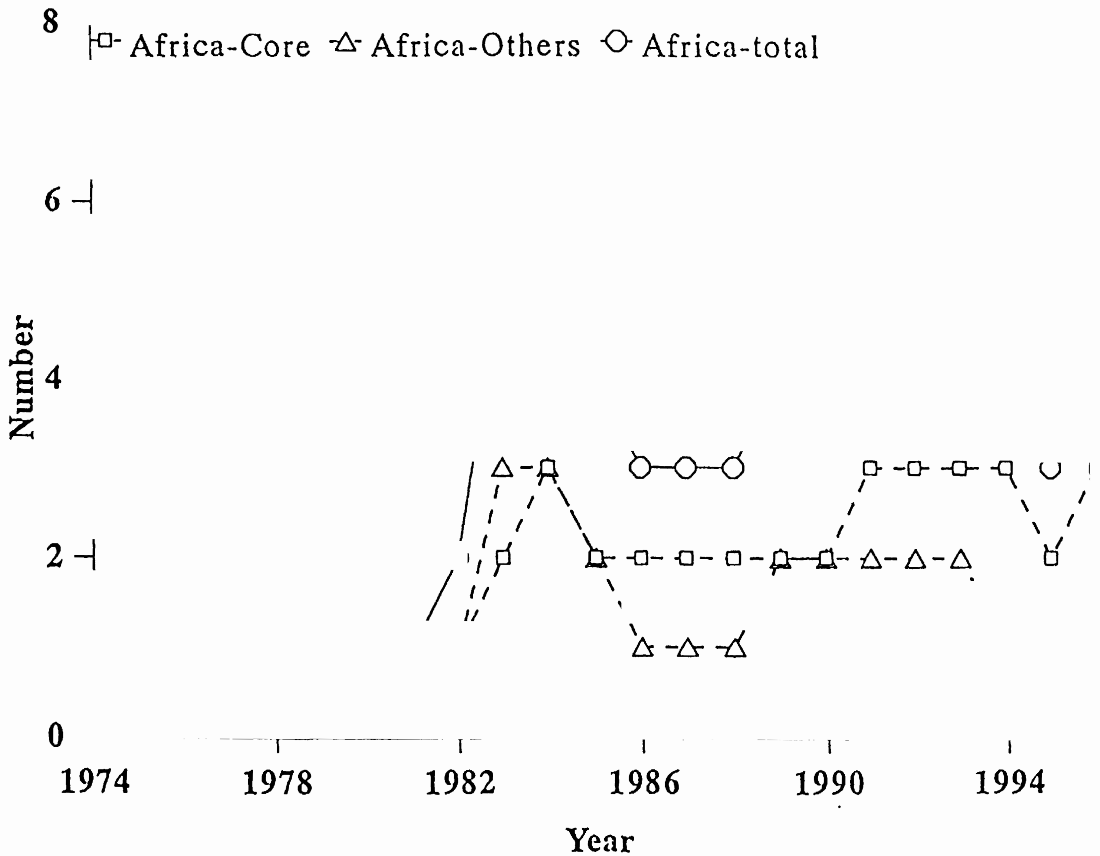

Fig. 2. Number of full time ICRISAT core scientists, scientists of other international institutes and special projects (others) involved in SWNM research in ICRISAT West and Central Africa region.

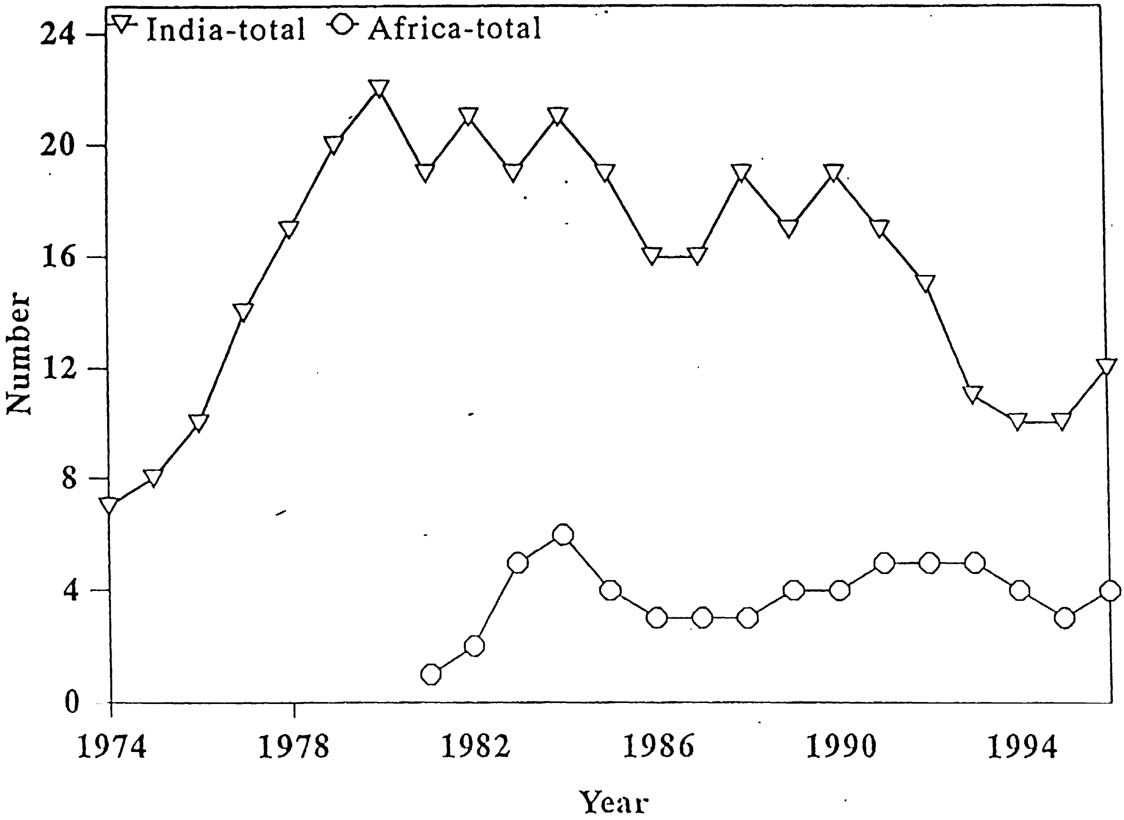

Fig. 3. Total number of scientists involved in SWNM research at ICRISAT Asia Center, India and ICRISAT West and Central Africa.

RAINFALL CLIMATOLOGY STUDIES

S.M. Virmani and M.V.K. Sivakumar

Introduction

Soil, water and nutrient management research in the context of the sustainable use of natural resources commenced in the Farming Systems Research Program in 1973 soon after the establishment of the institute. The goals of this research are to design technologies that lead to consistently sustainable agricultural production in the seasonally dry tropics, especially for small farmers of limited means. Because the applicability of improved food production technology varies with the natural resource endowments, our research efforts in the area of agroclimatological studies have focused on the development of principles, concepts, and methodologies that are transferable and have a broad application. The agroclimatology research at ICRISAT has aimed to:

- describe and classify the agronomically relevant features of the soil and climatic resources of the SAT;
- identify the physical and biological processes that largely determine crop performance in the various agroclimates of the SAT, and establish basic principles that describe these processes;
- develop in collaboration with interdisciplinary teams of scientists production practices and systems of farming that will result in improved, sustainable food production by optimum utilization of the SAT's natural resources; and
- determine regional research priorities by execution of simulation and modelling studies based on climatic, soil, and cropping systems data.

This research has been conducted at ICRISAT Asia Center, at several locations in West Africa, and at collaborating benchmark locations in several NARS. Specific agroclimatic factors influencing crop yields and their interactions often require interdisciplinary investigations with programs in ICRISAT and with scientists from national and international organizations.

Agroclimatology Studies

The distinctive characteristics of the tropical environment have a major influence on the distribution of natural endowments: soils and climate. Tropical regions are well supplied with radiant energy, however, due to the temperature regimes and orographic influences, a variety of rainfall patterns are produced. Variations in the timing and amount of precipitation are generally the key factors influencing agricultural production possibilities.

The effect of differences in rainfall on the availability of moisture in tropical agriculture is especially great because of its loss due to rapid evaporation and transpiration. As a result of consistently high temperatures during the year, the rate of evaporation is high. The agricultural value of rainfall varies with the climatic factors that influence the return of moisture to the air by evapotranspiration. Since plants absorb water from the rhizosphere, water retention and release characteristics of soils are important. Therefore, in determining the agricultural potential of any semi-arid area, quantification of the rainfall (timing, amount and durations), soil (hydraulic characteristics infiltration, moisture characteristics, hydraulic conductivity function) and evapotranspiration characteristics is of fundamental importance. Given the variability of the semi-arid tropical environment, such measurements also help in the delineation of the potentially most rewarding areas for agricultural research.

Climatic characteristics of SAT environments

The semi-arid tropics are characterized by a high climatic water demand. The mean annual temperature is > 18°C and rainfall exceeds evapotranspiration for 2-4.5 months in the dry semi-arid tropics and 4.5-7 months in the wet/dry semi-arid tropics. High rates of evaporation coupled with the limitations imposed by rainfall distribution pose particular problems for sustainable agriculture. In the SAT, rainfall is markedly seasonal in character and so it greatly limits water availability during the dry season of the year. These temporal variations have a marked influence on length of growing season and hence on crop growth and development. Apart from the temporal variations, spatial variations in rainfall make regional crop planning a technically challenging proposition.

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. There are marked differences in the rainfall, soils and other agroecological factors between different climatic zones in West Africa, not to mention the socioeconomic environment. The low and highly variable rainfall, and the high demand for water imposed by the high temperatures and radiation throughout the year cause large variability in crop yields from year to year. Such varied environments necessitate the development of a range of solutions and general concepts for the management of resources.

Temporal variations in rainfall

The semi-arid tropics exhibit considerable variability in rainfall from season to season and year to year. For example, the mean annual rainfall at Hyderabad is highly erratic (CV = 27%). The data of the last 15 years presented in Table 1 show that the rainfall could vary from as much as 558 mm in 1985 to as high as 1265 mm in 1995. The variability is true not only annually but also seasonally. The rainfall distribution shows that seasonal rainfall is erratically distributed. For example in 1995, October was the wettest month whereas in 1986, it was driest month. In 1988, August received the highest amount of rainfall whereas in 1985 it was the driest.

Temporal variations in rainfall are quite common in West Africa as well, and can be represented at three time scales: annual, monthly, and daily. The coefficient of variation of annual rainfall ranges between 15-30%. For example the variation in mean annual rainfall at Banfora in Burkina Faso over the last 64 years (Fig. 4) is about 25%. Although the mean annual rainfall at Banfora 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 of May to October. Aridity prevails during the rest of the year and is most pronounced from December to February. Large differences exist 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. Our analysis of the generalized characteristics of daily rainfall for four locations in the Sudano-Sahelian zone showed that the number of rainy days as well as the average rainfall per rainy day increase from May to a maximum by August. Differences in the average duration between the rainy days of different locations show that at low rainfall locations such as Hambori (Mali) and Niamey (Niger) the risk to crop establishment in June is higher. At Kolda (Senegal), where the rains begin late, duration between rainy days in May is similar to that at Hambori.

Spatial variability of rainfall

Rainfall in the semi-arid regions is characterized by a high spatial variability. 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. In order to study this aspect, we installed 17 raingauges on a 400 m grid over the 500 ha research center at ISC. Data from the rain gauges were plotted after each rain storm, and maps were made showing the spatial variability of rainfall. At IAC, over 50 raingauges have been operated for the last 20 years on a 1400 ha area. On any one day the rainfall during the rainy season has varied from 0 to over 100 mm within a distance of 800 m; however over the season the rainfall totals varied ± 5%.

Analysis of the data collected during 1986 and 1987 at ISC showed that the average relative variability of individual rain storms, 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.

Spatial variation in the climatic environment is illustrated by comparing the rainfall and potential evapotranspiration of 4 SAT areas. These four locations are: Bamako, Niamey, Dakar, and Hyderabad. Some generalized characteristics of these locations are presented in Table 2. Figure 5 depicts the spatial variation in the rainfall and PE characteristics of the SAT environment. Bamako appears to be the most favorable with almost four months in a year when water supply could meet the potential requirement. Dakar is at the other end of the picture with only two months when rainfall could satisfy the potential demand of water. Niamey also presents a similar situation. Hyderabad is intermediate between the two with three months in a year that meet the water demand situation.

The potential evapotranspiration curves in Fig. 5 shows some interesting patterns. At Hyderabad the curve shows typical low values beginning January peaking to high values around May-June and culminating in low PE values by November-December. This pattern is typical of the locations situated away from the equator, the high values of PE coinciding with the hot summer and low values with the cool winter periods. Bamako, Niamey and Dakar situated closer to the equator than Hyderabad do not exhibit such large fluctuations. A good example is the pattern shown by Dakar. Bamako shows a sudden dip during July-September mainly because of cloudy skies and rain. The PE values are low on those days which have some amount of rainfall.

Persistency and extreme magnitude of variability

The rainfall variability discussed above leads to instability for sustainable crop production. The recent drought in the Sahel is not unique. Annual rainfall deviations from the mean at Niamey for the past 80 years indicated that droughts occurred between 1910 and 1920, 1940 and 1950, 1968 and 1973, and 1976 and 1984. The 1950s were generally wet (Sivakumar, 1986). Severe, extended droughts are a recurrent feature in the region but the 1960-80 drought around Niamey was unique in its persistence. Rainfall deviations 20-40% below the mean were common. In 1950, rainfall all over West Africa was above normal, up to even 2.5 folds above normal in some locations. However in 1970, rainfall was below normal throughout the region. In Asia, the annual rainfall has been normal (±1 SD) over the past 30 years.

Further, the rainfall fluctuations in the SAT are associated with a certain geographic pattern. For example, the reduction in the mean annual rainfall in Niger after 1969 is characteristic of the entire country (Sivakumar, 1989). Pre- and post-1969 rainfall averages were used to examine the effect of the post-1969 droughts on the long-term averages of rainfall. 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 or weekly precipitation totals for a long period of time are available for numerous locations in the Sudano-Sahelian zone and in Asia 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.

Weekly precipitation totals can be analyzed using first order Markov chain for the probability of receiving a certain amount of precipitation—for example 5, 10, and 20 mm. The program used for the computation of initial and conditional probabilities is listed by Sivakumar *et al.* (1979).

Results are reported for the initial probabilities of a wet week, P(W); conditional probabilities of a wet week following a wet week, P(W/W); and of a wet week following a dry week, P(W/D). A discussion of the formulae employed in the calculation of these probabilities has been presented by Virmani *et al.* (1978).

Constant precipitation analysis has been carried out for those stations with rainfall records exceeding 15 years to cover 100 locations in India and about 300 locations in West Africa. Results of the constant precipitation analysis are presented for 77 locations of Niger in the ICRISAT information Bulletin 5 'Rainfall Climatology of West Africa: Niger' and for 78 locations of India in an enlarged second edition of the ICRISAT Research Bulletin No. 1, 'Rainfall Probability Estimates for Selected Locations of Semi-Arid India'.

Application of Probability Analysis for Defining Moisture Environment of a Location

Discussion of some of the methodologies and approaches that have been adopted at ICRISAT for investigation of climatic water availability is given below, taking the Hyderabad and West Africa regions as examples. In Hyderabad the ratio of mean rainfall to potential evapotranspiration shows that rainfall could meet about 55% of the evaporative demand in the month of June, whereas in the subsequent rainy months, rainfall adequately meets the demand (0.85-1.37). August and September show a positive moisture balance. In the postrainy season, rainfall is not adequate to meet potential demand (Table 3).

Probabilities of receiving rainfall ≥ 10 mm during each decade for several locations in Niger show clearly the differences in the onset of rains from north to south (Sivakumar *et al.* 1993). Rainfall probabilities could be effectively used to show the seasonal progression of rainfall dependability thereby providing a useful means to differentiate locations. At Hambori (Mali) the probabilities do not reach the dependable level of 75% until after decade 19 while at Ouagadougou (Burkina Faso) located further south, this occurs 40 days earlier by decade 15. Such large differences in the probabilities between these two locations are however, not observed towards the end of the season.

The mean monthly rainfall data do not yield information on the dependability of precipitation to meet potential demand. Hargreaves (1975) has defined dependable precipitation (PD) as the amount of rainfall which could be received at 75% probability. It is evident that the dependable precipitation amounts are much lower than the mean rainfall received at Hyderabad, and so one must consider dependable precipitation rather than mean rainfall. The moisture availability index—defined as the ratio of dependable precipitation to mean rainfall—shows that adequate moisture is available for the rainy months of July, August, and September at Hyderabad. These analyses, however, do not give information on the continuity or breaks in rainfall and its adequacy to meet crop demand on a short-term basis.

Probabilities of rainfall at Hyderabad as a function of time during the year are plotted in Fig. 6. It is seen that in the dry months of January to June there is little chance of receiving rainfall that would be adequate to satisfy at least a third of the potential demand. But starting from the last week of June, these probabilities exceed the 70% level. Figure 6 also shows that the onset of rainfall at Hyderabad is abrupt and that there is also a continuity in the rainfall once the rains begin. It also shows another interesting feature in that rainfall that meets at least one-third of the potential demand are fairly adequate throughout the months of July and September. In August however, drought may be encountered in about 40% of the years. After October these probabilities again start declining due to recession of monsoon rains. Using these probabilities, Virmani *et al.* (1978) showed that differences in the performance of a given cropping system at Hyderabad and Solapur during the rainy season could be interpreted in terms of the initial and conditional probabilities of rainfall.

This methodology of rainfall probabilities could also be used to demarcate the risk associated with dry seeding of rainy season crops in the SAT. Dry seeding is an important component of the improved technology for deep Vertisols (Srivastava *et al.* 1982). The dry seeding period for rainy season crops will be a couple of weeks before of the onset of seasonal rainfall which is abrupt at Hyderabad and the probabilities of continuance of rain are high. Therefore, Hyderabad offers excellent scope for dry seeding. At locations such as Solapur, the onset of rains is not marked and the chances of continuity of rains after onset is not high. Such locations therefore pose a risk to dry seeding. Based on rainfall probability analysis of more than 90 stations in India, the areas offering possibilities of dry seeding on Vertisols have been mapped (Binswanger *et al.* 1980). Again the methodology is to use the dependability of precipitation and soil moisture storage. It appears that one could distinguish very easily the risk associated with dry seeding possibilities at different locations in the Vertisols spread over large areas in India. For example, the technology for dry seeding of crops generated at ICRISAT Center could be transferred with a fair degree of success to Akola, Jabalpur, Indore, and Udaipur, whereas at Solapur, Dharwar, Jalgaon, and Ahmedabad the likely success of dry seeding is low due to the high risk associated with it.

Date of onset of rains and length of growing season in West Africa bear a strong relationship. The date of the first rains in the Sahel is important in planning agricultural operations, particularly sowing. Sivakumar (1988) computed the dates of the first and last rains and the length of the growing season for each year from data base for 58 locations in the Sudano-Sahelian zone. A highly significant relationship was observed between the date of onset of 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 onset of rains. Early onset of rains, relative to the computed mean date of onset for a given location, results in a longer growing season. This is illustrated in Table 4 for Niamey, Niger (data base 1904-1984). The average date of onset of rains at Niamey is computed as 12 Jun, and the average length of the growing season is 94 days. However, if the onset of rains occurs early ie., by 19 May, there is a 49% probability that the growing season will exceed 130 days. On the other hand, if the rains are delayed until the end of June, there is only a 11% probability that the growing season will exceed 110 days.

Using the methodologies of agroclimatic analyses developed at ICRISAT we analyzed rainfall data and prepared reports on the exploitation of the relationship between the onset of rains and the length of the growing season in Senegal (Gueye and Sivakumar, 1992), Burkina Faso (Some and Sivakumar 1994) and Mali (Tekete and Sivakumar 1995). In other parts of the semi-arid tropical world several reports using ICRISAT methodologies on rainfall analysis have appeared. As examples, Vorasoot *et al.* (1985) conducted studies on the rainfall analysis for the Northeast Thailand; Patil and Kale (1988) reported weekly rainfall probabilities of selected places in scarcity zone of Maharashtra; Wagnew *et al.* (1987) conducted analysis of agroclimatic data of ILCA stations in Ethiopia; Weerasinghe (1988) studied agroclimatology of Sri Lanka; and Shekh (1988) carried out an extensive analysis of the agroclimate of Gujarat. In Ethiopia where a substantial area of Vertisols exist and where potential for the application of the Vertisols technology developed by ICRISAT is great, Regassa *et al.* (1987) conducted an agroclimatic survey of selected locations of Vertisol areas to establish their potential and problems for adopting a double cropping technology. Several other agroclimatological studies have been conducted at ICRISAT by Scientists from the NARS. Some of these are, Mvula *et al.* (1988) for Zambia; May *et al.* (1981) for Magarinin area of Kenya; Kannangara (1988) for dry zone of Sri Lanka; and Rivera (1988) for Marin region of Mexico.

In field trials conducted at ISC, Sivakumar (1990) showed that in years with an early onset of rains, the long growing season could be exploited by growing a relay crop of millet and cowpea. Relay cropping avoids the competitive effects inherent in intercropping systems, while offering the additional advantages of rotating cereals with legumes (Sivakumar, 1993).

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 point to the need for a clearer understanding of the length of dry spells, their frequencies and probabilities (Sivakumar, 1992). The simplest calculations of dry spells for general applications involves computation of the probabilities of maximum and conditional dry spells exceeding a user specified threshold value from a given calendar date. For more precise applications in agriculture, it is important to consider the different periods after sowing a crop 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 in each year is also the date of sowing, the length of dry spells (or days until next day with rainfall greater than a threshold value) at different probability levels can be computed for consecutive 10-day periods from sowing (Sivakumar, 1991a). Data on dry spell lengths 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 Fig. 7 for Niamey, Niger (mean annual rainfall 560 mm), Kaolack, Senegal (800 mm), Ouagadougou, Burkina Faso (830 mm) and Bougouni, Mali (1260 mm). At Niamey, the length of dry spells increased at periods beyond 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 at periods beyond 90 DAS at Kaolack and at periods treater than 120 DAS at 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 (1991a) presented the length of dry spells and their frequencies for 150 locations in West Africa. Analysis of drought occurrence showed that the frequencies of the lowest dry spell of < 5 days increase asymptotically with increasing annual rainfall and with dry spells > 20 days, the frequencies decrease sharply with increasing mean annual rainfall.

Stochastic Modelling Using the Water Balance Approach

One other important component that affects length of the growing season is the water holding capacity of the soils. The average pattern of changes in profile moisture on a weekly basis in three typical soils of Hyderabad region is shown in Fig. 8. These curves are based on rainfall records from 1901 through 1970. From water-balance analysis carried out according to methodology developed by CSIRO (Keig and McAlpine 1974), it is apparent that in shallow Alfisols, there is very little soil moisture storage for crop use over extended drought periods. In deep Alfisols and medium Vertic Soils, there is a fair degree of storage for extended periods during the growing season. Thus, under identical rainfall conditions, the effects of short-term intra-seasonal droughts on crop-moisture status will differ in the three soil types. The amount of water lost as runoff would also differ, and the potential benefits derived from supplemental applications of water would vary with the soil type. It is apparent that a long-duration crop in a soil with 50 mm available water-storage capacity will be exposed to soil-moisture inadequacy at several growth stages, but on the other hand if the soil-moisture storage capacity were 150 or 300 mm, the risks of water deficiency are much less. Thus one might select for shallow soils a drought-hardy crop (e.g., castor *Ricinus communis*), whereas in deeper or heavier soils a crop with medium sensitivity to drought (such as pigeonpea, *Cajanus cajan*) would be suitable. Similarly one could fit in other short- and medium-duration crops. Effects of changes in seeding dates and the influence of different phenological characteristics on crop performance could also be assessed as a first approximation in such analyses.

The real-time rainfall data collected through the large network of rain gauges that exists in the Sudano-Sahelian zone need to be adequately exploited in estimating soil moisture for crop growth by employing geostatistical and GIS approaches.

Currently, several water balance models with varying flexibilities of input data requirements, computer processing time and output data features are available and these models should be used in determining soil water available 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). An atlas of length of growing season for 232 locations of India has been assembled by Virmani (1991).

Climate Change Research

Recurrent droughts and associated famines in West Africa, over the past two decades, have caused considerable concern in the international community as to whether the agricultural production could be sustained in the long term in this region. One of the basic questions related to this aspect is the continuity of rainfall decline observed so 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, 1991b) for the periods 1945-64 and 1965-88. Variations in the average dates of beginning and ending of rains and the length of the growing season for the two periods for the selected locations in Niger showed 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. 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 (1991b).

In India on the other hand the general trend of annual rainfall shows no significant change. For an example, the annual rainfall at Hyderabad mostly shows a variation within ± 1 SD of annual rainfall. It is too early to say anything definite on the climate change in this SAT region but the recent trend points to a higher variability (Fig. 9).

Rainfall and Population Dynamics of Pests

After the 1968-72 droughts 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).

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 2-3 days later. The majority of pupae are located in the top 10-25 cm soil layer. In collaboration with the millet entomology scientists at ISC, we monitored the population dynamics of *Raghuva* and studied the relationships between rainfall, soil physical parameters, diapause and subsequent adult emergence during 1983-86 (Nwanze and Sivakumar, 1990).

We found majority of the diapausing pupae (51%) at 10-20 cm of soil depth. The onset and continuity of rains, favorable soil moisture, and temperature conditions were key factors in diapause termination, duration of post-diapause development and adult emergence. The number of surviving pupae was closely associated with changes in soil temperature and moisture at different depths from November to May. Moth emergence from the soil usually started 40-50 days after the first 15-25 mm of rain. Panicle damage is highly dependent upon the date of sowing, crop phenology or maturity cycle and the synchronization between cultivar panicle exertion and adult moth emergence. These studies underline the importance of a knowledge of interactions between 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 quantify the major factors required for models of agroecosystems that are essential for designing pest management programs.

Crop-Weather Modelling

In recent years, crop models have advanced from restricted academic exercises to tools with wide applications in agriculture. Crop Environment Resource Evaluation Systems (CERES) models, for example, aim at predicting the yield of any genotype, in any soil, at any location, and in any weather.

In 1982, an international group of agricultural and systems scientists met at ICRISAT to define the minimum data set required to simulate crop growth and development. The aim was to develop a solid foundation for research dealing with the soil-plant-atmosphere continuum, and to encourage strong links between scientists who study the biophysical and socioeconomic components of the agroecosystem. The scope of work was limited to 10 food crops, including four cereals (maize, rice, sorghum, and wheat) three grain legumes (dry beans, groundnut, and soybean), and three root crops (aroid, cassava, and potato). Barley and pearl millet were later added to the list.

The conference participants wrote two reports. The first *Minimum Data Sets for Agrotechnology Transfer*, was published by ICRISAT, and the second, *Experimental Design and Data Collection Procedures: the minimum data set for systems analysis and crop simulation*, was published by IBSNAT. The latter publication has been revised twice, and continues to serve as a guide for designing field experiments to validate models. Subsequently, the group decided there was a need to standardize the input and output format of existing crop models so that they all accessed a common database and application program. This eventually led to a plan to combine the database, crop models, and application programs into a Decision Support System for Agrotechnology Transfer (DSSAT).

ICRISAT has used DSSAT because it enables users to easily access soil, weather, and crop databases, crop models, and application programs to evaluate alternative strategies to attain desired outcomes. It was developed through the combined efforts of scientists from many countries, and international and regional agricultural research centers. DSSAT is still being developed and users can expect it to become more versatile and reliable in the years ahead. To do so, DSSAT needs continued input from current and new collaborators so that the existing global knowledge base can be captured, organized, and retrieved for solving site and situation-specific problems (Virmani *et al.* 1989).

ICRISAT agroclimatologists have cooperated with a number of groups in validating crop models. The groups are:

- Texas A&M University - Blackland Research Station. Validation and rewriting of some subroutines of SORGF and Sorkam models.

- Michigan State University. Development and validation of CERES Sorghum and Millet models.

- International Fertilizer Development Center. Validation of N and P subroutines in CERES sorghum.

- University of Florida - Gainesville. Validation of PNUTGRO model.

- IBSNAT, University of Hawaii. Database development systems for crop modelling.

ICRISAT scientists have developed following models:

- RESCAP: a general crop model based on process of resource capture.

- PGNPGRO: Pigeonpea growth and development model based on SOYGRO frame.

- CHIKPGRO: a chickpea crop model based on PNUTGRO.

One of ICRISAT's mandates is to identify constraints to agricultural development in the semi-arid tropics and evaluate means of alleviating them. Another is to assist in the development and transfer of technology by sponsoring workshops, conferences, and training programs. Therefore, ICRISAT has in cooperation with ICAR, SAUs, WMO, US universities, NARS, IBSNAT and IFDC, hosted several training workshops on crop modelling.

The aim of these activities has been to familiarize and train agricultural researchers in the principles and operational aspects of research on rainfall climatology and crop modelling, and obtain feedback about the potential and limitations of current models.

Cooperation

All the meteorological data used by ICRISAT scientists is obtained from the national meteorological services and from the World Meteorological Organization (WMO). Cooperation with these services and allied institutions (national soils bureau's, USDA, FAO etc.) has been an integral part of our research planning. In Asia we have worked intimately with the India Meteorological Department and with Central Research Institute for Dryland Agriculture (CRIDA). Agroclimatic Resource characterization has been the main area of cooperative research and training.

Since ISC is a Regional Center, we conduct our research in cooperation with national and regional programs located in West Africa. As in Asia, 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 programs. In addition, we assisted these programs by implementing programs for data analysis on their computers. We have 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 was scheduled for October 1991. In addition, we have also received agrometeorologists from the Sahelian countries for short periods of 6-8 weeks for training in agrometeorological data collection and data analysis.

Our collaboration with the National Meteorological Services of Niger has extended 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 have also provided training to several students from the University of Niamey and AGRHYMET.

Future Plans

The agenda for agroclimatological research at ICRISAT would be driven by the vision of CGIAR on sustainable agriculture and would complement the TAC's initiatives on natural resource management. We propose the work for an integrating framework of international climate-related research that encompass ecoregional activities envisaged in the Integrated Systems Projects (ISPs 1-4). The mission of rainfall climatology research would evaluate, explain, and predict in collaboration with other scientific groups how soil, water and nutrient resources respond to management practices, natural climatic variations/change, and to identify practices which sustain SAT agricultural productivity in ICRISAT's production systems framework.

The agenda will be developed along four main thrusts:

1. Observe macro- and micro-climatic features in different SAT production systems at the ICRISAT research centers and at selected benchmark NARS stations for the assessment of long- and short-term effects of management factors on soil water and nutrient changes in different production systems;

2. Participate in interdisciplinary assessments of seasonal changes in soil water and water use by crops in response to different land use practices;

3. Provide rainfall climatology related information to a wide range of partner projects/institutions for activities related to sustainable agriculture research and development; and

4. Involve institutes of learning in advancing new frontiers in tropical climate science through modelling research to predict weather impacts on sustained productivity of semi-arid tropical lands (eg. APSRU Group).

Table 1. Annual and monthly rainfall at Hyderabad 1980-1995.

Month	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
1	15	0	0	5	2	53	4	0	0	10	16	0	0	2	40
2	0	0	0	1	0	44	0	4	0	0	3	0	0	6	0
3	77	0	12	21	20	0	2	0	76	6	1	0	0	0	52
4	3	34	0	31	31	35	6	99	6	2	67	4	18	31	9
5	2	38	47	0	19	0	30	16	31	141	37	28	26	2	44
6	203	193	87	92	89	118	143	12	99	84	238	128	110	144	136
7	209	155	211	172	173	131	144	256	416	83	145	129	183	143	252
8	218	68	305	148	46	231	98	273	109	269	172	258	174	197	246
9	287	180	286	99	76	57	62	247	286	96	106	43	121	66	113
10	154	59	132	80	93	0	149	2	27	129	55	28	170	247	361
11	2	12	1	6	0	37	240	0	0	11	3	77	0	10	13
12	0	0	17	0	8	6	1	7	5	0	0	0	29	0	0
Total	1170	739	1099	655	558	713	879	1026	1054	831	843	706	831	848	1265

Table 2. Climatic characteristics of 4 selected SAT locations.

Location	Latitude	Longitude	Mean annual rainfall (mm)	Potential evapotranspiration (mm)
Bamako (Mali)	12° 38' N	08° 02' W	1099	1804
Niamey (Niger)	13° 29' N	02° 10' E	636	2057
Dakar (Senegal)	14° 44' N	17° 30' W	578	1825
Hyderabad (India)	17° 27' N	78° 28' E	761	1757

Table 3. Rainfall, PE, and MAI at Hyderabad (1940-1970).

Month	Mean rainfall R (mm)	Mean PE (mm)	R/PE[a]	Dependable Precipitation (mm)[a]	MAI[b]
Jan	2	110			
Feb	10	129		0	
Mar	13	181		0	
Apr	23	198		6	0.03
May	30	220		7	0.03
Jun	107	196	0.55	59	0.32
Jul	165	140	0.85	121	0.75
Aug	147	135	1.09	86	0.55
Sep	163	119	1.37	91	0.65
Oct	71	124	0.57	30	0.21
Nov	25	104	0.24	0	
Dec	5	99		0	

[a]At 75% probability, also referred to as PD
[b]Moisture Availability Index ≈ PD/PE

Table 4. Date of onset of rainy season and probabilities of length of growing season at Niamey.

Date of onset of rains	Growing season length (days)			
	90	110	130	150
19 May	99	88	49	11
29 May	97	70	29	2
8 June	88	49	11	0
18 June	70	29	2	0
28 June	49	11	0	0

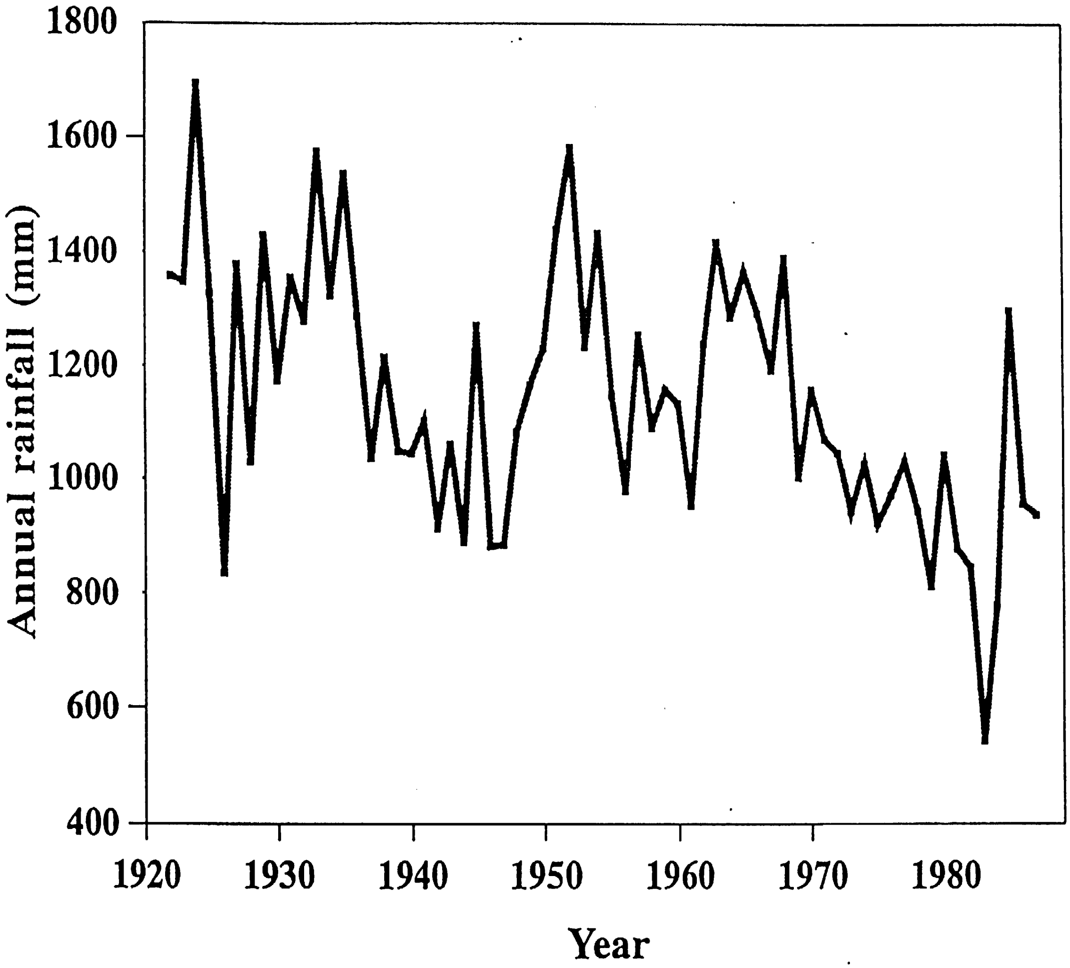

Fig. 4. Annual rainfall variation at Banfora, Burkina Faso.

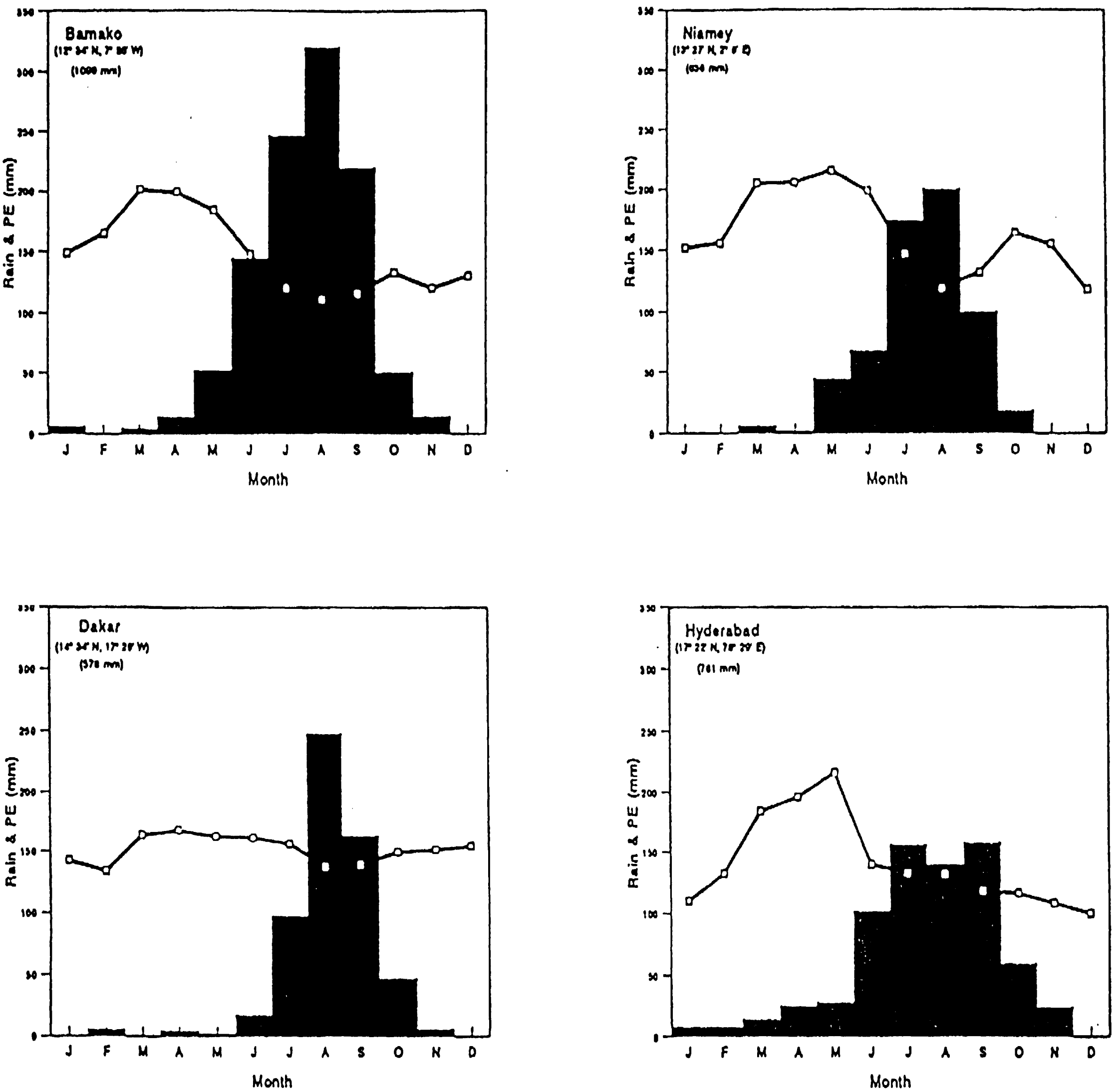

Fig. 5. Rainfall and potential evapotranspiration at four locations in the semi-arid tropics.

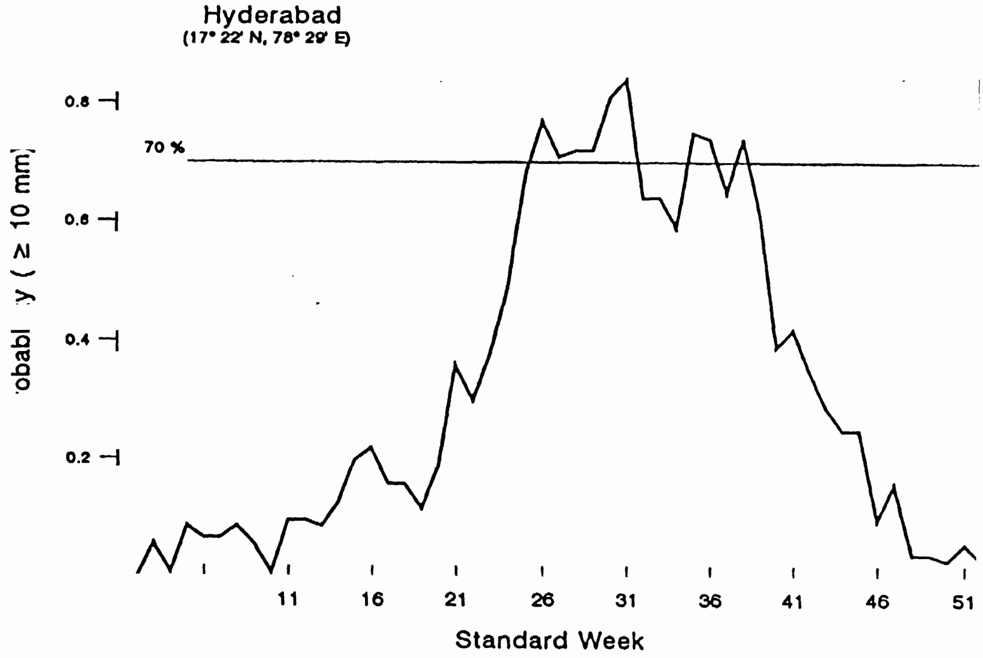

Fig. 6. Weekly rainfall probabilities at Hyderabad, India.

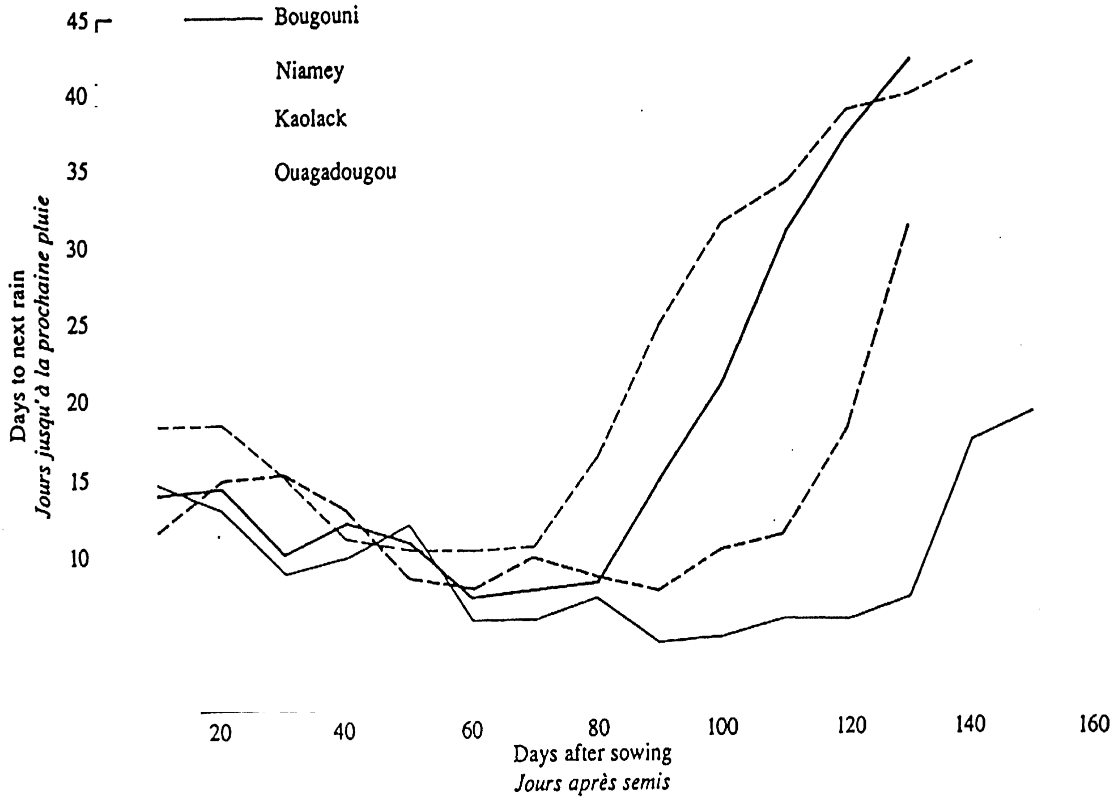

Fig. 7. Length of dry spells for 10 mm rainfall threshold at 90% probability for four locations in west Africa.

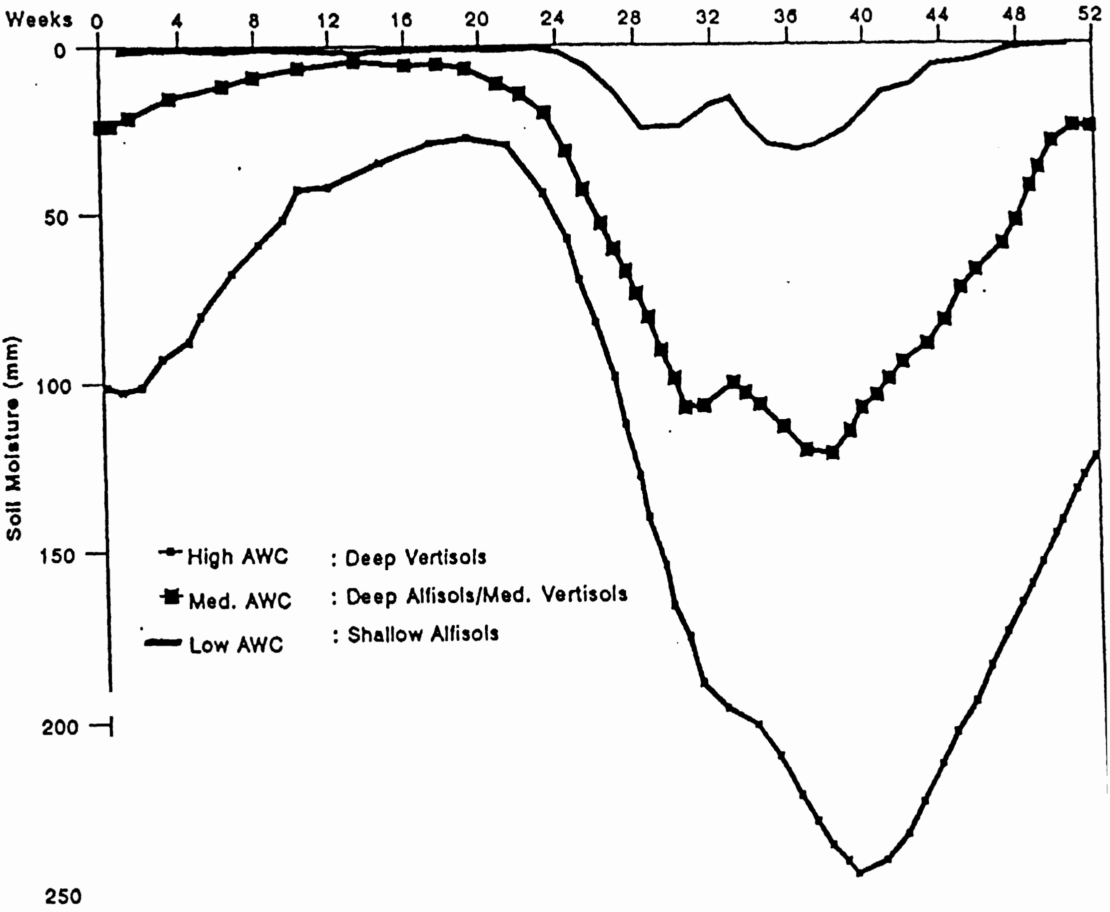

Fig. 8. Variations in soil profile moisture on a weekly basis in three typical soils of Hyderabad region.

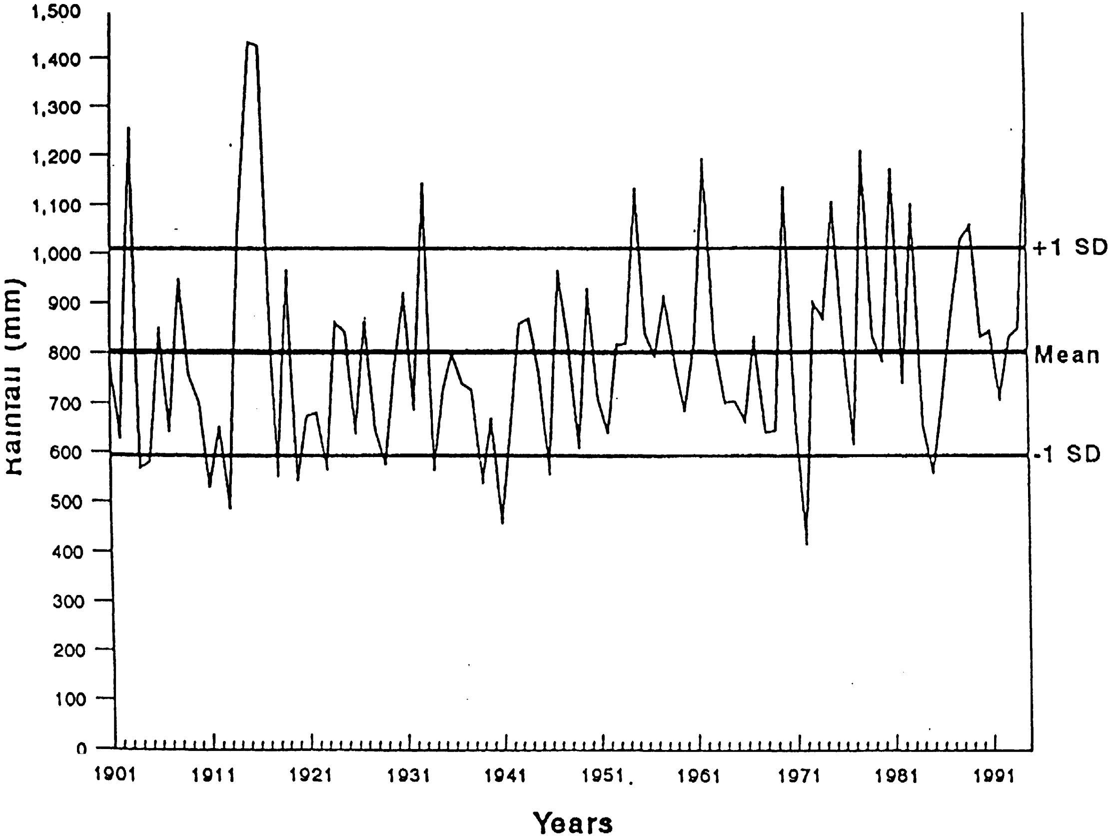

Fig. 9. Annual rainfall variation at Hyderabad, India.

SOIL BIOLOGICAL, CHEMICAL, AND PHYSICAL CHARACTERIZATION

K.B. Laryea, M.V.K. Sivakumar, K.K. Lee, A. Bationo and M.C. Klaij

Introduction

Soil characterization indicates the status of a particular soil property at a particular time and provides baseline information for comparison among imposed treatments. Soil is a dynamic system. Therefore, soil properties, particularly the biological ones, change over time. Consequently, the use of soil information at different time periods must be done carefully. At ICRISAT, most measurements aimed at characterizing soils have been taken as part of research experiments in order to facilitate interpretation of results. An exception however, was the soil survey of ICRISAT farms at IAC (Murthy and Swindale, 1993) and at Niamey (West *et al.* 1984) where various soil series were characterized. Before 1983, the major characteristics of Alfisols and Vertisols at IAC, and the sandy Alfisols (sandy, siliceous, iso-hyperthermic *Psammentic Paleustalf*) at ICRISAT Sahelian Center (ISC) had been determined and that for IAC reported by El-Swaify *et al. (1985). This review covers soil surveys and characterization at ICRISAT Asia* Center (IAC) and the West African Semi-Arid Tropics (WASAT). It also covers soil biological, chemical, and physical characterization done as part of experiments at IAC and ISC after 1985.

Soil Characterization

Soil Surveys and Characterization at IAC and WASAT

In our preliminary efforts to delineate research domains for West Africa using the Geographic Information system (GIS), we estimated the total area under semi-arid tropics in West Africa to be 218 m ha (Sivakumar, 1993). Areas covered under different soil types in WASAT are given in Table 5 which shows that Luvisols cover 72 m ha, followed by Arenosols (37 m ha), Lithosols (29 m ha), Regosols (24 m ha), Fluvisols (13 m ha), and Vertisols (13 m ha). Relative importance of these soils in the WASAT varies with the length of the growing period (LGP). The area covered under different soil types for each of the four LGP zones in the WASAT is shown in Table 6. In the shorter LGP zone of 75-100 days, Arenosols covering 25 m ha are the most important soils followed by Luvisols (5 m ha). For the other three LGP zones, Luvisols are the most dominant soils followed by Regosols, Arenosols, Nitosols and Vertisols.

During the period under review, the experimental farms at IAC, its Type Area (i.e., area located between 17° 25' to 17° 40' N latitude and 78° 05' to 78° 20' E longitude) and at ISC, were mapped, characterized, and classified to know their extent for effective transfer of agro-technology developed at ICRISAT to similar soils. The work at IAC was a cooperative project between ICRISAT and the National Bureau of Soil Survey and Land Use Planning (NBSS and

LUP) in India. That at ISC was a cooperative project between ICRISAT and the Texas A&M University System/Trop Soils. Also, in cooperation with the World Soil Resources Program of the Soil Conservation Service of the United States Department of Agriculture (USDA), we characterized the soils at ICRISAT Center in India and ICRISAT research sites in Niger, Nigeria, Mali, Zimbabwe, Malawi and Kenya. We also characterized the research sites of Institut Nationale de Recherche Agronomique du Niger (INRAN) and Institut Economie Rurale (IER), Mali where collaborative trials are conducted with ICRISAT. Characterization of these research sites has facilitated agrotechnology transfer of research findings from one location to another, as it allows better understanding and interpretation of the experimental results.

During 27 Apr–12 May 1990, soils were sampled at INRAN Research Stations in Kolo, Tara, Bengou, Birni N'Konni, Maradi, (all in Niger), ICRISAT Research Station, Bagauda, Nigeria, IAR Research Station, Kadawa, Nigeria, ICRISAT Research Station at Samanko, Mali, and IER Research Station at Cinzana, Mali. Soils were sampled during 7-20 May 1994 at the Bunda College of Agriculture, Chitedze Research Station, Chitala Research Station, Kasinthula Research Station, (all in Malawi), Matopos Research Station, Lucydale Research Station, (all in Zimbabwe), University of Nairobi Experimental Farm, Agricultural Experimental Station in Alupe, Agricultural Experimental Station in Kampi ya Mawe, and Agricultural Experimental Station, Kiboku, (all in Kenya). An example of the outputs from these soil characterization activities is presented in Appendix I.

There are six soil series occurring at ICRISAT farm at IAC. Two of them belong to the Alfisol order and the remaining four to the Vertisols. The Alfisols are Lingampalli series (fine-loamy, mixed, isohyperthermic family of *Lithic Rhodustalfs*) and Patancheru series (clayey-skeletal, mixed, isohyperthermic family of *Udic Rhodustalfs*). The soil series belonging to the Vertisol order are Icri (fine, montmorillonitic, isohyperthermic family of *Paralithic Vertic Ustropepts*) Kasireddipalli (very fine montmorillonitic, isohyperthermic family of *Typic Pellusterts*), Manmool (fine, montmorillonitic, isohyperthermic family of *Fluventic Ustropepts*), and Yamkunta (fine, mixed, isohyperthermic family of *Vertic Halaquepts*). Of these soils, Patancheru series (covering 248 ha or 18% of the farm area) and Kasireddipalli (occupying 552 ha or 40% of the area) are dominant. Tables 7 and 8 present the soil characteristics of these two series. Characteristics of the others are presented in Murthy and Swindale (1993).

There are five soil series at the ISC research farm. These are Dayobu series (coated, isohyperthermic family of *Ustoxic Quartzipsamment*), Gagani series (loamy, siliceous, shallow, isohyperthermic family of *Petroferric Haplustult*), Labucheri (sandy, siliceous, isohyperthermic family of *Psammentic Paleustalf*), Tondi (sandy, siliceous, isohyperthermic family of *Petroferric Haplustult*), and Zogoti (sandy, siliceous, isohyperthermic family of *Psammentic Paleustalf*). Of these, the Labucheri series (on 1-5% slopes) cover 418 ha or 84% of the farm area. The soil profile of this series is dominated by sand (88-91%). They are acidic (pH in water of 4.9 to 5.8), have low organic carbon content (<0.3%), and low cation exchange capacity (<2 cmol kg^{-1}) (Table 9).

Biological Characterization

Soil biological characterization was mostly made to obtain biological properties of experimental sites or base measurements that will enable different experimental treatments to be compared.

Soil fauna

We compared earthworm biomass from an Alfisol under natural vegetation and that from a cultivated soil in RM 19B at IAC. Three species of earthworms were identified and collected from the natural vegetation area. These were *Octochaetona philloti* (Michaelson), *Lampito mauritti* (Kinberg), and *Octonochaeta rosea* (Stephenson). Of these only *O. philloti* and *L. Mauritti* were identified and collected from RM19B. The average monthly biomass of earthworms in the Alfisol under natural vegetation (76 g m^{-2}) was several fold larger than that from plots that had undergone different managements in RM19B. The difference between the earthworm biomass in the soil under natural vegetation and the plots depended on the type of management the soil had undergone. For example, the earthworm biomass in zero-tilled bare treatments was 29 times less than that in the plots under *Stylosanthes hamata* treatment which in turn was four times less than the soil under natural vegetation.

Arthropods identified in the Alfisols under cultivation and the natural vegetation area included *Acarina* (e.g., *Mesostigmated nute, Protigmatid nute*, and *Actigmated nute*), *Collembola* (e.g., *Isotomids, Endomobrids, Sminthuride, Hypogastrands*, and *Onychiuride*), and a miscellaneous group (e.g., *Formicidae, Dermaptera, Coleoptera, Orthoptera, Thysanoptera, Psocoptera, and Lapidoptera*).

Soil flora

Soil microbial biomass is a living fraction of soil organic matter. It is an important source/sink for plant nutrients and can prevent leaching of plant nutrients. We used the dry season microbial biomass from an Alfisol and a Vertisol natural vegetation areas as yardsticks to compare dry season microbial biomass from an Alfisol and a Vertisol that have been under cultivation for some years. The Vertisol under natural vegetation had larger microbial biomass than the Alfisol under natural vegetation. Also, the microbial biomass from the cultivated Vertisol was larger than that from the cultivated Alfisol. The microbial biomass from natural vegetation areas was larger than that from cultivated areas. We infer that Vertisols have more microbial biomass than Alfisols and that soil under natural vegetation contains more microbial biomass than cultivated fields.

We studied the levels of mycorrhizal spores in four locations at IAC. At Akola and Solapur, Vertisols on research stations contained less vesicular-arbuscular mycorrhiza (VAM) spores than those on farmers' fields. Vertisols from farmers' fields at Akola contained 58 spores g^{-1} compared with 45 g^{-1} from research station. At Solapur, Vertisols from farmers' fields contained 16 spores g^{-1} compared with 9 g^{-1} from that on research station. These differences were not observed in Alfisols at Bijapur and Kovilpatti. Comparison of soil samples from the research stations indicated that Akola soils contained the maximum VAM spores (45 g^{-1}) while soils at ICRISAT farm had the least number of spores (4 g^{-1}).

Grain legumes (e.g., groundnut (*Arachis hypogeae* (L.), pigeonpea (*Cajanus cajan* (L.) Millspaugh, and green gram (Phaseolus mungo (L.) Reg. trop.) are important crops in the semi-arid tropics (SAT). These crops have often been found to be poorly nodulated on farmers' field due to low numbers of the cowpea-group of rhizobia in soil. In establishing the need for legume seed inoculation, we used the natural occurrence of the appropriate bacteria as an important diagnostic aid. We examined the number and distribution of cowpea-group of rhizobia in some typical soils in the SAT using siratro (*Macroptylium atropurpeum*) and pigeonpea as trap hosts. There was a large variability in *Rhizobium* numbers between sampling sites in the same field. The population was more consistent in Alfisols (ranging from 10^4 to 3 x 10^5 rhizobia g^{-1} soil) than in Vertisols (0 to 10^6 rhizobia g^{-1} soil) and decreased with depth (Kumar Rao *et al.* 1982). In paddy fields, the numbers were very low, generally < 10^2 rhizobia g^{-1} soil. In many rice-growing areas in India, it is common practice to grow legume after the main paddy crop if water is limiting. Therefore, if pigeonpea or other members of the cowpea inoculant group of legumes are planted after a paddy crop, it may be necessary to inoculate to ensure adequate nodulation.

Chemical Characterization

In collaboration with the International Fertilizer Development Center (IFDC), a range of soils in the Sudano-Sahelian zone of WASAT were collected and analyzed at ISC. One striking feature of the Sudano-Sahelian soils is their low organic matter content, low total nitrogen content, and low effective cation exchange capacity (Table 10). The main source of nitrogen is organic matter (OM). Therefore the natural low level of organic matter in these soils reflects the low total nitrogen contents. The accumulation of organic matter in West Africa is highly related to rainfall and the amount of total nitrogen (TN, ppm) in the soil was found to relate to the amount of annual rainfall (R, mm).

$$TN = 564 + 1.026\ R \qquad (r = 0.77)$$

The low cation exchange capacity (CEC) of Sudano-Sahelian soils is due to their low organic matter content, low clay content, and their dominant clay mineral (kaolinite). The effective cation exchange capacity (ECEC) was found to correlate better with OM (r = 0.85) than with clay content (r = 0.39) and demonstrates that most of the colloidal materials in these soils are from organic sources.

Phosphorus (P) deficiency is a major cause of low crop yields in the Sudano-Sahelian zone. The low contents of both total and available P (Table 10) may be due to several factors. These factors include:

• parent materials consisting of granites, sandstones and eolian sands which cover the continental terminal and have low mineral reserves;

• low levels of organically-bound phosphorus which is a consequence of the low organic matter *content;*

• inadequate nutrient cycling due to the removal of grain and biomass from the fields.

The P sorption maxima calculated using the Langmuir equation ranged from 27 to 406 mg P kg^{-1}. These relative low values show that the soils have a very low capacity to immobilize (fix) added phosphorus. It also indicates that additions of small quantities of P fertilizers will generally satisfy both the crop and soil needs. Using multiple regression to investigate the contributions of various soil parameters on the availability of P (Bray P1, ppm), the following model was developed:

Bray P1 = 0.09 (total P (ppm)) -0.02 (adsorption maxima (ppm)); (r = 0.97)

Total native P and the capacity of the soils to fix P are the factors responsible for P availability to plants. The native total P alone explains 92% of the variation of the available P. As the native P contents are very low, P deficiency is regarded as the primary constraint to crop production in these sandy soils.

We developed a regression model relating maximum P sorbed (MPS, ppm) to percentage clay (PC), Cmol kg^{-1} of exchangeable acidity (EA) and total P (TP, ppm) :

MPS = 1.91 + 13.25 cl + 247.04 EA + 2.28 TP (r^2 = 0.98)

Exchangeable acidity alone explains 48% of the variation of maximum P sorbed and when soil clay content is added to the model, a total of 71% of the variation in maximum P sorbed is explained.

Chemical Variability in Sandy Ustalfs

Extreme variability in millet stands over a very short distance (2 to 20 m) poses a major constraint to grain production in the Sahelian region. We initiated a study to characterize and examine chemical properties of associated productive and unproductive soils at ISC. Soil samples were taken at 26 sites along a 15 m transect between a productive and an unproductive region in a field of Labucheri soil series. Unproductive soils were associated with low pH (<4.5), high Al plus H saturation of the cation exchange sites, and decreased amounts of exchangeable K, Ca, and Mg when compared with productive sites (Table 11). These chemical properties may result in Al or Mn toxicity or deficiencies of K, Ca, Mg, and P and appear to account for the variability that existed in the millet stands (Scott-Wendt *et al.* 1988).

Physical Characterization

Hydraulic properties of some soils in Niger

In the WASAT, where rainfall variability is often large, plant available water is an important determinant of crop yields. Characterization of soil hydraulic properties is important for using models to estimate drainage, a component of the water balance which is often ignored. We collected soil samples from four different soil types in Niger, viz., a sand, a loamy sandy, a sandy loam and a loam, and determined the soil moisture characteristic [$\psi(\theta)$] curves. Saturated hydraulic conductivity (K_s) was also measured. The K_s values were used together with the $\psi(\theta)$ curves to calculate hydraulic conductivity as a function of water content [$K(\theta)$]. These hydraulic properties were then used in a simulation model to estimate drainage. Our studies showed that the drainage component can be significant, especially for the sandy soils (Sivakumar *et al.* 1990).

We also determined the $\psi(\theta)$ and the $K(\theta)$ relationships of Labucheri soil series as base data for our long-term factorial experiment that examined the effects of +/- fertilizer, +/- crop residues, tillage (i.e., no-till, ridging, and plowing), and cultivars (local versus improved millet cultivars). Figure 10 presents the base data for $\psi(\theta)$ and the $K(\theta)$ for the Labucheri soil series that was used in the long-term management experiments and also for modelling the seasonal water balance of pearl millet grown on that soil at ISC (Hoogmoed and Klaij, 1990; Klaij and Vachaud, 1992).

Physical characteristics of Vertic Inceptisols at IAC

About 35 million ha of black soils in India and about 30 million ha in Africa are classified as Vertic Inceptisols. These soils are generally characterized by their shallow depth to the weathered parent material (murrum) and the presence of many coarse fragments (stones) on the surface and within the soil profile. We determined the main soil physical properties of two profiles on the Vertic Inceptisols at the IAC as part of our studies on the water balance of sunflower (*Helianthus annuus* (L.)) grown on this soil. The variability in physical properties within this soil group is shown by the contrast between the two profiles in terms of texture trends with depth (Table 13). The presence of coarse fragments reduced the bulk density and hence increased the total porosity of the coarse fragment-free soil. The estimated porosity of 52-60 per cent for the soil between the coarse fragments at 25-70 cm depth suggests that it is a loosely packed porous matrix. We determined the $K(\theta)$ function for this soil using the instantaneous profile method and obtained the following regression equations (ICRISAT, 1988) for the depths 15, 30, 75, and 120 cm:

$$\text{Log}(K_{15}) = 29.2\theta_{15} - 17.5; \quad (r^2 = 0.997;\ \text{rse} = 0.048)$$
$$\text{Log}(K_{30}) = 50.2\theta_{30} - 13.3; \quad (r^2 = 0.996;\ \text{rse} = 0.049)$$
$$\text{Log}(K_{75}) = 87.8\theta_{75} - 22.7; \quad (r^2 = 0.997;\ \text{rse} = 0.050)$$
$$\text{Log}(K_{120}) = 98.0\theta_{120} - 32.3; \quad (r^2 = 0.915;\ \text{rse} = 0.274)$$

Its unsaturated hydraulic conductivities ranged from 10^{-5} to 10^{-8} m s^{-1} for various horizons of the profile (compare with that for a coarse sandy soil of 10^{-4} to 10^{-5}) and were greater in the subsoil than the surface soil indicating that the zone of restriction to water movement is the topsoil. It also confirmed our field observations over several years that the Vertic Inceptisols have good internal drainage.

Because Vertic Inceptisols in India are used generally to grow such rainy-season crops as castor (*Ricinus communis*) and sunflower, we characterized its properties and related them to the root development of castor. Soil around four 'large' and four 'small' plants of mature castor (cv Aruna) was drenched with water for 12 h and drained. The soil was excavated, physical and chemical properties of three horizons, and plant measurements (i.e., plant height, shoot mass, root length, and root mass) taken. The soil horizons were (i) the surface layer, the lower boundary of which ranged from 15 to 45 cm (referred to as the A horizon), (ii) a calcareous layer of strongly weathered material, often with coarse fragments and having a lower boundary ranging from 40-70 cm (C_1 horizon), and (iii) a less calcareous layer of weathered parent material (C_2 horizon). There were significant differences ($P < 0.01$ based on LSD test) between the A and C_1 horizons in the soil properties (Table 14). Properties of the C_1 and C_2 horizons were similar except for cation exchange capacity which was significantly higher in C_2 ($P < 0.05$ based on LSD test) than in C_1 (ICRISAT, 1990).

The root/shoot ratio was not significantly different for large and small plants (Table 15). Root length per unit root mass and per unit shoot mass was significantly higher ($P < 0.05$) for small plants. This suggests that small plants used relatively more assimilates to increase root length rather root diameter. Our observations on root morphology in relation to soil depth showed that (i) near or in the surface of the C_1 horizon or near coarse fragments associated with it, many roots ended, branched, changed direction abruptly (including growing horizontally), were either constricted or deformed; (ii) most roots penetrating the C_1 horizon to 50 cm grew deeper than 100 cm. These observations indicate that impediments in or near the C_1 horizon (where bulk density was 1.54 Mg m^{-3}, shear strength was 26.3 kPa, and penetrometer resistance was 2.65 MPa), restrict root growth (ICRISAT, 1990).

Variability of saturated hydraulic conductivity in Alfisols

Saturated hydraulic conductivity (K_s) has important implications in irrigation and drainage systems design, infiltration, hydrology and general water balance modelling. Its determination *in-situ* is tedious, time consuming, expensive and requires training. When we initiated measurements of soil hydraulic properties on Alfisols, we observed considerable variation in K_s within short distances. Because most Alfisols vary spatially in physical properties, it is often tenuous to use point-measured physical parameters to model large-scale hydrologic processes. Therefore, either a large number of determinations have to be made (and this is very expensive) or a way has to be found to coalesce the variable measurements so that the resultant functional relationship can be mathematically described. Scaling methods that employ the similar media concepts allow seemingly scattered measurements to be coalesced. The problem, however, is that scaling factors need to be determined. Their determination involves having to measure that physical parameter. We hypothesized that scaling hydraulic conductivity using scaling factors calculated from easily measured soil properties (e.g., particle size) is possible and will facilitate hydrologic characterization of Alfisol. Scaling factors were calculated, using K_s, sand pore-volume, clay pore-volume, clay content, and effective porosity determined on 109 undisturbed monoliths. We found that K_s of gravelly Alfisol can be reasonably scaled from clay pore-volume, clay content, or sand pore-volume if coarse fragments (particles > 2 mm) are discounted. (Bonsu and Laryea, 1989).

Variability of penetration resistance in Alfisols

Penetration resistance has been used successfully to study the increase in strength as hardsetting soils dry. However, when we initiated similar studies on Alfisols at the IAC, considerable variation in penetration resistance was observed within short distances. We were concerned that this large variability will make it difficult to accurately predict or model the effect of soil strength on root growth and subsequently on crop growth on the experimental plot. We therefore characterized the spatial variability in penetration resistance of this plot using geostatistical techniques which among other comparisons, allowed us to examine the spatial structure of the field and also to estimate values of penetration over the experimental plot by punctual kriging. Figure 11 shows the contour maps of estimated values of penetration resistance of an experimental field at IAC. Generally, the north and the north-west part of the field had greater penetration resistance than the southern part (Ley and Laryea, 1994) . This pattern was more evident in the dry soil (Fig. 11a) than in the same soil that had been wetted to saturation and left to drain for two days (Fig. 11b).

Characterizing rainfall erosivity and erodibility on very gentle slopes

The potential erosiveness of rainfall depends on the detachment of soil particles by raindrop impact and the ability of surface runoff to erode soil. Actual erosion however, would depend to a large extent on the interaction between rainfall erosivity on one hand and on the other hand on soil erodibility, slope steepness, slope length, and crop cover. We have used the commonly used index of rainfall erosivity, EI_{30}, [the product of total rainfall energy (E), and the maximum 30-minute intensity (I_{30})], to obtain the erosiveness of rainfall at IAC during 1980 to 1994. Over 80 per cent of seasonal rainfall erosiveness at IAC during 1980-1994 came from rainfall amounts > 12.7 mm (Table 16). Most erosive rainfalls occurred during the season (June to October). Annual rainfall erosivity ranged from 2490 to 10133 MJ mm ha^{-1} h^{-1} y^{-1} on the Vertisol and 2946 to 10064 MJ mm ha^{-1} h^{-1} y^{-1} on the Alfisol.

Most farm lands in the semi-arid tropics of India are on very gentle slopes (< 3 per cent). Nomograms based on the Universal Soil Loss Equation (USLE) developed in the USA for estimating the topographical factor (i.e., slope length factor (L) and slope steepness factor (S)) were based on 22.1-m length and 9 per cent slope. We characterized the topographical factor of the USLE using three slope lengths (viz., 11 m, 22 m, and 44 m) and four slopes (viz., 0.4, 0.8, 1.6, and 2.0 per cent). We obtained a linear relationship for the plot of soil loss (A) versus LS which we regressed to get for the Alfisol,

$$A = 7.362\ LS - 0.7391; \qquad r^2 = 0.790,\ s.e\ (coeff) = 0.7914$$

and for the Vertisol,

$$A = 15.403\ LS - 1.9717; \qquad r^2 = 0.877,\ \text{s.e. (coeff)} = 1.1533$$

Cooperation with NARS and International Agencies

Organic matter plays an important role in most soil chemical, biological, and physical processes. Compared with temperate soils, the organic matter content of most tropical soils is low because of the high rates of organic matter decomposition in the tropics. Very few studies have measured these rates in Alfisols and Vertisols in the semi-arid tropics. In cooperation with GTZ and the University of Hamburg, Germany, we measured rates of organic matter (groundnut haulm) decomposition in both Alfisols and Vertisols. Residual C^{14} percentage (RC) as a function of time (t, in weeks) was fitted to a power function of the form,

$$RC = mt^{n}$$

where m and n are fitted parameters. With the Alfisol, m = 53 and n = -8.4 with an $r^2 = 0.97$, while the Vertisol had, m = 81, n = -12.2 and $r^2 = 0.99$ (Singer *et al.* 1991). Decomposition was fastest shortly after addition of fresh organic matter to the soil at the beginning of each rainy season. Thereafter, organic matter decomposition rate declined. Decomposition was faster on Alfisols than on Vertisols. We attribute the faster rate of decomposition on Alfisols to its lower clay content than Vertisol, implying less protection of organic material against microbial decomposition. We also observed seasonal effects on organic matter decomposition. For example, losses for the Alfisol and Vertisol during the first week after addition in 1990 were 30 and 17 per cent, compared with 43 and 27 per cent in 1989. The higher rates in 1989 were associated with more rain , i.e., 861 mm (mid-June to December) compared to 588 mm in 1990. In both 1989 and 1990, the mean minimum and maximum temperatures in each year were 29°C and 29°C.The groundnut haulm had a C:N ration of 33, compared to the usual range of 80-120 for cereals.

The behavior of vesicular-arbuscular mycorrhizae (VAM) in Alfisols and Vertisols in the SAT is not well understood. Understanding VAM behavior in these soil will provide strategies for managing soil nutrients particularly P. In collaboration with the University of Dundee, United Kingdom, we studied the establishment and manipulation of indigenous and applied VAM in an Alfisol and a Vertisol. Field experiments were conducted with sorghum cultivar CSH 11 and pearl millet cultivar ICMV 88907. Rock phosphate (17 kg P ha^{-1}), urea (60 kg N ha^{-1}), and rice straw (4 t ha^{-1}) were used either singly or in combination, as treatments to enhance VAM growth. Each treatment was inoculated with either *Glomus clarum* imported from the UK or an indigenous VAM. Initial indigenous VAM spore count showed that the Alfisol contained three times as many spores as the Vertisol. In the Alfisol, neither the total biomass nor grain yield of sorghum in any treatment increased as a result of *G. clarum* inoculation. In the Vertisol, however, both total biomass and grain yield increased in all treatments.

In collaboration with the University of Reading, we characterized P in Vertisols and Alfisols at the IAC using ^{32}P to discriminate between the P already in the soil and that added. We measured the amounts of exchangeable, nonexchangeable, and total adsorbed P simultaneously in each soil by equilibrating the soil samples after adding 11 rates of P (as KH_2PO_4, ranging from 0 to 170 mg P kg^{-1} soil) in 0.01 M $CaCl_2$. The process was repeated for second desorption. For each soil, the relationships between phosphate in solution (C) and (i) exchangeable phosphate (P_e) and (ii) total adsorbed phosphate (P_t) were described by the Freundlich isotherm:

$$P = a\ C^{(b/a)}$$

where, a is the amount of the adsorbed P and b is the buffer capacity. Parameters a_e and b_e for exchangeable phosphate, and a_t and b_t for total adsorbed phosphate were calculated using an iterative method. Comparison of fitted parameters (Table 12) showed that there was no significant difference between a_e and a_t, or between b_e and b_t so that the fitted isotherms for total adsorbed and exchangeable P were identical, confirming that all the adsorbed P remained exchangeable both in the Vertisol and in the Alfisol (ICRISAT, 1989). The parameters a_e and b_e were larger for the Vertisol than for the Alfisol. Exchangeable and adsorbed P calculated for three C values with a wide concentration range, indicate that Vertisols adsorbed more P than Alfisols at all concentrations (Table 12).

Pearl millet population on farmers' fields in West Africa is often low. In fields with low plant population, most of the rainfall is often lost as direct evaporation from the soil. Conventional methods of estimating crop-water use in such sparsely populated fields can be inaccurate. We therefore collaborated with the Institute of Hydrology to characterize the evaporation process from a sparse dryland pearl millet crop at the ISC in 1985. A number of techniques for measuring soil evaporation was assessed on a 4-ha field of pearl millet. Total evaporation was measured using two "Hydras" (micro-meteorological devices designed at the Institute of Hydrology). Our measurements indicated that on a wet day (17 mm of rain had fallen two days earlier), transpiration was only 0.9 mm while soil evaporation was 2.1 mm, indicating the important contribution that direct soil evaporation can make on days following rain. The total evaporation calculated as the sum of transpiration and soil evaporation was 3.0 mm and this agreed very well with that measured with Hydra MK2 (2.9 mm). Soil evaporation then decreased rapidly as the soil dried, so that 5 days later, only 0.2 mm of water was lost directly from the soil while transpiration remained at 0.9 mm (ICRISAT, 1986).

Future Plans

Most of the future research activities relating to soil characterization are included in the Integrated Systems Projects (ISPs). In ISP 1, subproject 2 (activity 2a) aims to improve the management of nutrient and water resources in pearl millet-based cropping systems in Asia and West Africa. To achieve this aim, the activities in this subproject include monitoring farmers' current soil nutrient and water management practices, documenting how these are changing, identifying constraints and opportunities for improved management options, and use both on-station and on-farm research data to better understand the water and nutrient dynamics of pearl millet-based production systems. The outputs for this research activity will include characterization of the soil and climatic resources at selected benchmark sites in Asia and West Africa, a report detailing opportunities and constraints for improved soil fertility and soil water management strategies in pearl millet-based cropping systems, and an evaluation of farmers' perceptions of improved soil and water management options. In quantifying tree-crop-livestock interactions under this project (Subproject 3, activity 2), information will be required on the chemical and physical properties of soils adjacent to windbreaks and below trees (e.g., *Prosopis cineria* (Khejdi), *Tecomella undulata* (Rohida), *Vitellaria pardoxa* (Karite) or *Parkia biglobosa* (Nere) in parklands. Further, to achieve objective 1 of subproject 5 of this project (i.e., development of better understanding of the causes, extent, severity, and processes of land degradation in traditional crop, tree, and livestock production systems in the desert margins of Asia and West Africa), there will be the need to characterize the soil biological, chemical, and physical properties.

In ISP 2, the approach is to determine the extent of transferability of results from bench mark sites to regions within a research domain by characterizing the production system. The research domain is defined in ISP 2 as a homogeneous "ecoregions" where relevance of strategic research is expected to be pervasive throughout the area that the domain covers. Characterization of the production system is a multi-disciplinary activity that includes activities such as (a) collection and verification of available climate, soil, economic, and production databases to assess the agroecological potential and for targeting future research in Asia and West Africa; (b) quantitative description of important cropping/livestock systems and assessment of the major socioeconomic, biotic, and abiotic constraints to sustainable production in Asia and West Africa. Some of the outputs expected from this research are a well defined research domain, and GIS-compatible soil and climatic databases for the relevant production systems that can be used for extrapolation of results.

In ISP 3, crop intensification through double cropping the soils in the research domain with high profile water storage capacity is envisaged. The initial research need is to characterize the natural resource base, delineate potentially suitable areas, and identify constraints to and opportunities for double cropping. We will also embark on characterization of the socioeconomic and natural resources across a continuum from sandy Alfisols (Psamments) to those containing slightly more clay in West and Central Africa (WCA) and from shallow vertic soils to Vertisols (and associated Alfisols) in Asia. This activity will enable the identification of benchmark sites for collaborative research.

Table 5. Area ('000 ha) under different soil types in West African Semi-Arid Tropics.

Soil type	Area
Luvisols	71755
Arenosols	37352
Lithosols	29427
Regosols	24240
Fluvisols	13194
Vertisols	12745
Nitosols	8925
Gleysols	4711
Acrisols	3793
Cambisols	3567
Planosols	3416
Solonetz	1972
Solonchaks	1573
Ferralsols	484
Phaeozems	292
Total	217830

Table 6. Area ('000 ha) under different soil types in the four growing period zones in West African Semi-Arid Tropics.

Growing period zone	Area covered under the soil type														
	A	B	F	G	H	I	J	L	N	Q	R	S	V	W	Z	Total
75-100	1	939	0	2096	0	4057	2282	4845	92	24749	2790	1901	2739	2668	139	49399
100-125	379	597	0	1799	95	3171	3494	15429	1561	10179	12871	71	3582	538	1048	54901
125-150	290	1039	126	616	197	10464	4182	26646	2063	1777	8015	0	4627	147	386	60631
150-180	1322	992	357	200	0	11735	3236	24835	5209	646	564	0	1797	64	0	52899
Total	3793	3567	484	4711	292	29427	13194	71755	8925	37352	24240	1972	12745	3416	1573	217830

Legend

A: Acrisols
B: Cambisols
F:Ferrasols
G: Gleysols
H: Phaeozems
I: Lithosols
J: Fluvisols
L: Luvisols

N: Nitosols
Q: Arenosols
R: Regosols
S: Solentetz
V: Vertisols
W: Planosols
Z:Solonchaks

Table 7. Patancheru Soil Series.

Classification : Udic Rhodustalf

Horizon	Depth (cm)	Size class and particle diameter (mm): Sand 2.0-0.02	Silt 0.02-0.002	Clay <0.002	Coarse fragments > 2 mm (% of whole soil)	Organic Carbon (%)	pH (1:2.5) H_2O	E.C. (1:2.5) H_2O	Water retention: 1/3-bar (%)	15-bar (%)
		---------------- % of < 2 mm	---------------							
Ap	0-5	79.3	6.4	14.3	17	0.55	6.0	0.1	16.2	6.3
B1	5-18	66.7	5.5	27.8	17	0.52	6.9	0.1	20.0	12.4
B21t	18-36	41.6	6.8	51.6	36	0.63	6.9	0.1	21.9	13.9
B22t	36-71	45.0	4.4	50.6	54	0.40	6.8	0.1	24.8	17.4
B23t	71-112	54.1	7.4	38.5	50	0.10	6.5	0.1	23.6	16.2
B3	112-140	70.6	4.1	25.3	63	0.18	6.2	0.2	18.7	11.5

Depth	Extractable bases: Ca	Mg	Na	K	Sum	CEC NH_4O Ac	Base saturation (%)	Ratio CEC: Clay	Clay fraction minerology (%): Am	KK	MI	SM	QZ	Sand fraction minerology (%): QZ	FDM	FE	HE	FDP	Others
	-------------------meg/100g				--------------------														
0-5	2.6	0.5	-	0.4	3.5	4.8	74	0.34	11	37	12	17	17	35	25	10	10	5	15
5-18	3.8	0.9	-	0.5	5.2	8.2	64	0.29	12	37	10	19	14	45	20	5	5	10	15
18-36	5.8	3.8	-	0.6	10.2	14.8	69	0.29	14	37	10	23	14	40	30	10	-	10	10
36-71	7.9	3.1	-	0.6	11.6	14.1	82	0.28	12	38	11	20	16	30	30	5	5	15	15
71-112	5.4	2.5	0.3	0.4	8.6	9.8	88	0.25	12	44	9	18	16	40	20	5	-	10	25
112-140	5.7	1.9	0.5	0.3	8.4	9.1	92	0.36	10	39	8	21	16	35	25	5	-	15	20

AM = Amphibole; KK = Kaolinite; MI = Mica; SM = Smectite; QZ = Quartz; FDM = Feldspar - microcline; FDP = Feldspar - plagioclase; HE = Haematite; FE = Magnetite.

Table 8. Kasireddipalli Soil Series.

Classification : Typic Pellustert

Horizon	Depth (cm)	Size class and particle diameter (mm)				Coarse fragments > 2 mm (% of whole soil)	Organic carbon (%)	Carbonate as $CaCo_3$ (%)	pH (1:2.5) H_2O	E.C. (1:2.5) H_2O mmhos/cm
		Coarse sand 2.0-0.2	Fine sand 0.2-0.02	Silt <0.02-0.002)	Clay 0.002					
		------ % of < 2 mm ------								
Ap	0-25	8.5	14.0	19.6	57.9	19	0.96	1.4	8.2	2.2
A12	25-70	7.8	10.8	17.3	64.1	-	0.69	2.0	8.1	2.2
A13	70-143	5.6	10.3	18.1	66.0	9	0.60	2.4	8.0	0.2
A14	143-187	5.3	9.5	17.2	68.0	-	0.30	2.1	8.1	0.2

Depth	Extractable bases					CEC NH_4O Ac	Base saturation (%)	Ratio CEC: clay	Sand fraction minerology (%)							
	Ca	Mg	Na	K	Sum				QZ	FDM	FDP	BI	AM	CL	FE	HE
	------ meg/100g ------															
0-25	39.6	13.9	1.2	1.2	55.9	56.6	99	0.98	15	10	55	-	5	5	5	5
25-70	47.7	11.8	1.1	0.6	59.2	60.8	97	0.95	10	10	50	5	5	5	10	5
70-143	40.5	12.0	1.4	0.7	54.6	54.6	99	0.83	15	5	55	5	-	5	5	10
143-187	44.8	11.2	1.4	0.7	58.1	56.1	100	0.83	10	10	50	5	-	5	10	10

QZ = Quartz; FDM = Feldspar - microcline; FDP = Feldspar - plagioclase; BI = Biotite; AM = Amphibole; CL = Chlorite; FE = Magnetite; HE = Haematite;

Table 9. Labucheri Soil Series.

Lab No.	Depth (cm)	Horizon	Particle Size Distribution										Coarse Frag-ments
			Sand						Silt		Clay		
			VC (2.0-1.0)	C (1.0-0.5)	M (0.5-0.25)	F (0.25-0.10)	VF (0.10-0.05)	Total (2.0-0.05)	Fine (0.02-0.002)	Total (0.05-0.002)	Fine (<0.0002)	Total (<0.002)	
			%										
1479	0-9	A 1	0.0	4.1	24.0	44.3	18.3	90.7	1.4	6.2	2.6	3.2	0
1480	9-30	A 2	0.1	3.8	22.4	43.9	20.4	90.6	0.8	5.6	3.1	3.8	0
1481	30-58	BT 1	0.1	3.9	21.6	42.4	20.3	88.3	0.8	5.7	4.0	6.1	0
1482	58-78	BT 2	0.1	4.7	23.7	42.2	18.0	88.7	1.1	5.5	4.5	5.9	0
1483	78-98	BT 2	0.2	4.9	23.7	41.4	17.8	88.0	0.3	5.3	4.5	6.8	0
1484	98-122	BT 3	0.2	4.7	23.8	40.9	19.1	88.7	1.0	5.0	4.7	6.4	0
1485	122-146	BT 3	0.2	5.8	23.9	40.8	16.9	88.6	0.3	3.5	4.9	8.0	0
1486	146-173	BT 4	0.2	5.2	24.3	41.6	17.8	89.1	1.2	4.2	5.7	6.8	0
1487	173-200	BT 4	0.2	4.7	23.1	41.6	19.4	89.0	0.7	4.1	4.6	7.0	0

(Contd..)

(Table 9 Contd..)

Lab No.	ORGN C %	pH (H2O) 1:1	pH (0.1N KCl)	NH$_4$0AC Extra Bases CA	MG	NA	K	Total	KCl EXTR AL	NAOAC CEC	ECEC	BASE SAT	ESP	EXTR FE
				MEQ/100G								%		
1479	0.31	4.9	3.7	0.3	0.1	0.0	0.1	0.5	0.3	1.6	0.8	30	1	0.4
1480	0.18	4.9	3.8	0.1	0.1	0.0	0.1	0.3	0.4	1.1	0.7	28	3	0.4
1481	0.13	4.9	3.9	0.2	0.1	0.0	0.1	0.4	0.3	1.2	0.8	36	2	0.5
1482	0.11	5.0	4.2	0.4	0.2	0.0	0.1	0.6	0.1	1.1	0.8	60	3	0.4
1483	0.10	5.1	4.2	0.3	0.2	0.0	0.1	0.6	0.1	1.1	0.7	55	3	0.6
1484	0.09	5.6	4.5	0.3	0.3	0.0	0.0	0.7	0.0	1.1	0.7	63	3	0.5
1485	0.07	5.5	4.6	0.3	0.3	0.0	0.0	0.6	0.1	1.1	0.7	61	3	0.5
1486	0.10	5.5	4.5	0.3	0.3	0.0	0.0	0.6	0.1	0.9	0.6	66	3	0.5
1487	0.07	5.8	4.6	0.3	0.3	0.0	0.0	0.6	0.1	0.9	0.7	68	3	0.6

(Contd..)

(Table 9 Contd..)

Lab No.	Bulk density		Cole cm/cm	Water content		
	0.10 Bar	Air dry		0.10 Bar	15 Bar	WRD G/CC
	--------- G/CC --------			-------- wt % ---------		
1479	1.61	1.62	0.002	7.1	1.4	0.09
1480	1.50	1.53	0.007	10.1	3.1	0.10
1481	1.50	1.52	0.004	8.0	2.0	0.09
1482	1.50	1.52	0.004	8.1	1.9	0.09
1483					2.2	
1484	1.57	1.58	0.002	21.2	2.1	0.30
1485					2.3	
1486	1.59	1.59	0.000	21.5	2.2	0.30
1487					2.4	

Source: West *et al.* (1984)

Table 10. Ranges, means, and standard deviation of selected physical and chemical properties of soils in the West Africa Semi-Arid Tropics.

Parameters	Range	Mean	Standard deviation
pH H_2O (2:1 water : soil)	3.85-7.60	6.17	0.66
pH KCl (2:1 KCl : soil)	3.41-7.00	5.05	0.77
Clay (%)	0.7-13.0	3.9	2.67
Sand (%)	71-99	88	8
Organic matter (%)	0.14-5.07	1.4	1.09
Total nitrogen (mg kg^{-1})	31-226	446	455
Exchangeable bases (cmol kg^{-1})			
Ca	0.15-16.45	2.16	3.01
Mg	0.02-2.16	0.59	0.55
K	0.03-1.13	0.20	0.22
Na	0.01-0.09	0.04	0.01
Exchangeable acidity (cmol kg^{-1})	0.02-5.6	0.24	0.80
Effective cation exchange capacity (ECEC, cmol kg^{-1})	0.54-19.2	3.43	3.801
Base saturation (%)	36-99	88	17
Al saturation (%)	0-46	3	8
Total P (mg P kg^{-1})	25-941	136	151
Bray1 P (mg P kg^{-1})	1-83	8	14
P Adsorption maxima (mg P kg^{-1})	27-406	109	76

Table 11. Selected chemical properties of soils taken from the surface 15 cm of soil taken along a transect from an unproductive to a productive region.

Extreme	Site No.	Position m	pH	Exchangeable cation: Ca	Mg	K	Na	Al+H	ECEC cmol(+)/kg	Al+H Sat'n (%)
				cmol(+)/kg						
Unproductive soil	1	0.0	4.4	0.43	0.04	0.08	0.04	0 .66	1.25	53
	2	0.6	4.5	0.52	0.05	0.08	0.03	0 .61	1.29	47
	3	1.2	4.6	0.45	0.06	0.08	0.02	0 .64	1.24	52
	4	1.8	4.5	0.56	0.07	0.09	0.03	0 .56	1.30	43
	5	2.4	4.5	0.41	0.05	0.08	0.02	0 .61	1.16	53
	6	3.0	4.5	0.42	0.05	0.07	0.01	0 .62	1.17	53
	7	3.7	4.7	0.47	0.05	0.07	0.02	0 .60	1.20	50
	8	4.3	4.7	0.42	0.05	0.08	0.02	0 .59	1.16	51
	9	4.9	5.0	0.46	0.06	0.08	0.02	0 .50	1.12	45
	10	5.5	5.0	0.62	0.10	0.07	0.03	0 .43	1.24	35
	11	6.1	5.0	0.56	0.07	0.08	0.02	0 .41	1.14	36
	12	6.7	5.1	0.56	0.08	0.08	0.02	0 .42	1.16	36
	13	7.3	5.2	0.53	0.08	0.09	0.02	0 .42	1.14	37
	14	7.9	5.6	0.66	0.09	0.10	0.01	0 .24	1.09	22
	15	8.5	5.9	0.68	0.13	0.11	0.05	0 .23	1.19	19
	16	9.1	6.0	0.81	0.11	0.12	0.02	0 .18	1.25	14
	17	9.8	6.2	0.75	0.11	0.12	0.02	0 .13	1.12	12
	18	10.4	6.0	0.94	0.12	0.09	0.03	0 .15	1.33	11
	19	11.0	5.9	0.64	0.11	0.12	0.01	0 .16	1.04	15
	20	11.6	6.3	0.74	0.13	0.17	0.01	0 .12	1.17	10
	21	12.2	6.5	0.86	0.14	0.44	0.01	0 .11	1.55	7
	22	12.8	6.3	0.90	0.14	0.23	0.01	0 .11	1.39	8
	23	13.4	6.5	0.89	0.15	0.16	0.02	0 .14	1.35	10
	24	14.0	6.0	0.85	0.14	0.16	0.02	0 .11	1.28	9
Productive	25*	14.6	7.6	1.66	0.17	0.20	0.01	0 .05	2.09	2
Productive	26*	15.2	7.7	4.82	0.29	0.23	0.02	0 .00	5.36	0
Blowing sand	-	-	6.5	0.76	0.11	0.12	0.03	0 .09	1.11	8

*These soils had free calcium salts, and therefore the amount of calcium extracted is not representative of, and gives elevated values for, the exchangeable calcium

Table 12. Fitted parameters for Freundlich isotherms describing relationships of exchangeable P and total adsorbed P with solution concentration (mg L^{-1}) and computed amounts of exchangeable and total P at different solution P concentrations after adsorption of phosphate for an Alfisol and a Vertisol.

Exchangeable P (mg kg^{-1})	a_e	SE	b_e	SE	r^2	Solution P concentration (mg L^{-1})		
						0.05	0.2	1.0
Alfisol	56.4	±0.89	21.2	±1.06	0.99	18.3	30.8	56.4
Vertisol	108.3	±1.03	54.3	±1.53	0.99	24.1	48.3	108.3
Total adsorbed P (mg kg^{-1})	a_t	SE	b_t	SE	r^2			
Alfisol	54.7	±0.62	20.6	±0.75	0.99	17.7	29.8	54.7
Vertisol	110.2	±1.09	52.51	±1.53	0.99	26.4	51.2	110.2

Table 13. Sand, silt, and clay content and texture distribution in two Vertic Inceptisol profiles, ICRISAT Center, 1986.

Soil depth (cm)	Profile I			Texture/class	Profile II			Texture/class
	Sand (%)	Silt (%)	Clay (%)		Sand (%)	Silt (%)	Clay (%)	
0-10	41	19	40	Clay	38	22	40	Clay
10-25	50	14	36	Sandy clay	42	16	42	Clay
25-40	57	12	31	Sandy clay loam	33	19	48	Clay
40-55	58	12	30	Sandy clay loam	44	27	29	Sandy clay loam
55-70	58	13	29	Sandy clay loam	33	25	42	Clay
70-85	64	10	26	Sandy clay loam	32	25	43	Clay
85-100	66	13	21	Sandy clay loam	32	26	42	Clay
100-115	70	12	18	Sandy loam	-[1]	-	-	-
115-130	73	13	14	Sandy loam	-	-	-	-
130-145	69	17	14	Sandy loam	-	-	-	-

1. Samples not taken

Table 14. Properties of soil horizons found during excavation of castor root systems on a Vertic Inceptisol, ICRISAT Center, March 1987.

Properties (mean values)	Horizon			
	A	C_1	C_2	SE
Bulk density (gm cm^{-3})	1.37	1.54	1.54	±0.02
Water (% by weight)	22.9	16.7	18.7	±0.7
Shear strength (kPa)	10.8	26.3	23.1	±1.8
Penetrometer resistance (MPa)	0.91	2.65	2.33	±0.18
Gravel >2 mm (%)	23.7	36.9	30.6	±1.8
Coarse sand (%)	24.4	38.5	32.2	±1.8
Fine sand (%)	23.8	19.6	25.7	±1.37
Silt (%)	16.5	15.2	17.1	±0.69
Clay (%)	35.3	26.7	25.0	±1.5
pH	8.1	8.4	8.4	±0.1
Electrical conductivity (dS cm^{-1})	0.151	0.114	0.113	±0.005
Carbonate $CaCO_3$ (%)	3.4	17.4	11.5	±1.9
CEC[1] (meq/100 g of soil)	22.4	20.9	25.9	±1.0

1. CEC = Cation Exchange Capacity
Source: ICRISAT (1990)

Table 15. Above-ground and below-ground components for large and small mature castor plants on a Vertic Inceptisol, ICRISAT Center, March 1987.

Plant components (mean values)	Large plants	Small plants
Plant height (m)	2.98 (±0.27)[1]	1.83 (±0.23)
Shoot mass[2] (g)	921 (±162)	115 (±26)
Root length[3] (m)	11.9 (±0.5)	0.55 (±0.24)
Root mass (g)	201 (±2.8)	27.7 (±4.0)
Root mass/shoot mass ($g\ g^{-1}$)	0.22 (±0.009)	0.23 (±0.049)
Root length/root mass ($cm\ g^{-1}$)	5.92 (±1.00)	22.51 (±5.3)
Root length/shoot mass ($cm\ g^{-1}$)	1.29 (±0.28)	4.74 (±3.24)

1. Figures in parentheses are standard errors
2. Oven dried
3. Roots of diameter > 2 mm

Table 16. Rainfall erosivity EI_{30} for IAC during 1980-1994.

Soil	Year	Seasonal EI_{30} MJ.mm ha^{-1} h^{-1}	Annual EI_{30} MJ mm ha^{-1} h^{-1} y^{-1}	EI_{30} for rainfall > 12.7 mm (June-October)	% of seasonal EI_{30} from rainfall > 12.7
Vertisol	1980	5792	5915	5320	91.84
	1981	9015	9660	8635	95.78
	1982	3879	4169	3417	88.10
	1983	4299	4499	3710	86.28
	1984	2675	2905	2373	88.70
	1985	1970	2491	1480	75.15
	1986	2549	3695	2345	92.00
	1987	3203	5559	2700	84.30
	1988	5830	7653	5539	95.00
	1989	8552	10133	8142	95.20
	1990	2469	4934	1968	79.71
	1991	5125	5702	4750	92.67
	1992	3172	3549	2907	91.65
	1993	3885	4576	3452	88.85
	1994	5109	5198	4635	90.72
Alfisol	1980	5887	6057	5556	94.37
	1981	9431	10064	8759	92.87
	1982	3063	3329	2733	89.23
	1983	5904	6102	5248	88.89
	1984	3404	3675	3021	88.76
	1985	2223	2946	1947	87.57
	1986	3440	3926	3228	93.87
	1987	3508	5449	2990	85.22
	1988	3624	5366	3029	83.60
	1989	4181	5888	3813	91.20
	1990	3943	4914	3435	87.11
	1991	3941	4446	3587	91.02
	1992	3330	3691	2968	89.11
	1993	4323.05	4717.53	3806.39	88.05
	1994	3121.53	3435.71	2799.59	89.69

Appendix I. Characterization of Soils of ICRISAT Research Station, Bagauda, Nigeria.

Location: Bagauda, Nigeria
PEDON 90P 759, SAMPLES 90P4424-4430
PEDON CLASSIFICATION: FINE-LOAMY OVER SANDY OR SANDY-SKELETAL, MIXED, ISOHYPERTHERMIC FLUVENTIC UMBRIC DYSTROCHREPT

			PARTICLE SIZE DISTRIBUTION															
			(----------TOTAL-----------)			(--CLAY--)	(-------SILT-------)		(-----------------SAND--------------------)					(COARSE FRACTIONS) <----------Weight ------------- >				(>2 MM) WT
SAMPLE No.	DEPTH (CM)	HORIZON	CLAY <0.002	SILT 0.002 -0.05	SAND 0.05 -2	FINE <0.0002	FINE 0.002- 0.02	COARS 0.02 0.05	VF 0.05 -0.10	F 0.10 -0.25	M 0.25 -0.50	C 0.5 -1	VC 1 -2	2-5	5-20	20-75	.1-75	PCT OF WHOLE SOIL
			<------------------------- PCT OF <2 MM										------------------------->	<----- PCT OF <75 MM ----->				
90P4424S	0-13	Ap1	7.9	23.0	69.1	6.9	4.5	18.5	60.0	6.7	1.3	0.9	0.2	--	--	--	9	--
90P4425S	13-31	Ap2	9.7	23.6	66.7	9.0	4.0	19.6	56.9	7.4	1.3	0.8	0.3	TR	--	--	10	TR
90P4426S	31-55	Btv1	13.7	21.2	65.1	12.6	3.4	17.8	55.9	6.9	1.2	0.7	0.4	TR	--	--	9	TR
90P4427S	55-86	Btv2	24.6	21.8	53.6	18.4	4.1	17.7	44.5	6.6	1.2	0.9	0.4	1	--	--	10	1
90P4428S	86-138	Btv3	27.7	21.2	51.1	22.7	5.3	15.9	41.0	7.4	1.3	1.0	0.4	TR	TR	--	10	TR
90P4429S	138-200	Btv4	25.4	16.4	58.2	20.5	4.1	12.3	42.8	11.1	1.9	1.3	1.1	1	TR	--	16	1
90P4430S	0-0													--	--	--		--

	(RATIO/CLAY)		(ATTERBERG) - LIMITS -		(- BULK DENSITY -)		COLE WHOLE SOIL	(--WATER CONTENT--)				WRD WHOLE SOIL	---------------pH----------------		
DEPTH (CM)	CEC	15 kPa	LL	PI	33 kPa	OVEN DRY		10 kPa	33 kPa	200 kPa	1500 kPa		KCl 1:1	CaCl2 .01M 1:2	H_2O 1:1
			PCT <2 mm		<------------ Kg m^{-1}	---------->	Cm Cm^{-1}	<---------- PCT OF <2MM			---------->	Cm Cm^{-1}			
0-13	0.56	0.49		NP	1.40	1.40	--	18.0	13.3	5.1	3.9	0.13	4.3	4.7	5.2
13-31	0.49	0.37			1.59	1.60	0.002	10.0	8.2	6.3	3.6	0.07	5.1	5.7	7.2
31-55	0.45	0.40	22	6	1.57	1.63	0.013	18.9	12.1	8.6	5.59	0.10	7.0	7.8	8.9
55-86	0.47	0.46			1.61	1.79	0.036		18.2	17.4	11.4	0.11	7.2	8.0	8.9
86-138	0.48	0.47			1.72	2.14	0.075		15.3	19.8	12.9	0.04	7.1	7.9	8.9
138-200	0.48	0.46			1.86	2.09	0.039		12.6	17.7	11.7	0.02	6.8	7.7	9.0

(Appendix I. Contd..)

DEPTH (CM)	EXTR P	TOTAL S	(--DITH-CIT--) EXTRACTABLE			(- NH4OAC EXTRACTABLE BASES -)					EXTR ACID-ITY	EXTR Al	(------------- CEC -----------)			--- BASE SAT ----		
			Fe	Al	Mn	Ca	Mg	Na	K	SUM BASES			SUM CATS	NH4-OAC	BASES + Al	Al SAT	SUM	NH4 OAC
	PPM	<-----PERCENT OF <2MM------>				<---------- Cmol kg^{-1} ---------->										<---------- PCT ----------->		
0-13	6	TR	0.5	0.1	--	2.3	0.8	0.2	0.1	3.4	2.9	TR	6.3	4.4			54	77
13-31	6	TR	0.5	0.1	--	2.7	0.7	1.1	0.1	4.6	1.5		6.1	4.8			75	96
31-55	6	TR	0.7	0.1	--	5.0	0.9	2.0	0.2	8.1	0.6		8.7	6.1			93	100
55-86	4	TR	0.8	0.1	TR	13.9	1.8	3.2	0.3	19.2	--		19.2	11.5			100	100
86-138	3	TR	1.0	0.1	--		2.0	3.8	0.2		--			13.3			100	100
138-200	3	TR	1.0	0.1	--	8.4	1.9	3.4	0.2	13.9	1.2		15.1	12.2			92	100

SAMPLE No.	HZ NO	OPT DEN	ACID OXALATE EXTRACTION			PHOSPHORUS	KCl Mn	TOTAL C	ORG C	TOTAL N	Aggr. Stab.
			Fe	Si	Al	RET					<5mm
			<-------------- P C T of < 2 m m ------------->				<---p p m-->	<------ Percent ------->			%
90P4424	Ap1	0.03	0.17	TR	0.05	6		0.49	0.53	0.045	11
90P4425	Ap2	0.04	0.16	TR	0.05	6		0.33	0.33	0.031	2
90P4426	Btv1	0.03	0.09	0.02	0.03	6		0.16	0.13	0.017	
90P4427	Btv2	0.02	0.06	0.03	0.06	10		0.25	0.15		
90P4428	Btv3	0.02	0.03	0.02	0.05	6		0.12	0.08		
90P4429	Btv4	0.02	0.03	0.03	0.05	6		0.06	0.05		
90P4430											

(Appendix I. Contd..)

	CLAY MINERALOGY (<.002mm)							
	FRACTION	X RAY Peak size				Al_2O_3	Fe_2O_3	K_2O
NUMBER						ELEMENTIAL PERCENT		
90P4424	TCLY	KK 4	MT 3	MI 1		31.0	10.6	0.9
90P4425	TCLY	KK 4	MT 3	MI 1		28.0	9.4	0.7
90P4427	TCLY	KK 4	MT 2	MM 1	GE 1	30.0	9.7	0.9

SAMPLE NUMBER	SAND - SILT MINERALOGY (2.0-0.002mm)							
	FRACTION	OPTICAL						
		TOT RE	GRAIN COUNT					
		Percent						
43P4425	VFS	88	QZ84	FK 12	QI 3	OP 1	PRtr	ZRtr
90P4425	VFS		ARtr	GNtr	FPtr	RUtr	BTtr	GStr
90P4425	VFS		TMtr	KKtr				
90P4427	VFS	85	QZ82	FK 15	QI 3	MItr	OPtr	ARtr
90P4427	VFS		GNtr	FPtr	RUtr	BTtr	GStr	TMtr
90P4427	VFS		KKtr					

FRACTION INTEPRETATION:

TCLY Total Clay, <0.002mm   VFS Very Fine Sand, 0.05-0.10mm   FS Fine Sand, 0.1-0.25mm

MINERAL INTERPRETATION:

KK kaolinite   MT montmorill   MI mica   QZ quartz   FK potas-feld   QI fe-coat qz
OP opaques   PR pyroxene   ZR zircon   AR weath-aggreg   GN garnet   FP plag-feld
RU rutile   BT biotite   GS glass   TM tourmaline   GE goethite

RELATIVE PEAK SIZE:

5 Very Large   4 Large   3 Medium   2 Small   1 Very small   6 No Peaks

(Appendix I. Contd..)

NSSL Pedon Number: 90P0759

Pedon:	Nigeria 1 Bagauda	
Soil Survey Number:	S90-FN-670-001	
Pedon Classification:	Fine-loamy over sandy or sandy-skeletal, mixed, isohyperthermic Fluventic Umbric Dystrochrept	
Location:	Bagauda, Nigeria Cleared and leveled in Dec. 1988. Ripped to 40 cm in Jan 1989. Area is about 3 km to river but less than 10'	
Latitude:	__ __ 'N	Longitude: __ __'W
Physiography:	Playa or alluvial flat in level or undulating uplands	
Microrelief:	land leveled or smooth less than 20 cm linear on slope & crest	
Slope:	1% east facing	Elevation: m MSL
Water Table Depth:		Permeability: Slow
Drainage:	Somewhat poorly drained	Land Use: Cropland
Stoniness:	Erosion or Deposition: Severe	Runoff: Slow
Particle Size Control Section:	30 to 81 cm	
Parent material:	eolian from mixed material over alluvium	
Classification:	Coarse-loamy over clayey, mixed, isohyperthermic Plinthustalf	
Diagnostic Horizons:	0 to 13 cm Ochric, 30 to 137 cm Argillic	
Described By:	John Kimble and Maxime Levin	Sample Date: 5/90

No obvious cracks or fractures throughout the Btv horizons. Very large rounded insect castings 5-7 cm throughout profile. When we took the monolith Ap2 separated into 3 CO ABK blocks ans it dried and was removed from the rest of

Ap1 -- o to 13 cm; 10% grayish brown (2.5Y 5/2) interior and 90% light olive brown (2.5Y 5/4 interior dry fine sandy loam and 10% dark gravish brown (10YR 4/2) interior and 90% yellowish brown (10YR 5/4) interior moist fine sandy loam; weak fine and medium subsangular blocky structure parting to weak fine and medium granular; extremely hard, very friable, brittle, nonsticky, nonplastic; many very fine rootss throughout; many very fine and fine tubular and many fine and medium tubular pores; clear smooth boundary. Matrix, chunks of harder material (see rock fragments) from ripping, rupture resistance dry; 10-25 cm 15% chunks of ripped cemented slightly hardened plinthite/ironstone (breaks down) 90P4425.

Ap2 -- 13 to 30 cm; brown (10YR 5/3) interior dry fine sandy loam and dark gravish brown (10YR 4/2) interior moist fine sandy loam; weak fine and medium angular blocky structure; hard, very friable, nonsticky, nonplastic; common very fine and fine roots throughout; many very fine and fine interstitial and tubular and common very fine and fine tubular pores; common fine irregular ironstone nodules; gradual smooth boundary. Matrix, chunks of harder material (see rock fragments) from ripping, rupture resistance dry; 10-25 cm 15% chunks of ripped cemented slighly hardened plinthite/ironstone (breaks down) 90P4425.

Btv1 -- 30 to 56 cm; pale yellow (2.5Y 7/4) interior dry fine sandy loam and dark grayish brown (2.5Y 6/4) interior moist fine sandy loam; weak fine and medium angular blocky structure; hard, very friable, nonsticky, nonplastic; common very fine and fine roots throughout; many very fine and fine interstitial and tubular and common very fine and fine tubular pores; common fine irregular ironstone nodules and common very fine and fine irregular ironstone nodules and common very fine and fine irregular iron-manganese concretions; gradual wavy boundary. 90P4426.

(Appendix I. Contd..)

Btv2 -- 56 to 86 cm; pale yellow (2.5Y 8/4) interior, 10% yellow (2.5Y 8/6) interior and 80% yellow (2.5Y 7/6) interior dry sandy clay loam and 40% yellowish brown (10YR 5/4) interior and 60% pale yellow (2.5Y 7/4) interior moist sandy clay loam; weak medium and coarse subangular blocky structure; extremely hard, very friable, strongly cemented, slightly sticky, slightly plastic; few very fine roots in cracks; few very fine and fine tubular pores; common fine irregular ironstone nodules and few fine and medium rounded iron-manganese concretions; gradual wavy boundary. 15% estimated clay. 90 P4426.

Btv3 -- 86 to 137 cm; 50% yellowish brown (10YR 5/8) interior, 50% light gray (2.5Y 7/2) interior dry sandy clay and 50% yellowish brown (10YR 5/8) interior and 50% light gray (2.5Y 7/2) interior moist sandy clay; extremely hard, friable, strongly cemented, slightly sticky, slightly plastic; few very fine roots in cracks; few very fine and fine tubular pores; few patchy faint iron stains on faces of peds and in pores; many fine and medium irregular plinthite segregation and common fine and medium irregular iron-manganese concretions; 5 percent pebbles limestone, gradual smooth boundary. 45% estimated clay; breaks in some places along planes with extreme pressure to fm/sbk. 90P4428.

Btv4 -- 137 to 201 cm; 50% yellowish brown (10YR 5/8) interior, 50% light gray (2.5Y 7/2) interior dry sandy clay and 50% yellowish brown (10YR 5/8) interior and 50% light gray (2.5Y 7/2) interior moist sandy clay; extremely hard, friable, strongly cemented, slightly sticky, slightly plastic; few very fine tubular pores; many fine and medium irregular plinthite segregation and few fine and medium irregular iron-manganese concretions; 45% estimated clay; breaks in some places along planes with extreme pressure to fm/sbk. 90P4429.

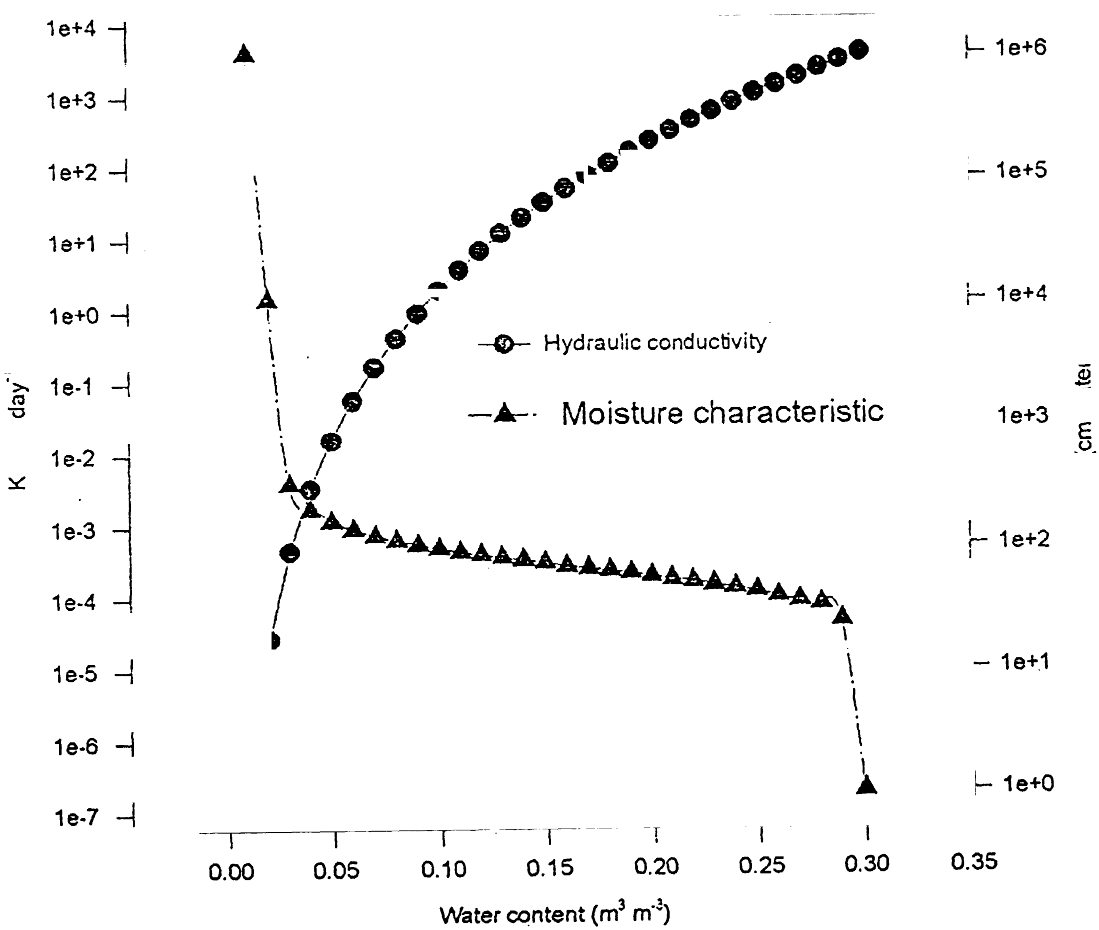

Fig. 10. Moisture characteristic and hydraulic conductivity functions of Labucheri soil series.

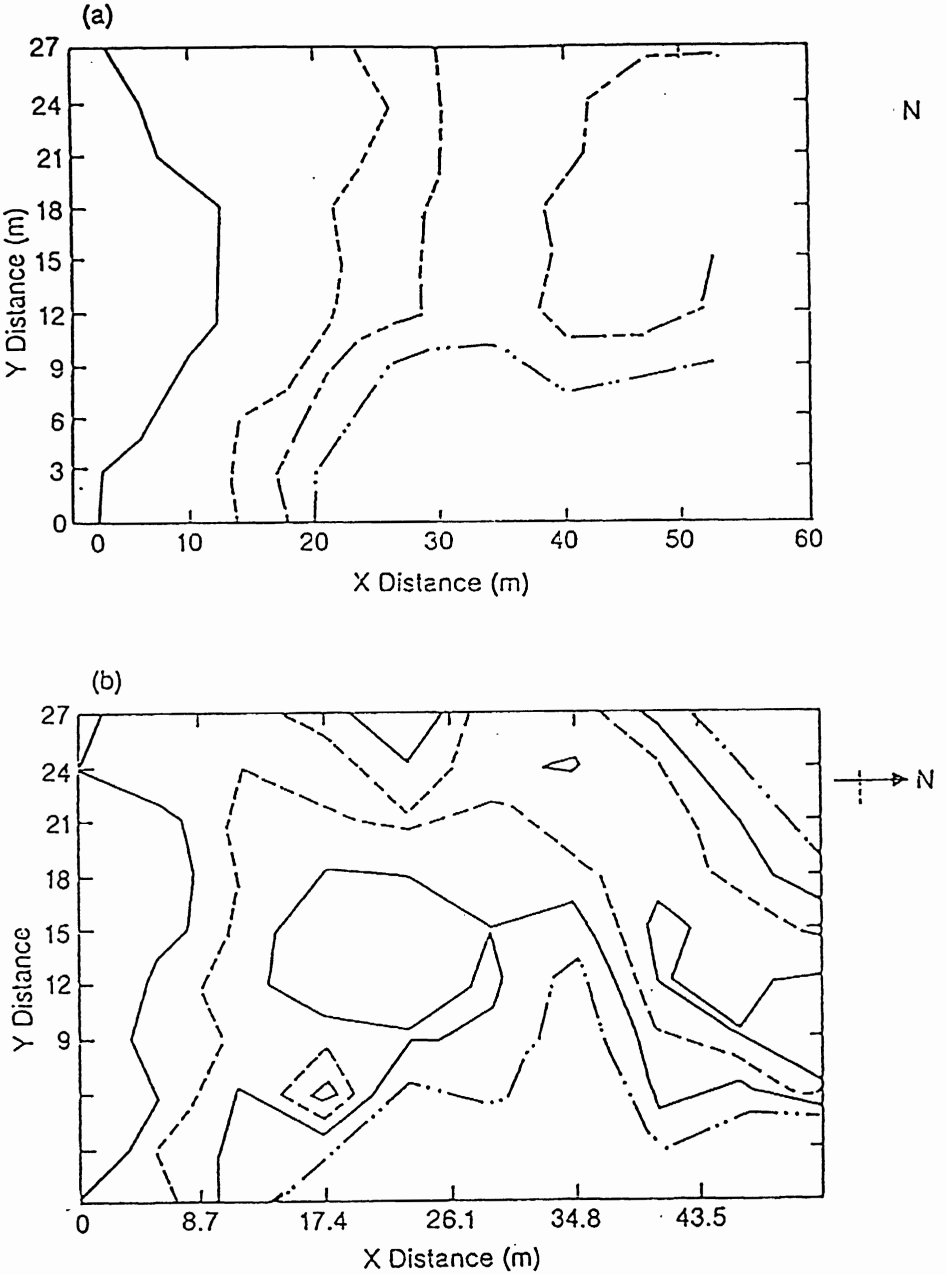

Fig. 11. Contour maps of kriging estimates of penetration resistance at 7.5 cm depth on (a) 29 October 1991 and (b) 4 November 1991. The symbols (——), (-----), (.....) and (——** —**——) represent values of penetration resistance for (a) of 1.0, 1.81, 2.42 and 3.07 MPa, respectively, and for (b) of 0.16, 0.19, 0.21 and 0.26 [log (MPa+1)], respectively.

Source: Ley and Laryea (1994).

LAND AND WATER MANAGEMENT

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The research on land and water management attempts to develop principles and techniques for improving rain water management for increasing and stabilizing agricultural production on farms in seasonally dry semi-arid tropics. Priority objectives include determining the effectiveness of alternate land, water and cropping management practices in controlling the losses and maximizing the utilization of soil and water resources, and integrating the above with other relevant information for use in developing productive and conservation-effective farming systems for the semi-arid tropics.

This report summarizes our relevant achievements in the area of land and water management over the past 11 years. Unless otherwise stated, the progress is for work performed at ICRISAT's research center in Patancheru. Selected data are given as illustrative examples of listed research achievements.

Land Management Studies on Alfisols

Land Surface Configurations

Graded type configurations: In our studies on land surface configurations, we found that graded type raised land configuration (e.g., BBF, ridge and furrow system) does not offer any particular advantage over flat seed bed for cereal production on Alfisols occurring on gentle slopes (Pathak *et al.* 1987). Where supplemental irrigation is a part of rainfed crop production, ridge and furrow system is appropriate. The performance of many of these practices have been discussed in detail by El-Swaify *et al.* (1985) and Pathak *et al.* (1987).

However, for groundnut, raised land surface configurations such as broadbed and furrow has been found to be beneficial in increasing pod yield (RMP Annual Report, 1990 and Sujatha, 1992). In an experiment at ICRISAT Asia Center, using two groundnut genotypes ICGS-11 and ICG(FDRS)10, grown on three land surface configurations-broadbed and furrow, 30-cm narrow ridge and furrow, and flat seedbed cultivation, Sujatha (1992) observed throughout the growing season, that the bulk density of 0-15 cm soil layer was significantly lower in BBF than in the narrow ridges and the flat seedbed treatments in that order. Differences in bulk density between treatments persisted at 30, 60, 90 and 145 days after sowing. During the growing season, the total porosity of the 0-15 cm soil layer was significantly greater in the BBF system than in the ridge and flat seedbed systems. Similar differences in penetration resistance were observed between the different systems. Lowest penetration resistance was recorded in the BBF system. Significantly higher pod yields were obtained in the BBF followed by ridge and flat seedbed systems (Table 17). This trend was observed in both the varieties.

Non-graded type surface configurations: On SAT Alfisols the options to reduce runoff are limited to soil amelioration, improving stubble cover or by storing excess rainfall in-situ by surface roughness. In most parts of SAT good stuble cover is not feasible because of the very high value of crop residues. Under these circumstances soil surface roughness could be an effective means of controlling runoff and soil loss.

We conducted studies both under simulated and natural rainfall conditions to compare the performance of three surface roughness treatments : pitting, tied ridges and flat cultivation for their effectiveness in controlling runoff and soil loss. Analysis of 4 years (1989-91) results from these experiments with and without crops indicated that (Pathak & Laryea 1995) :

- Surface roughness, i.e. pittings and tied-ridges, significantly reduced runoff and soil loss compared with flat seedbed cultivation. Using runoff and soil loss from the flat land as a basis for comparison, pitting reduced seasonal runoff by 69%, and soil loss by 53% while runoff in the tied ridged system was reduced by 39% and soil loss by 28%.

- Pittings were more effective in reducing runoff and soil loss than tied ridges. They were also relatively more stable than tied-ridges, particularly, during high-intensity rainfall and runoff conditions. In general, there was less number of breachings in pittings than in the tied-ridges.

- In terms of controlling runoff and soil loss, the largest advantage of pittings over flat cultivation was observed during the early part of the crop-growing season. This is mainly due to the fact that problems of surface crusting and sealing were more during that period of the cropping season due to sparse vegetation and poor crop canopy. Consequently, in flat seedbed cultivation, a major proportion of the rain that fell during the early part of the rainy season on Alfisols was lost as runoff while in pittings, most of this runoff was stored in depressions.

- Pittings significantly increased crop yields compared with tied ridges and flat seed bed during the low and normal rainfall years.

- The stability of pittings can be greatly increased by providing a graded outlet system. During big storms, a graded outlet design of pittings was relatively more stable than a conventionally designed pittings.

Bunds

Earthen bunds: For Alfisols having slope more than 1.5% (Pathak *et al.* 1989), a modified contour bunding system with gated outlet was developed. This system when compared with the conventional designed contour bunds on watershed at ICRISAT Center, consistently produced the higher crop yields, while still providing adequate control on runoff and soil loss. In the modified contour bund system the original system is modified by installing gated outlets in the lower field sections, land smoothing, and planting on grade instead of on contour, which allow runoff water to be stored above the bund for a certain period and then released at the desired rate through the gated outlet (Pathak *et al.* 1987). Most of the erosional sediments are deposited so that relatively sediment-free water drains through the outlet and the releasing excess water considerably reduces waterlogging.

Rock and earthen bunds in Burkina Faso: We conducted pilot-scale trials of a system of rock bunds for water harvesting in farmers' fields in Burkina Faso (ICRISAT, 1985). The bunds were approximately 0.3 m high and were placed about 20 m apart along the contour lines of the field.

Our results from the researcher-managed pilot trials indicated that the bunding package can increase yields by more than 500 kg ha^{-1} in both zones. Average yield increases from the package in trials managed by farmers varied considerably and appear to be associated with total rainfall and runoff intensity. Table 18 suggests that particularly high yield increases may be obtained from the package in regions where rainfall is low but runoff is high, and where higher rainfall levels are combined with occasionally heavy or moderate runoff. Bunding has only a moderate effect on yield where moderate runoff prevails in low rainfall zones. Virtually no additional yields can be expected in moderate rainfall zones with infrequent or light runoff.

We have collaborated with The Fond de l'eau et de l'equipment rural (FEER) agency to evaluate the short-term effects of earthen bunds for water management. Compared to the rock-bund systems, earthen bunds are less stable and their objective is to eliminate runoff rather than collect it and control its flow.

Earthen bunds increased sorghum grain yields by 30% and pearl millet grain yields by 43%. Absolute increases in grain yields were highest in the central and southeastern regions of Burkina Faso (ICRISAT, 1985). Regression analysis showed that earthen bunds have significant positive effects on grain yields when combined with fertilizer and when used on fields with a steep slope in high rainfall areas.

Vegetative and porous bunds: Porous and biological measures of erosion control based on the principle of decreasing the velocity and carrying capacity of overland flow are considered potential alternatives to conventional methods of erosion control. We conducted experiments for 4 years (1990-93) in 22 m long plots on two land slopes (2.8% and 0.6%) on an Alfisol site to measure the effects of porous barriers viz. vetiver, lemon grass, and stone bunds on runoff and soil loss (Srivastava *et al.* 1993).

Seasonal runoff and soil loss for 1993 are given in Table 19. It is evident from this table that runoff and soil loss from different treatments can be ranked in the following order : Vetiver < lemon grass < stone bund < control. Similar trends were obtained during earlier years 1990-92. Four years data clearly show that the properly established vegetative barriers are quite effective in reducing runoff and soil loss (ICRISAT, 1990 to 1993).

Multiple regression analysis of 4 years rainfall-runoff data (1990-1993) was carried out to identify the important factors that are contributing to runoff in different treatments (ICRISAT, 1993). There was a progressive decline in runoff during the first two seasons probably due to progressively improved establishment of the barriers. However, runoff from lemon grass plots on 2.8% slope started showing an increasing trend after third year. This may be attributed to formation of gaps in the lemon grass hedges after third year.

Based on a review of hydrologic and sedimentation process and our observations (qualitative as well as quantitative), the following two points emerged illustrating the importance of understanding of hydrologic processes in assessing the effectiveness of porous barriers and their management.

- As the sedimentation process causes a selective deposition of coarse particles on the upslope side and within the barrier strip, there is a gradual slope modification through "terracing effect". Also, the presence of coarse particles on soil surface improves infiltration rate in the sediment deposition zone. This suggests that effectiveness of porous barriers in controlling runoff and soil loss will increase over time provided the barriers are well-maintained.

- The waterflow at the downstream side of porous barrier usually has low sediment concentration because a part of the sediment load has been deposited upstream. As the flow velocity increases the sediment transport capacity of flow can easily exceed the existing sediment load. This can lead to scouring of soil at the downstream side of barriers and may require protective measures in many situations.

Improvement of Degraded Soil Structure

Soil management options to reduce the rate of land degradation and to ameliorate degraded lands are urgently needed for the SAT Alfisols. We in collaboration with QDPI (Queensland Department of Primary Industries, Australia) initiated a project in 1988 to investigate the effect of several management practices on soil structure and related processes (Smith *et al.* 1992).

Runoff

Effect of tillage: Tillage has no significant effect on annual runoff (Table 20). Lack of response to tillage can be explained by the inherent capacity of these soils to form a crust at the surface. Runoff, representing rainfall in excess of infiltration, reflects these changes well (Cogle *et al.* 1996). In all the years runoff decreased to a minimum with tillage and reverted back to the initial level during successive rainfalls. A plot of cumulative rainfall since tillage against runoff (Fig. 12) indicated that most of the tillage benefits were lost by the time cumulative rainfall reached 150 mm in case of shallow tillage and 200 mm in case of deep tillage (Rao *et al.* 1994).

Effect of organic amendments: Application of organic amendments resulted in significant reduction of runoff over control. The ameliorative effect of FYM was evident from the decline in runoff over the years. Runoff from plots amended with FYM declined to 45% of bare and those amended with rice straw recorded a decline of 65%. Data from the past three years indicate that these systems reached an equilibrium stage and further reduction in runoff is difficult to achieve. The amendments were more effective during crop season i.e. during the first four months after the application compared to the off-season.

Effect of perennials: Among the perennials tested, systems with *Stylosanthes hamata* were found to be more effective. Runoff from sole *Stylo* system was negligible after four years. This is attributed to the protective function of the cover provided by the crop and to the ameliorative action of the litter and roots on soil structure (Cogle *et al.* 1995, Rao *et al.* 1992). The soil structural changes brought by these systems were lost at about the same rate they accrued, after their return to annual cropping. Runoff from these plots was about 50% of that from zero tillage bare treatment after three years of annual cropping.

Soil loss

Similar to runoff, soil loss values showed large variations across different soil management options and values ranged between few kgs to 6.3 t ha^{-1} (Table 21). Soil cover seems to be the major factor affecting soil loss. All perennials and straw amended plots with an average cover of more than 50% during the runoff causing rains produced little soil loss. The reduction in soil loss was relatively more than the reduction in runoff.

Crop performance

Tillage has no significant effect on yields. Organic amendments significantly increased grain yield in all years except in 1989 sorghum had the lowest grain yield when straw was applied as an amendment (Cogle *et al.* 1996). Crops with FYM produced the highest yield, regardless of crop species. Grain yields from systems amended with FYM and straw were between 16 and 59% higher than from unamended systems. The response of fodder yields to the treatments was generally similar to that of grain yields. Among the perennials lowest average biomass yield per year was from the *Cenchrus ciliaris* system. All mixtures with *Stylo* recorded higher biomass yield per year.

Simulation modelling

Systems simulation model PERFECT (Productivity Erosion Runoff Functions to Evaluate Conservation Techniques) developed by QDPI, Australia was adopted by incorporating the required changes for the range of soil management options tested in this trial (Littleboy *et al.* 1996). The changes include modification to the curve number functions to predict the effect of tillage, amendments and perennials, removal of entire dry matter at the time of harvest, criteria for predicting tillage and planting dates and allowing the user to specify the type of tillage and type and amount of amendment. The model explained between 71% and 91% of the variation in daily runoff volumes due to tillage, amendments and perennials.

Effect of Erosion on the Productivity of an Alfisol

Soil erosion reduces productivity of soils through a variety of ways, e.g. by selectively removing finer particles, thus reducing the overall fertility or the available water capacity. It may also produce physical effects such as crusting, compaction, or increased soil strength. We initiated this study on the effect of erosion by water on the productivity of an Alfisol in 1988 to (a) quantify the relationship between soil erosion and groundnut yield; and (b) measure changes in soil properties that are associated with erosion (ICRISAT, 1990 & 1991 and ICRISAT, 1994).

The mean yield of groundnut pods and haulms from the naturally eroded nonfertilized (NF-) plots decreased rapidly as the cumulative erosion by water increased (Fig. 13). In the case of the naturally eroded fertilized (NF+) plots, the rapid rate of decline had decreased at erosion rates greater than 12 t ha^{-1}. It was postulated that addition of fertilizers would mask the yield decline due to erosion. Therefore, this relationship was unexpected and appears to indicate that either the fertilizer rate was not sufficient to offset the decline due to erosion or that other factors such as lower water content resulting from loss of clay may be involved. This hypothesis would be examined when particle size distribution measurements are examined in future. There was no consistent yield decline due to erosion in the desurfaced plots. In the desurfaced plots which were not fertilized (DF-), total yield was almost constant over erosion rates ranging from 6 to 325 t ha^{-1}.

There was a drastic decrease in total nitrogen content of the soil by 1993 due to erosion. With the exception of DF- plots which had a slight increase in total nitrogen, there was no significant difference in total nitrogen content of the other treatments by 1993. Available phosphorus for the nonfertilized plots (i.e. NF- and DF-) was lower than that in the NF+ and DF+ plots. By 1993, there was no difference in available phosphorus in the NF- and DF- plots. The exchangeable potassium for the nonfertilized plots (NF- and DF-) was similar and greater than that for the fertilized plots (NF+ and DF+).

Land Management Studies on Vertisols

Watershed-based Vertisol Technology

We continued the evaluation of vertisol technology on operational scale watersheds up to 1987. A total of 11 successive years of data (1976-87) have been analyzed to judge the sustainability of the improved vertisol technology (Virmani *et al.* 1991).

Improved technology clearly reduces runoff and soil loss (Table 22). A simple index of the stability of production is the standard deviation of the 11-year mean. The double-cropping system shows much less variation (CV=13%) compared to the traditional practice of a single crop (CV=40%) (Table 22). The stability of the traditional system appears to be more susceptible to the vagaries of the weather as the CVs for yield and rainfall are similar (40% vs. 30%). Annual rainfall totals can be misleading because they do not indicate seasonal distribution and the timing of rainfall or stress can be critical to crop yield. However, crops grown under the improved technology are evidently less affected by drought.

There is no indication that productivity has declined under either system during the 11 years. This is expected as the soil is very deep (> 2 m) and fertility is maintained either by regular input of fertilizer or by natural mineralization. Nevertheless, the watershed concept has clearly demonstrated the efficiency of the soil-and-water-conservation practice and has increased the stability of crop production in an erratic rainfall regime typical of many parts of the SAT.

Management of Vertisol Cracks

The development of cracks due to shrinkage upon drying is a major structural feature of Vertisols. The frequency, size, and rate of development of surface cracks influence infiltration, aeration, and plant growth. Widely spaced, large and deep cracks could increase infiltration, but aeration and seedling emergence may be improved by small, frequent cracks. We conducted study on small plots to see whether crack size and distribution could be influenced by soil compaction and by shading (Srivastava *et al.* 1989).

Soil was compacted by repeated rolling of a pneumatic wheel on wet soil and shaded by covering the soil with a sheet of milky white polythene. The depth of major cracks (>5 mm width) were measured by probing with a 2-mm diameter wire. Photographs of the cracking patterns were analyzed by an Area Meter.

Srivastava *et al.* 1989 observed that the depth of cracks increased from 2.0 ± 0.1 cm to 5.1 ± 0.3 cm and the area of intercrack structural units (ISUs) increased from 23.3 ± 1.5 cm^2 to 199.4 ± 25.0 cm^2 due to soil compaction. Thus, soil compaction resulted in bigger ISUs separated by deeper and wider cracks. Similarly, shading resulted in bigger ISUs, and deeper and wider cracks. The area of ISUs under shade was 140.1 ± 9.6 cm^2 compared with 37.0 ± 2.9 cm^2 in the unshaded plots. The crack depth increased from 1.8 ± 0.1 cm to 3.1 ± 0.1 cm due to shading. This study has shown that the distribution of cracks with a width of > 5 mm can be managed by both compaction and shading.

Land Water Research on Vertisols in Ethiopia

Since 1990 we have been collaborating with International Livestock Research Institute, (ILRI) the Institute for Agricultural Research (IAR), and Alemaya University of Agriculture in Ethiopia to develop strategies and technology options to raise and sustain crop and livestock production on Vertisols (ICRISAT, 1992).

In the collaborative trials, perched water table fluctuations in experimental plots at Ginchi and Akaki were characterized. Measurements showed that, during the rainy seasons of 1991 and 1992, the perched water table was within 30 cm of the ground level at certain times, thus exposing crops grown there to the risk of waterlogging. An analysis of wheat yield data from

Ginchi and Akaki showed that yields were significantly higher from crops grown on 26-cm high broadbeds than on beds made to the standard specifications of 13 cm. This suggests that the height of broadbeds constructed at a particular site should depend on the intensity of the risk of waterlogging.

By 1993 it was well recognized that the broadbed and furrow technique developed by ICRISAT might have good potential in some Ethiopian Vertisol areas. Poor drainage/ waterlogging is identified as major technical constraint limiting the productivity of crops in Ethiopian highlands.

In 1994, this Joint Vertisol Project entered a new phase, with a project on resource management for crop and livestock production in the Ethiopian highlands. An important feature of this new phase is the watershed-based disposal system for excess rainwater, to reduce waterlogging and simultaneously reduce soil erosion and gully formation.

Water Harvesting & Supplemental Irrigation

Assessment of Water Availability in Tanks

There is considerable evidence from our earlier experiments, that the yield of dryland crops can be increased and stabilized with one or two supplemental irrigations at the critical periods of crop growth. However a major problem is the availability of water for supplemental irrigation. The feasibility of providing such irrigations from stored runoff in a farm reservoir (tank) was studied by us in collaboration with CRIDA (Central Research Institute for Dryland Agriculture, ICAR). The study was carried out at four locations in Anantapur, Akola, Ranchi and Hyderabad. The runoff model (Pathak *et al.* 1989) and water harvesting model (Kumar, 1991) developed at IAC, ICRISAT were used to assess water availability in farm tanks. The complete water harvesting model (Fig. 14a) has a runoff component and a soil moisture accounting procedure for predicting daily runoff and soil moisture in a watershed. Thereafter, it calculates daily net inflow and outflow from the tank by subtracting daily evaporation and seepage losses from the watershed runoff. Based on the net inflow and outflow estimations available water in the tank is calculated on daily basis. We have completed the analysis for probabilities of getting 40, 60, 80 and 100 mm of water from the tank for supplemental irrigation (ICRISAT, 1993, Pathak and Laryea, 1991). The output from the model for Akola region is shown in Fig. 14b, which clearly shows the probabilities of getting water for irrigation from the tank are high for most part of the crop growing season. This indicates a good prospect of runoff water harvesting in Akola region. We also estimated the conditional probabilities of the availability of 40, 60, 80 and 100 mm water from the tank during periods of drought. Probabilities of occurrence of drought stress in 3 crop growth stages viz. growth stage 1 (GS 1, sowing to panicle initiation), growth stage 2 (GS 2, panicle initiation to anthesis) and growth stage 3 (GS 3, grain-filling stage) were also estimated (Pathak & Laryea, 1991).

It was found that considerable information on various aspects of water storage in tanks can be obtained by using these runoff and water harvesting models.

Response of Crops to Supplemental Irrigation

On Alfisols and Vertisols, striking benefits have been reported from supplemental irrigation at ICRISAT and elsewhere (El-Swaify *et al.* 1985, Pathak *et al.* 1987). Good yield responses were obtained in both rainy and postrainy seasons. On Alfisols, the irrigation water use efficiency for pearl millet, sorghum, cowpea, pigeonpea and tomato was found to be 12, 18, 20, 23 and 93 Rs mm^{-1} ha^{-1}, respectively. Similar responses were obtained on Vertisols (Laryea *et al.* 1989, Pathak & Laryea 1991). Results from various experiments clearly indicate that on SAT Alfisols and Vertisols significant returns can be gained from relatively small quantities of supplemental water on rainy and post-rainy season crops. Generally the benefits from supplemental irrigation was found to be better on Alfisols than Vertisols.

Wind Erosion Research during 1984-95 at the ICRISAT Sahelian Center (ISC)

The need for long-term research in soil erosion and land use systems, in order to provide options and opportunities for policy makers, has been emphasized for several years. However, the role of wind erosion in soil degradation and crop production in the Sahelian zone was tainted with uncertainty. Frequent short sand storms occur especially in the beginning of the rainy season, and in areas susceptible to wind erosion, farmers must replant their millet crop several times. Wind erosion damage to millet production consists of both abrasive action and plant burial by accumulation of deposited material. In combination with environmental stress like lack of water and nutrients, high soil temperature or soil crusting, the partial or total burial of seedlings induces growth and development delays as well as plant mortality. In years with a short rainy season, growth delays caused by wind erosion may prohibit grain production altogether.

For the transfer of erosion control techniques to farmers, information on their profitability and on farmers' perception of these techniques is crucial. The motivation of farmers is a core task of extension, but policy and institutional support must be assured first. Economic incentives and favorable agricultural price policies reinforce the impact of research and extension. The current rate of soil degradation in the West African Sahel demands immediate intervention to stop soil degradation and rebuild a sustainable ecological system. The fact that some erosion control techniques are financially unattractive to farmers influences their decision-making. To increase the adoption rate, national and international policy-makers must create conditions to favor the implementation of innovations for decreasing soil degradation, increasing soil fertility and, consequently, long-term productivity.

Wind erosion research at the ISC in Sadoré, Niger was initiated in 1984. A series of field and wind tunnel experiments were conducted by different groups of researchers on many aspects of the extent and the control of wind erosion. Integration of wind erosion control techniques into millet-based cropping systems was studied not only from the point of agronomy, but was also approached from the socio-economic point of view. More recently, we started placing more emphasis on simulation modelling in wind erosion research and on-farm testing of control strategies.

Following is a brief summary of 17 studies on wind erosion conducted at ISC during the past 11 years. This research involved several disciplines including agroclimatology, agroforestry, agronomy, soil and water management, socio-economics and geostatistics showing thereby the complex nature of the issues involved and the need for a multidisciplinary approach to wind erosion research. Our research was conducted in collaboration with advanced research institutions in Germany, Netherlands, United Kingdom and the United States, which reflects the importance attached to wind erosion research in Europe and the United States.

a) From 1984 through 1986 two field experiments were conducted on the effects of different **tillage methods** on millet establishment and yield. The treatments included plowing, ridging and the use of a 'sand fighter'. The latter is a tillage implement used to quickly roughen the surface of sandy soils after each rain event. Plowing and ridging produced the best stands, whereas the clods produced by the sand fighter were not sufficiently stable to reduce the wind erosion hazard (Klaij and Hoogmoed, 1993).

b) From 1985 through 1987, we conducted a large study covering 12-ha on the effectiveness of **soil ridging** and of **low windbreaks** comprising natural savannah revegetation, in collaboration with the University of Hohenheim, Germany. The effects of ridging on wind speed, evaporation, and wind erosion were small and mostly non-significant. Average wind speed in the center of cowpea and millet strips, however, was reduced as windbreak distances narrowed. The amount of wind blown soil particles in sheltered plots declined by 50% in ridged and by 70% in flat treatments. Average subsoil water reserves were 14 mm smaller in the 6- than in the 20-m windbreak spacing indicating excessive water extraction by the windbreak vegetation. Ridging did not change total dry matter or grain yield in millet but increased cowpea grain yield. Dry matter production at maturity and grain yields were similar in all windbreak spacings for millet and cowpea (Banzhaf *et al.* 1992; Leihner *et al.* 1993).

c) From 1986 to 1989, a field trial on the impact of 10 m wide **strips of the perennial grass** *Andropogon gayanus* on the amount of sand captured within the strips was conducted. The *Andropogon* borders did not increase millet grain yield in adjacent fields. However, the increase in soil surface by captured sand within the borders during three years was up to 0.2 m (Renard and Vandenbeldt, 1990).

d) From 1988 to 1989, **tree-crop interactions in a millet-windbreak system** were investigated in a collaboration with the University of Edinburgh. Below-ground competition reduced grain and stover yields. Effective competition did not extend beyond a distance of 1.5 times the height of the windbreak. The optimum distance between windbreaks was calculated to be between 10 and 15 times the height of the windbreak in order to increase stover production and to compensate for the loss in grain yield due to the reduced crop growing area (Brenner *et al.* 1994).

e) In 1990, **sand storms and their effects on millet burial and growth** were monitored in collaboration with the University of Hohenheim, Germany. During the growing season, the accumulated sand captured at 0.1-m above the soil surface attained 1262 kg m^{-2} vertical sampler opening. Ninety percent of the millet pockets sown with the first rains were covered at 22 days after emergence and the crop was resown. Surviving plants from the partially covered pockets showed delays in growth and development. The maximum plant height and leaf number were lower with a significant reduction in the leaf area index. Grain yield from unaffected pockets was nearly twice that of the pockets which were partially covered (Michels *et al.* 1993).

f) From 1991 through 1993, the **effects of millet straw residue on wind erosion and surface soil properties** were determined in collaboration with the University of Hohenheim, Germany. Soil flux 0.1 m above the ground was significantly reduced with 2000 kg ha^{-1} residue but not with 500 kg ha^{-1}. Amounts of 500 kg ha^{-1} decreased the soil flux at 0.1 m height only during less severe events of the Harmattan season. Topographic measurements indicated that soil removed from the soil surface was less with either residue level than in the control. After 2 years, the soil surface of both residue treatments had less coarse sand than the control, but more fine sand and clay, more organic carbon and an increased cation exchange capacity. The organic-C content of blown material was higher than that of surface soil. An amount of 500 kg ha^{-1} residue can be considered useful for soil conservation, but 2000 kg ha^{-1} are required for a significant reduction of soil flux caused during severe wind erosion events (Michels *et al.* 1995a).

Effects of three levels of millet straw residue on establishment and growth of pearl millet were determined in the same experiment in 1991 and 1992. The extent of millet seedlings buried by blown soil in plots with 500 kg ha^{-1} residues was similar to that of control plots. A residue amount of 2000 kg ha^{-1} reduced the extent of covered millet, but did not provide complete protection during severe sand storms. The partial covering of millet seedlings by blown soil resulted in decreased biomass yields of those plants compared to uncovered millet. Grain production, averaged over two years, was about 500 kg ha^{-1} for the control, 570 kg ha^{-1} with 500 kg ha^{-1} residue, and 730 kg ha^{-1} with 2000 kg ha^{-1} residue. Increased yields were caused by both wind erosion protection and direct growth stimulating effects of residue. Straw yields for all treatments in both years were less than 2000 kg ha^{-1} and thus insufficient to sustain the levels required for protection of crops against wind erosion damages (Michels *et al.* 1995b).

g) From 1991 to 1993, an **agroforestry** field experiment with six tree and shrub species and one perennial grass was conducted at ISC in collaboration with the University of Hohenheim. Windbreaks decreased the amounts of moving soil effectively up to 7 times their height. Windbreaks shaped like *Bauhinia rufescens* were more effective for wind erosion control than perennial grass barriers like *Andropogon gayanus*. However, wind erosion during the study years was not a major constraint to millet production at the observation site. Thus, the measured effects of windbreaks on millet yields cannot be explained by erosion control. *Faidherbia albida* improved millet yields significantly up to 10 times its height, probably due to a nutrient recycling by litter decomposition and to the lack of competition for moisture and nutrients during the millet growth period. *Acacia holosericea* showed also yield increasing effects. The effects of *B. rufescens* and *A. gayanus* on chemical soil properties and yields were restricted (Michels 1995).

h) From 1991 through 1993, **water use of different windbreak species within millet crops** was investigated in collaboration with the University of Edinburgh. *Azadirachta indica* (neem) used the least amount of water, probably as a result of lower stomatal conductances. Competition for water was shown to be most severe with tree species which extract water through lateral roots and at locations where trees cannot access groundwater (Smith *et al.* 1995).

j) From 1991 to 1993, **financial and economic analyses of wind erosion control techniques** in Niger were done in collaboration with the University of Hohenheim. The profitability of windbreaks for farmers depended primarily on the yields of the protected millet crop, while the products from the tree windbreaks were secondary. Since it could not be guaranteed that the total costs would be covered by the total benefits, it was found that a general implementation of windbreaks without considering the species may even decrease farmers' income. Reliable markets for the products from the trees must be developed before the direct benefits of windbreaks can be fully exploited. In areas more prone to wind erosion (northern regions), a lack of alternatives may demand the implementation of windbreaks on a larger scale, if only as an wind erosion control technique. Mulching with crop residues for erosion control is economically feasible only under certain conditions, since labor for weeding is often more constraining than land. Mulching becomes competitive with the traditional crop residue uses when land is limited. Due to the high opportunity costs of crop residues, farmers may use them to increase their present income, but doing so depletes soil fertility. The use of external inputs, such as mineral fertilizers, could alleviate the need for land and, consequently, overcultivation and soil degradation.

It could be shown that the long-term benefits of soil protection (yield stabilization, yield improvement, protection of natural resources) more than compensate for the costs of implementing erosion control techniques. Therefore, in developed countries subsidies are granted to farmers to insure their implementation. Similar incentives are also justified to stop further depletion of land in the Sahel. Given the budget limitations of Sahelian governments, the support of developed countries is required. Motivating farmers to use innovations which have, primarily, a long-term profitability, is vital because it would allow them to sustain their families and maintain their resource base. Economic incentives and favorable agricultural price policies reinforce the impact of research and extension. Also, the presence of an established market for firewood and feed may assist in the adoption of windbreaks (Lamers et al 1994a; 1994b; Lamers 1995).

k) From 1991 to 1994, **nutrient analysis of dust depositions** during the dry and the wet seasons were investigated in collaboration with the University of Hohenheim. Dust deposits were rich in potassium, calcium and magnesium. Quantities were smaller in the South compared to northern areas. In particular the potassium balance of agricultural and fallow does benefit from the input by dust. On the other hand, dust deposits increase the formation of crust and subsequently also runoff. A strategy was developed for quantifying a mass budget of eolian transported material at a regional scale in a Sahelian environment (Herrmann et al, 1994; Herrmann and Sterk 1995).

l) In 1992, two **laboratory wind tunnel experiments** were conducted at the Wind Erosion Laboratory in Manhattan, Kansas, to determine the kind and extent of damage to millet caused by sandblasting and burial. In Exp. I, millet was exposed for 15 min to wind, or wind plus sand at plant ages of 8 and/or 16 d after emergence (DAE). Viable leaf area, leaf net photosynthesis, and nitrate content were measured through 21 DAE (days after emergence) and dry matter production through 57 DAE. In Exp. II, millet was seeded as three single seeds or in tufts, exposed to sand flux for 15 min at the one-, two- or three-leaf stage, and manually covered by 15 mm sand. Survival was monitored weekly, and dry matter production was determined 70 DAE. Exposing millet seedlings to wind and windblown sand reduced leaf area, photosynthesis, and dry matter production, but increased nitrate contents. Effects got smaller a few days after the exposure. Millet can withstand sandblasting without a reduction in survival rate. Growth was most reduced by sandblasting at the One-leaf stage, by high sand flux levels, by a sequence of wind erosion events during early growth, or by combination of sandblasting with burial and other agroclimatic growth constraints. Wind speed during erosion events was less important for leaf area losses and dry matter production than the sand flux level (Michels *et al.* 1995).

m) From 1992 through 1994, the effects of the **soil surface management** on the amount of windblown sand and on millet establishment were studied in a field experiment. The treatments included no-tillage, ridging, shallow tillage using a donkey-drawn implement, and in combination with residue application. Data are in the process of being evaluated (Personal Communication, M.C. Klaij, ICRISAT).

n) During the 1993 through the 1995 rainy season, in collaboration with the University of Wageningen, we conducted field measurements of wind erosion with the objective to **calculate mass transport** by modeling spatial variability (Sterk and Raats, 1995; Sterk and Stein, 1995)

o) During 1994, a socio-economic study was undertaken by the University of Hohenheim "Impact of institutional and legal pluralism on the introduction of anti-erosion measures-the case of Niger". It was shown that tenure security of certain rural dwellers is limited by both customary land right systems and state legislation. Customary tenure does not allow non-owners to plant trees which is an important constraint for the introduction of agroforestry systems. The success of projects promoting these systems depends on the percentage of fields operated by non-owners and on the distance of the project region from the village because there is a significant difference between owned and leased fields with regard to distance from the compounds. Forest legislation further limits peasant rights to trees on their own land (Neef *et al.* 1995).

p) In a study on institutional and policy issues relevant to wind erosion control, it was found that control techniques perceived as most preferred in the short-term included dune fixation and soil surface protection using crop residue or branches. The factors that favor adoption of wind erosion control interventions were low cost and simplicity as well as reliance on local skills and inputs (Baidu-Forson and Ibro, 1995).

q) In 1995, field experiments were started on the effects of soil tillage and crop residue on wind erosion, soil properties and the growth of millet-cowpea intercrops. Focus is on the kind of residue placement, the impact of rock phosphate on crop yields and the residual effect of cowpea on millet growth. Part of the treatments are also tested on an on-farm site northeast of Niamey (Personal Communication, Bielders and Michels, ICRISAT).

r) A collaborative project was initiated with the modelling group from the USDA Grassland, Soil and Water Research Laboratory in Temple, Texas, was initiated in early 1995 to calibrate and evaluate the Erosion/Productivity Impact Calculator (EPIC) for conditions in the Sahel region (Michels 1995).

Cooperation with NARS and Other Agencies

During the period of research reported in this review, we collaborated with several national and international research institutes and agencies in the area of land and water management. We had several joint research projects with NARS on various aspects of land and water management both under on-station and on-farm situations. Some of the cooperative links are listed below:

- Water harvesting and supplemental irrigation (modelling aspects)
  - CRIDA, Hyderabad, India
  - AICRPDA, Punjabrao Krishi Vidyapeeth, Akola, India
  - AICRPDA, APAU Anantapur, India

- Watershed based research on Vertisols, Ethiopia
  - International Livestock Research Institute, Addis Ababa, Ethiopia
  - Institute of Agricultural Research, Addis Ababa, Ethiopia
  - Alemaya University of Agriculture, Alemaya, Ethiopia

- Management of soil structure (Alfisols)
  - Queensland Department of Primary Industries, Australia

- Land management studies on Vertisols and Alfisols
  - CRIDA, Hyderabad, India
  - AICRPDA, University of Agricultural Sciences, Bangalore
  - AICRPDA, College of Agriculture, Indore
  - Dept. of Agriculture, Karnataka, India
  - Dept. of Agriculture, Madhya Pradesh, India

- Land surface configurations studies on Alfisols (Gunegal)
  - CRIDA, Hyderabad, India

- Wind erosion research at ISC
  - University of Hohenheim, Stuttgart, Germany
  - Kansas State University, Manhattan, USA
  - University of Wageningen, Wageningen, Netherlands
  - USA Wind Erosion Laboratory, Manhattan, USA
  - Texas A &M University, Temple, Texas, USA

Future Plans

In future the research on land and water management will be conducted to study the integrative effects of soil, water, nutrient and crop management practices on crop productivity, resource conservation, and its use efficiency. All the research will be carried out within the new Integrated System Projects (ISPs 1-4).

Wind erosion research at ISC will be continued as a component of Integrated Systems Project (ISP 1) and will aim at testing proven means of controlling wind erosion in farmers' fields. In addition, we will continue our strategic research efforts to more fully understand the wind erosion processes and provide the necessary input data to calibrate and evaluate EPIC for conditions in the Sahel.

In the Integrated System Project 2 (ISP2) we plan to evaluate some of the promising *in-situ* moisture conservation strategies for low rainfall zones in southern India. Initially this work will be done on Alfisols. We also plan to review and evaluate the impact of land degradation on crop productivity, document farmer perceptions of land degradation, and their indigenous systems to deal with this problem. In collaboration with QDPI Australia, we plan the assessment and simulation of the rates of degeneration of soil structure in a low input sorghum-based system.

In the Integrated System Project 3 (ISP3) we plan to identify strategies to alleviate waterlogging and improve soil aeration to facilitate rainy season cropping in high water holding capacity soils in central parts of India. We also plan to integrate and evaluate promising strategies for double cropping including intercropping in collaboration with NARS. On shallower Vertic Inceptisols we plan assessment of soil degradation or impacts on crop productivity and quantification of different degradation processes. In Africa (WCA) we plan to work on development of integrated nutrient management and water strategies for sustainable crop production in sandy Alfisols.

Table 17. Groudnut pod yield, as influenced by different land surface configurations on an Alfisol at ICRISAT Asia Center, 1991-92.

Treatment	Pod yield (t ha^{-1})	
	ICG(FDRS)10	ICGS 11
Flat	3.45	2.86
Ridges	3.71	3.09
BBF	4.22	3.39
SE	± 0.09	± 0.09
CD (0.05)	0.20	0.20

Table 18. Effects of rock bunding and sorghum variety ICSV 1002 on grain yield (kg ha^{-1}) in farmers' fields in four villages in two agroclimatic zones, Burkina Faso, 1985.

Yield and other aspects	Agroclimatic zone			
	Sudanian		Guinean	
	Kolbila	Ononon	Koho	Sayero
Number of fields	8	7	8	8
Rainfall in 1985 (mm)	514	487	922	715
Fields receiving heavy runoff	5	1	0	1
Fields receiving moderate runoff	2	5	2	1
Sorghum grain yield (kg ha^{-1}) with bunding and ICSV 1002	730	350	670	1010
Control	230	160	650	600
SE	±118	±67	±206	±233

Table 19. Effect of porous barriers on runoff and soil loss from bare plots during the 1993 rainy season (total rainfall = 657 mm).

Barrier treatment	Runoff (mm)	Soil loss (t ha^{-1})
2.8% slope		
Control	278.4	6.2
Stone bund	257.6	4.2
Lemon grass	227.0	3.1
Vetiver	98.3	1.6
0.6% slope		
Control	222.1	2.0
Stone bund	102.7	0.9
Lemon grass	38.6	0.7
Vetiver	32.2	0.6

Table 20. Annual runoff under different management systems on an Alfisol.

Treatment	1988	1989	1990	1991	1992	1993	1994
ZTB	133	281	106	222	269	151	159
ZTF	112	198	79	124	132	51	84
ZTS	63	120	35	54	59	47	52
STB	132	262	109	226	238	123	126
STF	121	209	66	103	103	57	84
STS	76	139	46	49	59	47	77
DTB	112	199	82	199	224	126	108
DTF	102	191	68	112	124	57	50
DTS	80	121	36	48	60	54	54
P	120	227	94	104	29	31	91
PSt	122	92	15	6	23	23	58
PCSt	134	149	22	6	51	41	71
C	143	176	67	49	31	28	83
CSt	155	180	51	41	33	26	90
St	126	83	13	8	22	22	68
LSD (0.05)	34	32	22	33	35	21	37

Legend: ZT = Zero tillage; ST = Shallow tillage to 10 cm; DT = Deep tillage to 20 cm; B = bare without any amendment; F = Farm yard manure @ 15 t/ha/yr; S = Straw @ 5 t/ha/y; P Perennial pigeonpea; C = Cenchrus ciliaris; St = Stylosanthes hamata.

Table 21. Annual soil loss (kg/ha) under different management systems on an Alfisol.

Treatment	1989	1990	1991	1992	1993	1994
ZTB	1681	536	3107	6299	3964	2065
ZTF	3115	630	2559	5052	1494	1426
ZTS	589	480	556	2146	1531	675
STB	2654	1010	3204	5208	3540	1713
STF	2056	621	2057	2575	1912	1058
STS	685	411	497	1949	1374	740
DTB	1593	825	2950	4552	3201	1097
DTF	2130	822	2234	3559	2400	1323
DTS	1142	105	953	2820	1956	908
P	799	735	1710	1101	1595	821
PSt	77	256	693	67	435	293
PCSt	138	219	245	113	434	500
C	115	65	368	443	922	678
CSt	348	35	298	646	883	939
St	216	229	214	467	517	526
LSD (0.05)	1486	620	1477	2350	1319	705
CV (%)	67	69	57	49	39	37

Legend: ZT = Zero tillage; ST = Shallow tillage to 10 cm; DT = Deep tillage to 20 cm; B = bare without any amendment; F = Farm yard manure @ 15 t/ha/yr; S = Straw @ 5 t/ha/y; P Perennial pigeonpea; C = Cenchrus ciliaris; St = Stylosanthes hamata.

Table 22. Grain yield, runoff, and soil loss under improved and traditional technologies on deep Vertisols in 11 successive years, ICRISAT Center, 1976-1987.

Year	Cropping period rainfall (mm)[1]	Improved system (double cropping)			Traditional system (single crop)		
		Total yield[2] (t ha^{-1})	Runoff (mm)	Soil loss (t ha^{-1})	Chickpea (t ha^{-1})	Runoff (mm)	Soil loss (t ha^{-1})
1976/77	708	3.92	73	0.98	0.54	238	9.20
1977/78	616	4.29	1	0.07	0.86	53	1.68
1978/79	1089	3.40	273	2.93	0.53	410	9.69
1979/80	715	3.49	73	0.70	0.45	202	9.47
1980/81	751	4.50	116	0.97	0.56	166	4.58
1981/82	1073	4.24	332	5.04	1.04	435	11.01
1982/83	667	4.36	10	0.20	1.23	20	0.70
1983/84	1045	4.81	154	0.80	0.47	289	4.70
1984/85	546	4.36	11	N[3]	1.23	75	N
1985/86	477	3.42	4	N	0.84	18	N
1986/87	538	4.83	35	N	1.27	114	N
Mean	748	4.15	98.4	1.46	0.82	183	6.38
SE	±223	±0.52	±113	±1.69	±0.32	±147	±3.97
CV (%)	30	13	114	116	40	80	62

1. Average rainfall for Hyderabad (29 km from ICRISAT Centre) based on 1901-1984 data is 784 mm with a CV of 27%.
2. Total yield of sorghum and pigeonpea
3. N = Measurements were not taken

Fig 1. Effect of rainfall since tillage on runoff from a. Shallow tillage b. Deep tillage

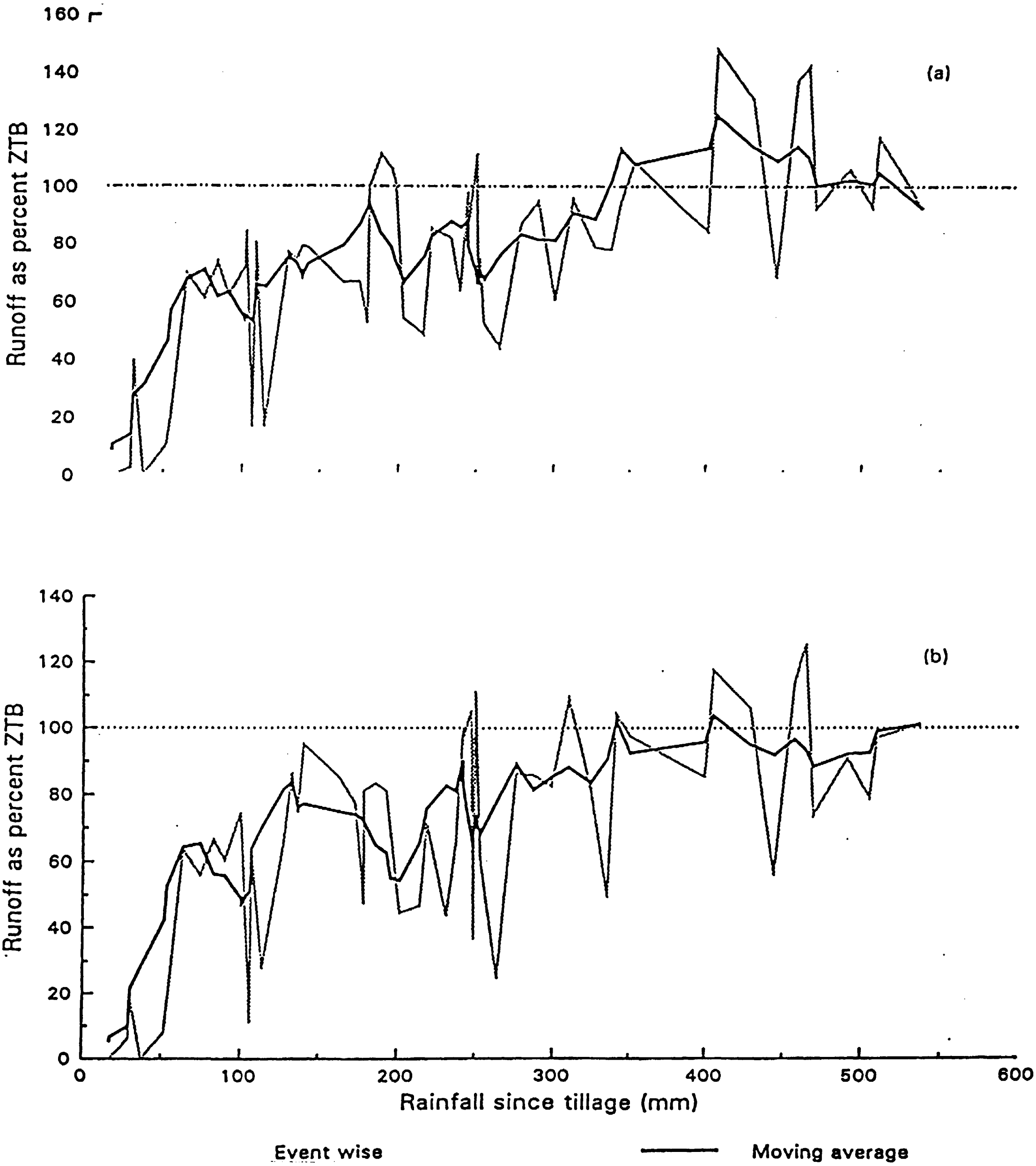

Fig. 12. Effect of rainfall since tillage on runoff from (a) Shallow tillage, (b) Deep tillage.

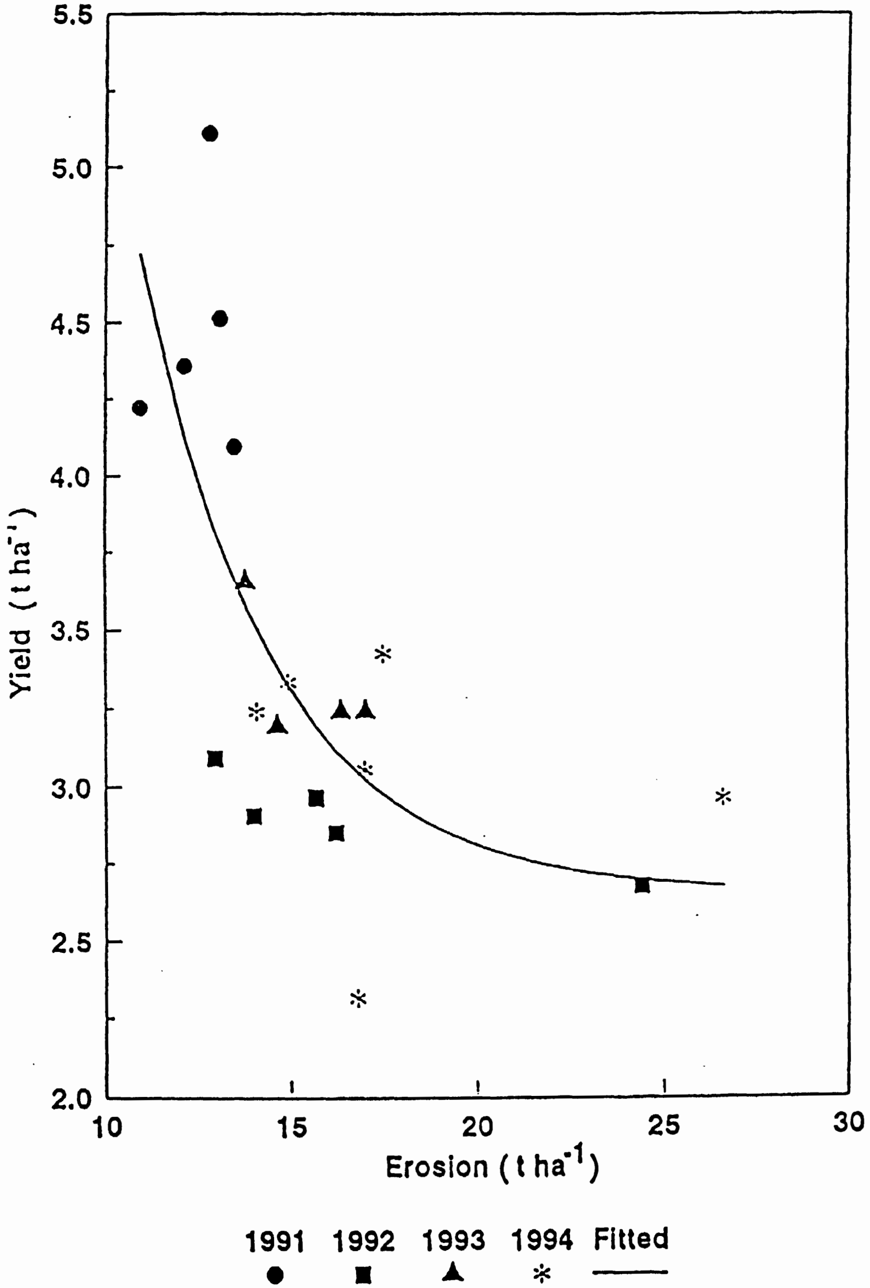

Fig. 13. Yield of pods and haulms versus cumulative erosion in NF plots.

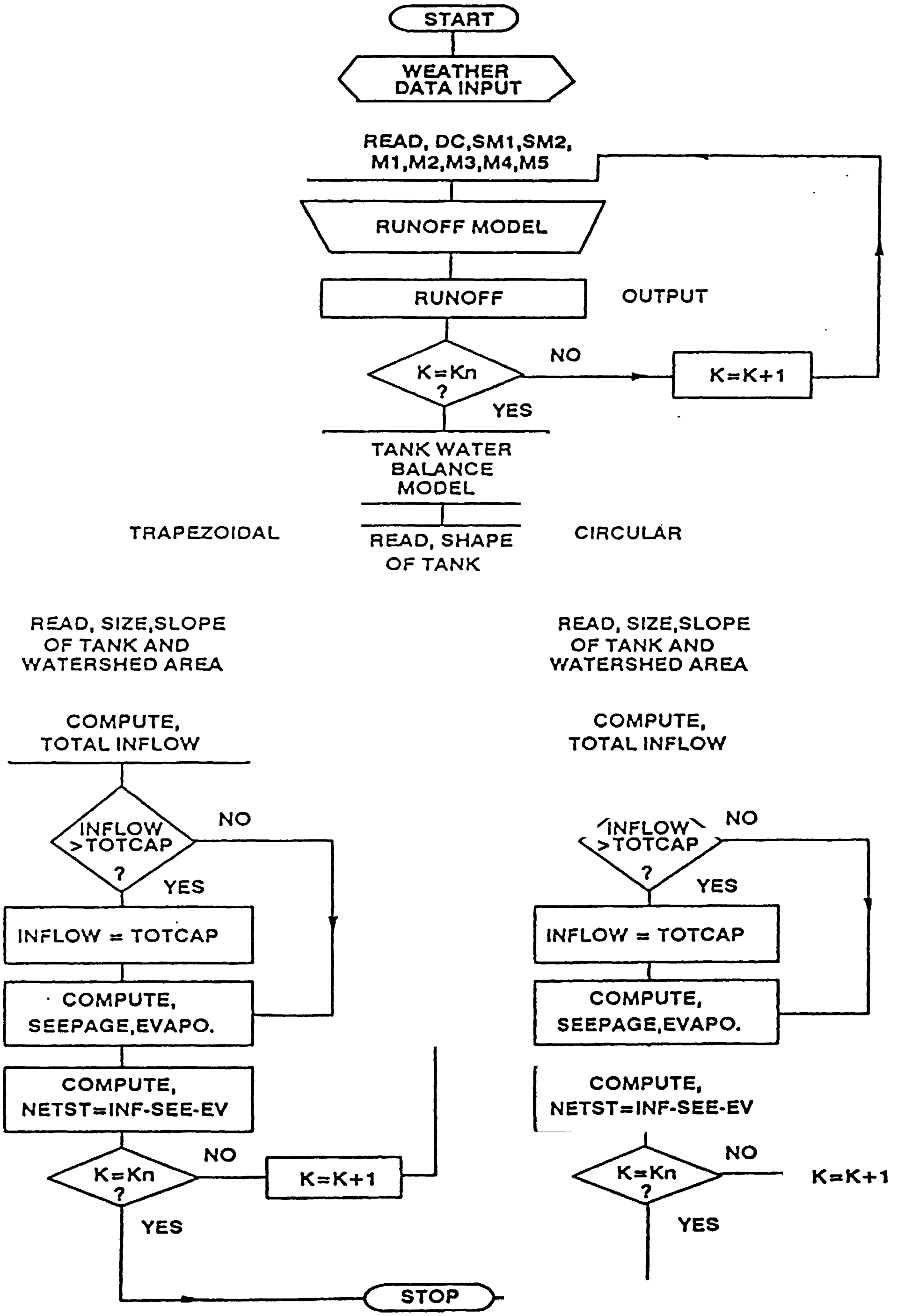

Fig. 14a. Flow chart of water harvest model.

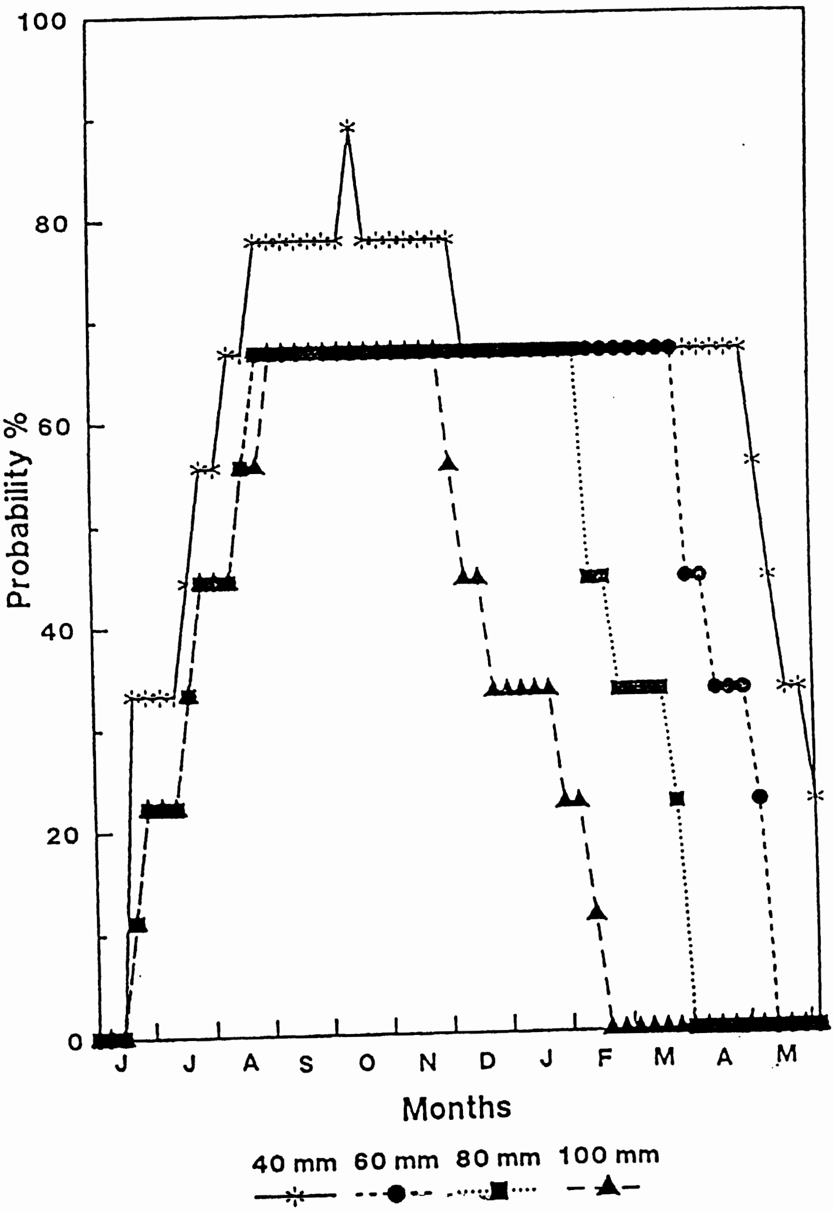

Fig. 14b. Probabilities of having 40, 60, 80 and 100 mm of water for irrigation from a tank at Akola (based on 10 years simulated data).

SOIL WATER BALANCE AND CROP WATER USE

Piara Singh, M.V.K. Sivakumar, M.C, Klaij and W.A. Payne

Introduction

Semi-arid regions of the world have significant variability in soils and climate. Rainfall in these regions varies spatially and temporally which has tremendous effect on crop production, resource use, and quality of the resource base. An understanding of soil water balance and its management in favor of crop production is fundamental to increasing crop productivity and sustainability. Since 1982 significant progress has been made to characterize soil water balance of semi-arid areas of India and Africa. Water use of crops and cropping systems has been quantified and their response to water deficiency has been studied. Research was also conducted on the development of methods for better assessment of water balance components at both experimental plot and regional scales. In the following sections research done at ICRISAT on soil water balance and crop water use is described.

Regional Scale Water Balance Studies in West Africa and Asia

Using the water balance model WATBAL (Keig and McAlpine, 1974) and the average weekly rainfall, potential evapotranspiration, and the data on available water holding capacity of soils as inputs, the lengths of the soil water availability periods have been computed for the 232 locations in India (Virmani, unpublished report). This analysis provides an average picture of water availability periods in various regions of the country. It does not consider the year-to- year variability in soil water availability. This information is useful to know the potential of regions for crop production and for extending new agrotechnologies to different ecologies. Piara Singh and Virmani (unpublished report) studied the water balance and water availability in soils of Andhra Pradesh using the same approach. The length of water availability periods ranged from 120 days in southern districts to 229 days in the northern districts of the state. Probabilities of a given amount of excess water (runoff plus deep drainage) during the rainy season were greater in the northern districts than for the southern districts. Based upon this analysis it was suggested that because of assured soil moisture availability in the northern parts of the state, sustainable agriculture based upon high inputs is possible; whereas in the southern districts mixed cropping systems including agroforestry were emphasized to make better use of water resources. Throughout the state, efficient land and water management techniques are needed to improve productivity and sustainability of resource base. Sivakumar *et al.* (1987) studied the water balance and length of water availability periods for the Alfisols of India and Africa. They envisaged that water use efficiency of crops on Alfisols could be improved by appropriate management practices, including the selection of suitable genotypes, crops, and cropping systems.

Since evaporation plays a dominant role in the water balance of the Sudano-Sahelian Zone, Monteith (1991) estimated the regional evaporation rates for southern Niger for the dry (1984) and wet (1988) years using the Penman formula, Penman-Monteith equation, and Priestley-Taylor equation. Annual evaporation from bare soil was estimated to be 230 mm. Potential evaporation from crops in the wet season was 6 mm day^{-1}, but was underestimated in the dry season by the Penman formula and by Priestley-Taylor equation. Annual regional evaporation (ET) estimated between 1984 and 1989 ranged between 300 and 500 mm. Corresponding estimates of runoff were consistent with the published data ranging from about 30 to 120 mm for areas with little vegetation, and from zero to 110 mm for areas with 50% vegetation.

Water Balance and Crop Water Use Studies in West Africa

Multilocation 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. Hence to evaluate the field water cycle as a whole, and the relative magnitude of the various processes comprising it over a period of time, it is necessary to consider field water balance. To accomplish this, we analyzed samples from four different soil profiles in Niger, at Sadore, Dosso and Bengou for physical, chemical and hydraulic properties (Sivakumar *et al.* 1990). These data show distinct differences between these soils (Fig. 15). Since these three sites were located on a rainfall gradient from 560 mm to 840 mm, they offered an unique opportunity to examine the variations in the components of soil water balance.

From 1984-87, we conducted multilocation water balance studies in Niger to understand the variations in crop growth and development with changes in available soil water on the different soil profiles shown in Figure 15. 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 an important consequence of the use of fertilizers is increased water use efficiency (Table 23). Early, vigorous growth results in a better ground cover. This reduces to some extent the proportion of water that would be lost through soil evaporation, thus helping in an effective and efficient use of rainfall. Our studies also pointed that different cropping possibilities exist under the same climatic regime because of differences in the soils under consideration and their management.

Effect of genotype, planting density and fertilizer on water use and water use efficiency

Several soil water balance studies made by ISC and by other research institutes have shown that water supply is seldom the primary production constraint to pearl millet production in semi-arid West Africa. (Payne *et al.* 1990).

It has been found that, within any given year, pearl millet genotype, planting density, and fertilizer have only slight to insignificant effects on crop water use (soil evaporation + crop transpiration, ET), which therefore has almost no relation to yield. As a result, crop ET efficiency is highly-correlated with yield. When high planting densities (20,000 hill ha^{-1}) are combined with high fertilizer rates during wet years, total ET can be increased by ~50 mm, but this combination may reduce yield during drier years, especially for the late varieties, by depleting available soil water reserves during dry spells. Compared to traditional practices of wide spacing and zero fertilizer input, moderate increases in planting density and fertilizer application substantially increase yield and approximately triple WUE without increasing risk even during very dry years. In general, grain yield is better correlated with ET when corrections are made for mean daily vapor pressure deficit calculated from standard meteorological data, but correction factors may differ among planting densities (Payne, 1996).

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

In West Africa, millet is traditionally grown in wide rows and plant densities are very low. In such sparse canopies, evaporative losses constitute a significant proportion of the total water loss and to improve the productivity of such traditional cropping systems it is essential to have an improved description of the energy balance and evaporation from the sparse canopies. In a collaborative project with the Institute of Hydrology (IH), U.K. and the ISC, we made measurements of the plant, soil and total evaporation in a sparse millet stand. 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 salient points 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) 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). Because of the low leaf area index in the sparse canopies, canopy conductances are very low and varied both diurnally and seasonally.

c) With proper installation and operation, the Hydra can provide routine measurements of evaporation and sensible heat flux to an accuracy of around $\pm$10% (Wallace *et al.* 1989b).

d) Total evaporation as measured by Hydra, generally agreed well with the sum of the independently measured soil and plant evaporation (Wallace *et al.* 1993).

e) Transpiration was calculated using the above canopy conductance values using the Penman-Monteith and Shuttleworth-Wallace models. In comparison to the Shuttleworth-Wallace model, Penman-Monteith equation underestimated transpiration when soil was dry and overestimated it when the soil was wet. These differences in transpiration arise because of the modification of the in-canopy vapor pressure deficit caused by heat and water vapor fluxes from the soil, a mechanism which is only present in the Shuttleworth-Wallace model.

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

The widespread deterioration of large areas of savannah in the semi-arid regions of Africa is believed to be associated with the over-exploitation of marginal land via the removal of wood and overgrazing. Whatever the cause, the net effect is to degrade the savannah 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 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 Cunnigton 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 three 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 (Fig. 16). Net radiation over the bush vegetation was 20 per cent greater than that over the bare soil, but only 12 per cent 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 bare soil the fraction of net radiation used as latent heat to evaporate water increased from 50 per cent before rain to 65 per cent 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.

Conditional cropping systems to optimize soil water use

Our analysis of the relationship between the date of onset of rains and the length of the growing season, which was described in the section on rainfall climatology, 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). To ensure yield stability at the farm level, it is essential to match the maturity duration of the crop species/variety to the probable season length. 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 in 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.

In field studies conducted at ISC during 1986-1991, we tested this concept of CCS. Data on soil water 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 by tailoring management tactics to weather conditions, in years with early onset of rains it is possible to establish a second rainfed crop of cowpea for hay where the farmers traditionally grow only millet (Sivakumar, 1990). 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.

Use of microlysimeters to measure evaporation from sandy soils

We have studied the measurement of evaporation from microlysimeters with different dimensions and of different ages on the sandy soils at the IAC and at ISC (Daamen *et al.* 1993).

Our data showed that the evaporation recorded from microlysimeters of diameters 51, 152 and 214 mm was not significantly different. A comparison of 100 and 200 mm deep microlysimeters showed that depth had no significant influence during the first 2 days after extraction from the soil profile. For periods beginning 2 or more days after rain, significant differences in evaporation owing to depth may not occur for up to 7 days. Soil cores extracted at different times showed significant differences in evaporation immediately following a rain, and no significant differences 2 or more days thereafter. The period of significant difference was extended when the method was used within a crop (ie., root extraction of water in the field significant).

Measurements of evapotranspiration and drainage from sandy soils of Sahel

In the Sahel, estimation of field water balance from neutron-probe measurements is often difficult for field crops which is due to rapid drainage (D) in the predominantly sandy soils. We developed a simple method of calculating D in these soils from weekly neutron-probe data (Klaij and Vachand, 1992). The method divides the water balance into two phases. In the first, applicable early in the season, when flux across the maximum depth of probe measurement (Z_m) is assumed negligible, and evapotranspiration (ET) and D are calculated from the change in water content (θ) between the bottom of the root zone (Z_r) and Z_m, thus allowing calculation of unsaturated hydraulic conductivity, $K(\theta)$, from the flux across Z_r. In the second phase, when soil water starts to percolate across Z_m, D is calculated from $K(\theta)$, assuming a hydraulic head gradient of -1. This method has been used to calculate a one dimensional water balance of a pearl millet grown in a number of experiments at the ISC on a deep sandy soil.

Results showed that the calculated K(θ) functions compared well with those on laboratory and field measurements. An acceptable estimate of D, and therefore ET could be made. The cumulative ET and D were 268 and 148 mm for the fertilized millet with 440 mm of rainfall received during the crop cycle. The water balance for fertilized millet was also simulated using DUET, which compared to the method resulted in an about 10% higher seasonal ET and a 10% lower seasonal D. DUET is a crop growth simulation model coupled with the water balance model SWATRER.

Our study showed that ET can be corrected for D using a simple but accurate method, and consistent with other studies in the region indicates that rainfall is usually not the primary limiting factor for pearl-millet production.

Effect of shallow cultivation on soil water use

Theoretically, evaporation from sandy soils can be reduced by altering the physical properties of the surface layer such that the "first stage" of evaporation is of shorter duration. However, few field studies have tested this theory. In a two year study, a tradional, shallow-cultivating hoe, known locally as the *hilaire*, was used to loosen the upper 0.05 m of soil within thirty minutes after a rain of ≥10 mm. During the rainy season, soil water storage, soil albedo, and surface soil temperature were measured regularly. Water conservation relative to non-cultivated plots steadily increased until fourteen weeks into the rainy season, at which point 70 mm more water was present in the upper 2.4 m of soil. Thereafter, water conservation rapidly decreased and was insignifcant toward the end of the season due to rapid drainage in both cultivated and non-cultivated plots. The darker color of cultivated plots was associated with a considerably reduced albedo. Soil surface temperature was as much as 12° higher in cultivated plots, suggesting greater energy interception. Our results suggest that the *hilaire* has evolved over the centuries to conserve water as well as to control weeds. (Payne, 1995).

Effect of fallowing on soil water conservation on sandy soils

Contrary to model predictions of Hall and Dancette, bare (or summer) fallowing conserves little to no water in sandy soils of Niger. Storage efficiencies from three sites ranged from 0% to 12%. Zero flux plane data show that most of the water conserved during the rainy season by bare fallowing was lost to drainage. Evaporation during the growing season from bare soil ranged from 41 to 65% of rainfall, which is in agreement with previous studies. (Payne *et al.* 1990).

Use of capacitance probe for water use estimation

We have found that the capacitance probe offers an attractive alternative to the radioactive neutron probe for estimating crop water use, but ET estimates could probably be improved if the installation equipment allowed for deeper access tubes. (Payne and Brück, 1996).

Water Balance and Crop Water Use Studies in Asia

At ICRISAT Asia Center, water balance and crop water use studies formed a part of the wider objectives of studies on understanding of crop growth and development as influenced by climate and agronomic management. These studies were primarily conducted to parameterize various crop growth and development processes so that the information generated is useful for crop simulation modelling as well as to increase crop yields. In the following sections only the water balance and crop water use aspect is emphasized.

Sowing geometries and water use by pearl millet

Pearl millet productivity and water use as influenced by sowing geometries and timing of water deficits were studied during 1982 to 1984 seasons at the IAC (ICRISAT, 1987). Three levels of rectangularity of inter-and intra-row spacings were imposed at a fixed population of 100,000 plants ha^{-1}. These spacings were 37.5 x 26.6 cm (S_1), 75.0 x 13.3 cm (S_2), and 150.0 x 6.6 cm (S_3). The cultivars were BJ 104 and ICH 226.

The most rectangular plant spacing consistently reduced grain and total dry matter yields, but did not affect the partitioning of dry matter into grain. BJ 104 yielded less than ICH 226 at the S_3 geometry, but not at the S_1 and S_2 geometries. Over the two years total dry matter production ranged from 4,220 to 5,990 kg ha^{-1} for BJ 104 and 4,260 to 6,310 kg ha^{-1} for ICH 226. The grain yields ranged from 1,730 to 2,490 kg ha^{-1} for BJ 104 and 1,660 to 2,350 kg ha^{-1} for ICH 226.

Sowing geometry did not affect water use by pearl millet, but ICH 226 used more water than BJ 104. Water use across treatments ranged from 36.4 to 36.5 cm for BJ 104 and 37.7 to 38.3 cm for ICH 226. For both the genotypes, S_3 caused lower water use efficiency (WUE) for both grain and TDM yields than S_1 and S_2. WUE for grain yield ranged from 52 to 69 kg $ha^{-1}.cm^{-1}$ for BJ 104 and 56 to 61 kg $ha^{-1}.cm^{-1}$ for ICH 226. Similarly the WUE for TDM ranged from 136 to 165 kg $ha^{-1}.cm^{-1}$ for BJ 104 and 155 to 165 kg $ha^{-1}.cm^{-1}$ for ICH 226.

Timing of water deficit and water use by pearl millet

During 1983 and 1984 summer seasons the productivity, water use and WUE of millet as influenced by timing of water stress was studied at IAC. Drought stresses were imposed during various growth stages, i.e., from emergence to panicle initiation, particle initiation to anthesis, and anthesis to physiological maturity.

The results on TDM and grain yield production during 1983 showed that grain filling stage is the most sensitive to drought stress, water applied at this stage was most productive. Thus under limited water conditions, the irrigation water could be withheld at from emergence to anthesis for application during grain-filling stage. BJ 104 used water more efficiently than ICH 412 (Table 24). For both grain and TDM yield, due to greater contribution of tillers to the greater yield under both stressed and nonstressed conditions. Water used across treatments ranged from

22.8 to 37.7 cm for BJ 104 and 32.8 to 47.1 cm for ICH 412. WUE for TDM across treatments was 125 to 299 kg ha^{-1} cm^{-1} for BJ 104 and 81 to 228 kg ha^{-1} cm^{-1} for ICH 412. Similarly the WUE for grain yield ranged from 25 to 121 kg ha^{-1} cm^{-1} for BJ 104 and 15 to 74 kg ha^{-1} cm^{-1} for ICH 412. Similar trends in the results were obtained during the 1984 season, however the water use by the crop was higher and WUE for grain and TDM were lower. Seetharama *et al.* (1984) reviewed the work done at ICRISAT and at other sites on drought stress, water use, and WUE of pearl millet. Millets have different levels of rainfall utilization resulting in different rainfall and WUE. Water use by pearl millet at IAC ranged from 10 to 30 cm with the corresponding biomass and grain yields ranges from 3,130 to 8,090 kg ha^{-1} and 1,100 to 2,230 kg ha^{-1}, respectively. WUE ranged from 220 to 374 kg ha^{-1} cm^{-1} for biomass and 74 to 116 kg ha^{-1} cm^{-1} for grain yield.

Water use-yield relations in sorghum

During 1983/84 and 1984/85 postrainy season we conducted field studies to examine the yield response of sorghum (cv.CSH 8R) to water use, and to determine the sensitivity of yield to water deficit at different growth stages and at three nitrogen application rates (40, 80 and 120 kg N ha^{-1}) (ICRISAT, 1986). A line-source sprinkler irrigation technique was used to apply different amounts of water during different phenophases of sorghum (ICRISAT, 1987).

Total seasonal water use accounted for 70 to 80% of the variation in sorghum grain yield with different nitrogen application rates. Accountability improved to 84 to 86% when actual evapotranspiration (ET) or the ratio of actual to maximum evapotranspiration (ET/ET_m) was considered separately for GS1, GS2, and GS3 growth phases. Relative yield (ratio of actual to maximum yield, Y/Y_m) was also regressed against ET/ET_m with the assumption that when $ET/ET_m = 0$ at any growth stage then $Y/Y_m = 0$. About 84% variation in Y/Y_m could be accounted for when ET/ET_m was considered at three growth stages. Crop sensitivity to drought depended upon both the amount of nitrogen fertilizer applied and crop growth stage.

Water and nitrogen effects on water and light use by sorghum

In 1989, we studied the water and nitrogen (N) application effects on growth and yield, water and light use by rabi sorghum grown on a Vertisol. Water use by the crop ranged from 19.9 to 22.0 cm in the nonirrigated treatment and 36.7 to 41.6 cm in the irrigated treatment. Of the total water use soil evaporation was estimated to be 4.85 cm for the nonirrigated treatment and 8.24 to 9.45 cm for the irrigated treatment (Lee *et al.* 1996). Both water and N strongly affected leaf expansion, whereas specific leaf area was independent of the treatments. A decrease in radiation interception with decreasing N was the main source of yield differences. Radiation use efficiency (1.3 to 1.4 g/MJ) was independent of N application and leaf N concentration (Rego *et al.* 1996). Below 45 cm soil depth, volumetric water content was a negative exponential function of time after roots arrived and the maximum depth of water extraction moved downward at 2.6 to 4.9 cm d^{-1} in various treatments (Table 25) (Piara Singh *et al.* 1996). Averaged over N rates, the time constant of the exponential function was inversely related to the root length density increasing with depth from about 14 to 19 d as the root length density decreased from 4 to 2.5 km m^{-3}. The biomass-water ratio was almost independent of N but increased from a mean of 5.3 g kg^{-1} in the dry treatment to 6.9 g kg^{-1} with irrigation. When normalized by the seasonal mean difference in vapor pressure deficit within irrigated and nonirrigated plots the ratios were 13.1 and 13.3 kPa g kg^{-1} respectively.

Water and fertilizer use efficiency of sorghum and pearl millet

Kanwar *et al.* (1984) reviewed the work on fertilizer and WUE of pearl millet and sorghum in Vertisols and Alfisols of semi-arid India. N application resulted in better use of rain, irrigation, or stored water, and permitted the use of higher population density, or better cropping system for increasing crop productivity. Rainfall use efficiency of sole sorghum at IAC decreased with rainfall exceeding 550 mm during kharif, and by lower rate of N. The use of stored water and the applied N by rabi sorghum was related to water-holding capacity of soil, and the rainfall during the preceding monsoon. Sorghum with higher yield potential always had higher rainfall use efficiency and fertilizer use efficiency than pearl millet.

Timing of water deficit, water use, and yield of groundnut

Several experiments were conducted at IAC during the 1980 to 1983 to study the effect of water stress on groundnut yield, water use, and other physiological responses of groundnut (Rao *et al.* 1985; Sivakumar and Sarma, 1986; and Rao *et al.* 1988). In all these experiments the line source irrigation technique was used to create different intensities of water stress during various growth stages of groundnut. The growth stages studied were emergence to flowering, emergence to pegging, flowering to seed growth, seed growth to maturity, and continuous stress from emergence to maturity. Water use by the crop in these experiments ranged from 16.9 to 83.1 cm and pod yields from 75 to 5,480 kg ha^{-1}. The salient points of these studies were that evapotranspiration-yield relationship showed a strong interaction with timing of drought. That is, at the same level of crop water use different pod yields were obtained in some stress treatments. The greatest reduction in kernal yields occurred when stress was imposed during the seed filling phase. Decreased irrigation during the early phase increased pod yield relative to the fully irrigated control treatment by 13 to 19% during different years. This may be attributed to i) the promotion of root growth during water stress, which promoted subsequent stomatal conductance and growth rates during pod-fill; and ii) inhibition of the number of vegetative sites (leaves and branches). When the stress was released, the plants could set more fruiting sites with existing assimilates the vegetative sites demanding assimilates are seduced. Yield advantage due to moderate water stress during pre-flowering phase was associated with greater pod synchrony after the release of water stress, which resulted in the production of more mature pods combined with adequate canopy and crop growth rates.

Water use and water extraction by groundnut genotypes

Mathews *et al.* (1988) studied the water use and dry matter production of four groundnut genotypes to understand the physiological basis for yield differences between four genotypes of groundnut. The four genotypes transpired similar amounts of water (22.0 to 22.6 cm) over the season, but produced different amounts of shoot dry matter (3,900 to 4,900 kg ha^{-1} cm). The extraction front of Kadiri 3 moved most rapidly (1.24 ± 0.3 cm/d) down the soil profile which may have enabled it to maintain the fastest rates of transpiration when soil water depletion was the greatest (Fig. 17). The descent of water extraction fronts for other genotypes were 1.13 ± 0.03 for TMV2, 1.22 ± 0.04 for NCAc 17090, and 1.12 ± 0.02 cm/day for EC 76446 (292). Tap root extension of Kadiri 3 in the first 32 days after sowing was also the fastest. NCAc 17090 was most efficient compared to the other genotypes in extracting water from the upper 40 cm of the soil, immediately after irrigation, but this had little value in determining the pattern of water availability in this experiment. Differences in the water extraction characteristics of these genotypes explained little of the variation in dry matter : water ratio, and did not account for the major variation in harvest index associated with drought.

Sowing densities and water use by groundnut

Simmonds and Williams (1989) studied the transpiration and soil evaporation of groundnut grown at four plant densities (0.6, 6.6, 11.4, and 23.0 plants m^{-2}). Evaporation was estimated from the changes in soil water content and partitioned between transpiration and evaporation from soil. Seasonal transpiration was strongly influenced by plant population, and approached a maximum as the plant population density increased to 23 plants m^{-2}. Evaporation from soil surface was only a small component of the seasonal water balance in dense stand, and was little effected by planting density. Differences in transpiration rate between spacings were greatest early in the season, but diminished with the decrease in soil water availability towards the end of season. Denser stands extracted more water from deep in the profile. Plants in underlay spaced rows preferentially extracted water from near the row and water in mid-row was only used later in the season.

Sowing dates and water use by chickpea

Response of chickpea to water availability was studied in several experiments conducted at IAC. Sivakumar and Piara Singh (1987) found that irrigation and sowing dates had a significant effect on yields and water use by chickpea. The seed yields of the two cultivars (Annigeri and L 550) were maximum with early October sowing and the yields declined with later sowings. The seed yields of Annigeri ranged from 1,700 to 2,200 kg ha^{-1} and that of L 550 from 1,730 to 2,250 kg ha^{-1} over various irrigation and sowing date treatments. The total seasonal water use ranged from 9.6 to 29.4 cm for Annigeri and 10.5 to 27.9 cm for L 550. Similarly, the water use efficiencies for seed production ranged from 64 to 157 kg ha^{-1} cm^{-1} for Annigeri and 46 to 96 kg ha^{-1} cm^{-1} for L 550. Lower yields with late sowing were because of high temperatures during the period from flowering to maturity which reduced the time to maturity and seed size. Efficiency of applied water was also low for the late sown crops. Sivakumar (1986) further analyzed these data and found that total water use by chickpea was inversely related to the stress degree days (SDD) accumulated by the crop. He also found the SDD and the water stress index, which includes the water stress term, were also correlated with the chickpea yields over the three growing seasons.

Timing of water deficit, water and light use by chickpea

In order to develop parameters for modelling of chickpea growth and development, the work on response of chickpea to water availability was further pursued using the line source irrigation technique to create various intensities of water deficits during different phenophases of chickpea (Piara Singh and Srirama, 1989; Piara Singh and Virmani 1990; and Piara Singh 1990). The analysis of the two years' data showed that both total dry matter and seed yields were more strongly correlated with the normalized ET (r^2 = 0.92 for TDM and R^2 = 0.82 for seed yield), defined as ratio of ET to saturation vapor pressure deficit of the air, than with actual ET (r^2 = 0.56 for TDM and r^2 = 0.40 for seed yield). Further partitioning of total ET into two or three phenophases and regressing seed yield against them did not improve the predictability of the models.

The data were further analyzed for radiation use and transpiration efficiencies. Radiation use efficiency (RUE) was 0.67 g/MJ for the irrigated and 0.55 g/MJ for the stressed treatments. RUE was not effected by water stress when at least 30% of extractable soil water (ESW) was present in the rooting zone of chickpea; but below 30% ESW, RUE decreased linearly with the decrease in water content. RUE was also significantly correlated (r^2 = 0.61) with the ratio of actual to potential transpiration (T/Tp) and it declined linearly with the decline in T/Tp. Transpiration efficiency (TE) decreased with the increase in saturation deficit (SD) of air. Normalization of TE with SD gave a conservative value of 4.8 g kPa kg^{-1} (Table 26). Piara Singh (1991) also found that the duration of various phenophases was also inversely correlated with ET-deficit experienced by the crop. Water stress also increased the partitioning of assimilates to the pods by about 10%.

Water use by intercrop and sequential cropping systems

We studied the water use and WUE of intercrop and sequential cropping systems at low and medium fertility in operational scale plots on Vertisols, medium-deep Vertisols, Vertic Inceptisols, and Alfisols at IAC (ICRISAT, 1984). The water use by the cropping systems ranged from 64.9 to 73.7 cm on a Vertisol, 62.4 to 70.6 cm on a medium-deep Vertisol, 59.3 to 63.8 cm on a Vertic Inceptisol, and 55.0 to 59.7 cm on a Alfisol during the 1982-83 season. Across soil types sorghum/pigeonpea and maize/pigeonpea intercrop systems and sorghum-safflower sequential systems used more water than other cropping systems. Generally legume-based (except long duration pigeonpea) cropping systems used less water than the cereal based systems. Because of the high rainfall during the season the effect of fertility on water use (ET) was insignificant. It was concluded from this study that for efficient use of resources on deep and medium-deep Vertisols the best cropping systems are sorghum/pigeonpea, sorghum-chickpea, sorghum-safflower,and maize-chickpea. On Vertic Inceptisols and Alfisols the sorghum/pigeonpea and millet/pigeonpea were the most efficient systems. Groundnut/pigeonpea also had good WUE at low fertility. Millet/groundnut and mungbean/castor were relatively poor in WUE and seed yield.

Cooperation with National Agricultural Research System (NARS) and International Agencies

During the period of research reported in this review, we collaborated with several national and international research institutes and agencies in the area of water balance and resource use studies in the SAT environment. This provided an opportunity to the ICRISAT scientists in Asia and Africa to imbibe new techniques and methodologies in their research. We also developed joint research projects with the national scientists to quantify water balance components under on-farm situations. We also trained the national scientists in agroclimatic data analysis and soil water balance studies. In collaboration with international agencies an international workshop was held on water balance of the Sudano-Sahelian Zone in February 1991 at Niger to identify research priorities and to develop future plans on water balance research. In India, the scientists of the ICAR coordinated research project on agrometeorology were provided training in agroclimatic data analysis, soil water balance and crop water use, and instrumentation. Some of the cooperative links are listed below:

- Water balance and water use by pearl millet
  - University of Nottingham, School of Agriculture, U.K.
  - Institute of Hydrology, U.K.
  - Haryana Agricultural University, Hisar, India.

- Water balance and water use by groundnut
  - University of Nottingham School of Agriculture, U.K.

- Studies on microlysimetry to measure soil evaporation
  - University of Reading, U.K.

- Workshop on water balance in Sudano-Sahelian Zone
  - Institute of Hydrology, U.K.
  - Overseas Development Agency (ODA), U.K.
  - World Meteorological Organization (WMO)
  - International Association of Hydrology Sciences (IAHS).

- Risk—probability mapping for pearl millet production in West Africa
  - University of Hohenheim, Stuttgart, Germany.

- Water balance modelling
  - Michigan State University, USA.
  - Institute for Agricultural Research, Ahmadu Bello University, Zaria, Nigeria.
  - University of Hohenheim, Stuttgart, Germany.

Future Plans

In future the water balance and crop water use research in Asia and Africa will be conducted to study the integrative effects of different soil and crop management practices on crop productivity and resource use efficiency. This will be carried out within the new Integrated System Projects (ISPs) developed at ICRISAT.

In the Integrated System Project 1 (ISP1) Africa we will study the effect of various soil and crop management practices on water balance and water use efficiency of millet-based systems in West Africa. In India we will study the rainfall use efficiency of millet-chickpea system in the eastern margins of Thar desert. Soil water conservation and nutrient management practices will be evaluated to improve rainfall use efficiency.

In the Integrated System Project 2 (ISP2) we plan to quantify the water balance and rainfall use efficiency of groundnut- and sorghum-based systems under traditional and improved management in order to assess the opportunities for "in-situ" water conservation and thereby increasing crop productivity. Similar work will be extended to irrigated rabi groundnut system in India to improve irrigation use efficiency through the application of crop simulation and water balance models.

In the Integrated System Project 3 (ISP3) we will evaluate the opportunities for double cropping by characterizing soil water balance of Vertisols and Vertic Inceptisols. Various land-forms and soil management practices will be evaluated for modifying the soil water balance to improve rainfall utilization. Opportunities for increasing water supplies through water harvesting and ground water exploitation will be assessed.

The Integrated System Project 4 (ISP4) aims to improve legumes production in the rice and wheat based cropping systems of South and South-east Asia. We are quantifying the soil water availability spatially and temporally for more precise matching of phenology of legumes (pigeonpea, groundnut, chickpea, lentils, etc.) to available soil water. Genetic and agronomic management options will be evaluated to minimize the effects of hard plow pans in rice fallows on root development and water uptake by legumes.

Table 23. 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 rainy season 1985.

Site	Rainfall (mm)	Treatment	WU (mm)	Y (kg ha^{-1})	WUE (kg ha^{-1} mm^{-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

Table 24. Effect of five drought-stress treatments on WU and WUE for grain yield and TDM production by two pearl millet cultivars, Alfisols, ICRISAT Asia Center Patancheru, Summer 1983.

Drought stress treatments[1]	WU (cm)		WUE ($kg\ ha^{-1}\ cm^{-1}$) Grain yield		WUE ($kg\ ha^{-1}\ cm^{-1}$) TDM	
	BJ 104	ICH 412	BJ 104	ICH 412	BJ 104	ICH 412
M_0	37.7	47.1	75	38	197	187
M_1	34.4	43.7	83	51	232	228
M_2	22.8	24.1	121	74	229	213
M_3	30.9	32.8	25	18	125	187
m_4	35.8	36.2	71	15	176	81
SED[2]	±1.7		±7		±21	
SED[3]	±1.4		±7		±23	

1. M_0 = Adequate moisture supply throughout the growing season;
   M_1 = Drought stress during emergence to panicle initiation (GS1);
   M_2 = Stress during panicle initiation to anthesis (GS2);
   M_3 = Stress during anthesis to physiological maturity (GS3); and
   M_4 = Stress during later part of GS2 to end of GS3.
2. Standard error of the difference between two treatments for the same cultivar.
3. Standard error of the difference between two cultivar means at the same level of moisture.

Table 25. Parameters derived from the extraction equation $\theta(z, t) = \theta_a(z) \exp\{-(t_i - z/u)/\tau(z)\}$. See footnote for the explanation of symbols and parameters.

	Nitrogen levels (kg ha-1)					
Parameters	0	30	60	90	120	150
			Unirrigated			
t_i	25 ± 8	30 ± 5	26 ± 9	30 ± 11	27 ± 6	26 ± 8 *u*
(cm/d)	2.6 ± 0.3	3.3 ± 0.3	3.2 ± 0.5	3.6 ± 0.6	3.4 ± 0.3	3.2 ± 0.4
r^2	0.93	0.97	0.89	0.85	0.95	0.90
τ (d)	14.5 ± 4.2	15.7 ± 3.1	16.0 ± 4.8	13.5 ± 2.8	13.4 ± 5.1	17.8 ± 4.4
			Irrigated			
t_i	52 ± 27	49 ± 19	46 ± 9	43 ± 11	49 ± 12	50 ± 12 *u*
(cm/d)	5.6 ± 1.7	4.5 ± 1.0	3.9 ± 0.4	3.9 ± 0.5	4.7 ± 0.6	4.9 ± 0.7
r^2	0.64	0.78	0.94	0.90	0.89	0.90
τ (d)	13.4 ± 7.0	20.0 ± 6.0	16.2 ± 8.1	19.3 ± 5.2	20.4 ± 16.0	17.5 ± 4.6

θ_a (z) = Maximum available water at depth z and time t = 0 (cm^3/cm^3)
θ (z, t) = Available water at depth z and time t (cm^3/cm^3)
t_i = The apparent time when the extraction front started to desend (d)
u = Extracton front velocity (cm/d)
τ = Time constant of the equation (d)

Table 26. Effect of water supply on transpiration efficiency (TE) of chickpea and its normalization with saturation deficit of air (SD) for irrigated (I) and non-irrigated (NI) plots of the three experiments.

		TE ($g\ kg^{-1}$)		SD (kPa)		Normalized TE ($g\ kPa\ kg^{-1}$)	
Season[1]	Cultivar	I	NI	I	NI	I	NI
1984	Annigeri	2.16	1.77	2.46	2.81	5.3	5.0
	K 850	2.11	1.79	2.46	2.81	5.2	5.0
	G 130	1.94	1.42	2.46	2.81	4.8	4.0
1985	Annigeri	2.16	2.16	2.26	2.32	4.9	5.0
1986	JG 74	2.54	1.66	1.96	2.19	5.0	3.6
Mean		2.18	1.76			5.0	4.5
CV (%)		10.1	15.2			4.4	14.7
Grand mean			1.97				4.8
CV (%)			16.3				11.2

1 = For the 1985 and 1986 season experiments, irrigated and non-irrigated plots refer to the area 3.6 and 16.4 m away from the line source, respectively.

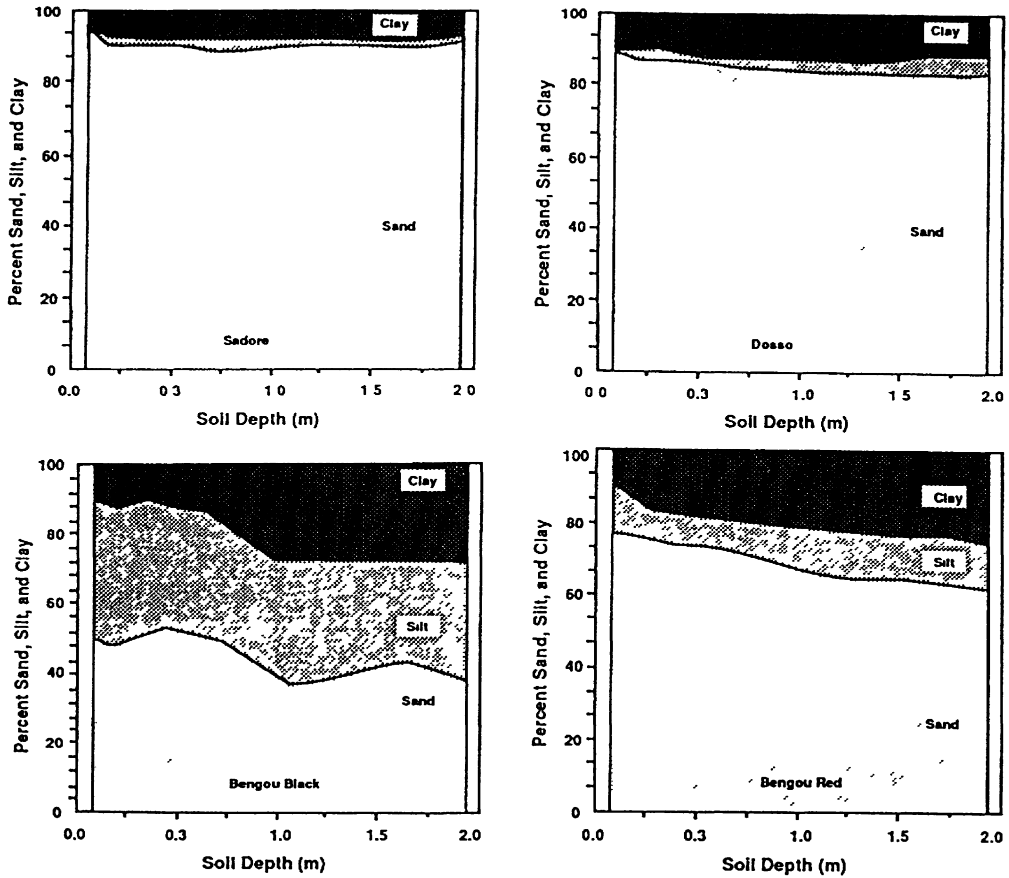

Fig. 15. Measured particle size distribution as a function of soil depth for four soil types in Niger.

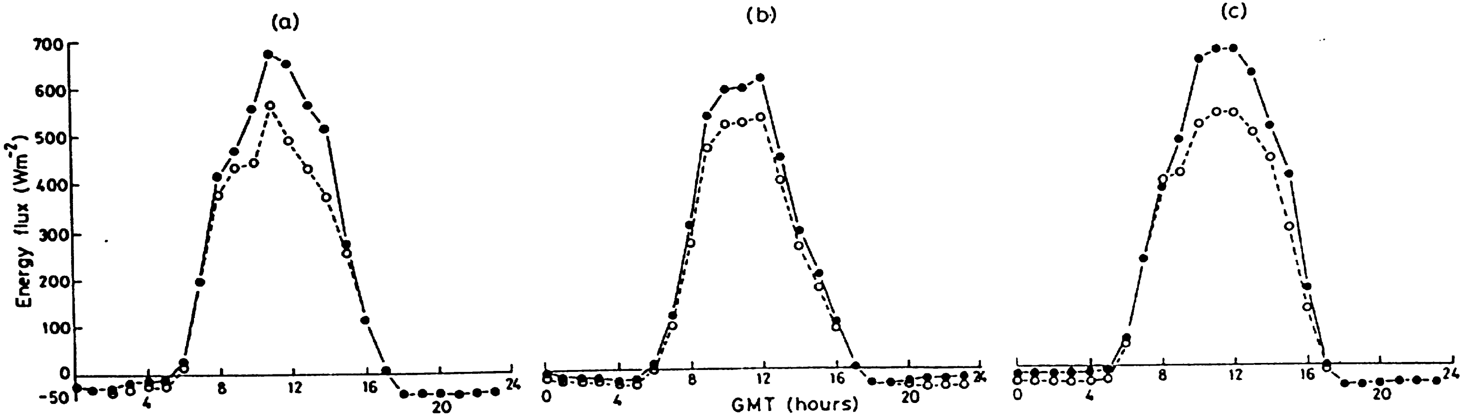

Fig. 16. Comparison of net radiation measured over fallow bushland (O-----O) and bare soil (O-----O) on 3 days (a) 6 September, 1986, (b) 8 September 1986, and (c) 9 September 1986. 39 mm of rain fell between 00.00 and 03.00 on 8 September.

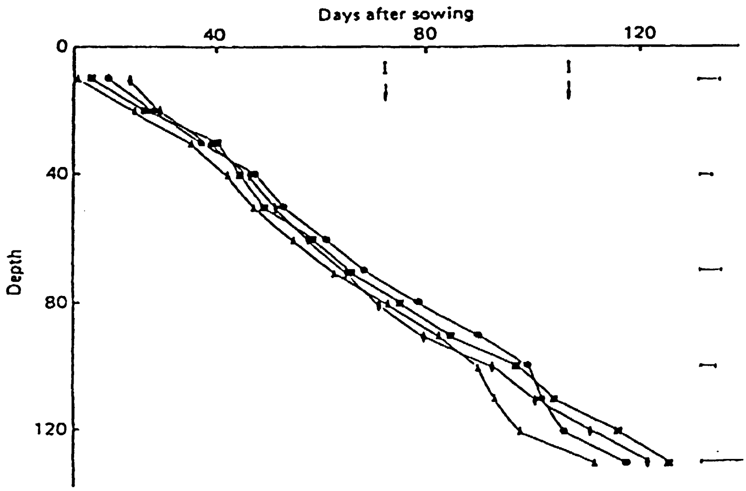

Fig. 17. Changes in depth of the water extraction front of 4 groundnut genotpyes with time.

Symbols: • TMV 2, Δ Kadiri, ♦ MCAc 18090, and ▪ EC 76446 (292).

NUTRIENT MANAGEMENT

T.J. Rego, A. Bationo, K.K.Lee, J.V.D.K. Kumar Rao, S.P. Wani, B. Seeling, C. Johansen and R.J.K. Myers

The objective of nutrient management research at ICRISAT was to determine the most appropriate means of alleviating the important nutrient constraints that limit crop productivity in the rainfed Semi Arid Tropics (SAT). This required substantial research activities in three main areas:

- Characterization of the occurrence and severity of the main nutrient deficiencies, and relating these to environmental and agronomic factors.
- Determination of technical options for alleviating these deficiencies.
- Selecting solutions which best accommodate the socio–economic constraints of the farmers.

The importance of individual nutrients in different crops was investigated in many previous empirical agronomic experiments both by the National Agricultural Research Systems (NARS) and ICRISAT. Nitrogen (N) and phosphorus (P) are the two most important nutrient deficiencies, addressed in ICRISAT research. Prior to 1990, at IAC, the major emphasis was on N with a lesser emphasis on P, whereas at ISC, P research received priority. At IAC annual experiments were conducted aiming to determine the N fertilizer requirements of cereals, and the environmental and agronomic factors that influence crop needs and N fertilizer use efficiency. Medium– to long–term (4 to 8 years) experiments were also conducted to investigate the needs for annual inputs of N, P, and K in improved cropping systems, especially the minimum inputs needed for long–term maintenance of soil fertility. At ISC, annual experiments aimed to determine the crop requirement of P and N fertilizers, and the efficiency of different sources of P. Experiments to quantify the benefits of crop residue incorporation were also conducted. During the last five years (1991–1995), research on N was again given priority at IAC, whereas at ISC there was emphasis on P, N, molybdenum, and organic amendments.

Nutrient Research at IAC between 1991 and 1995

Continuing from earlier work, the role of biologically fixed–N, mainly through legumes to alleviate the N deficiency in cereals was studied in greater depth. At the same time, some strategic research on fertilizer–N was also carried out with the aim of understanding processes in the soil–plant system. Some work was also carried out to understand the processes of P availability in Vertisols.

Nitrogen

Biological-N Fixation (BNF)

IAC has given considerable research attention to the study of nodulation and N fixation by groundnut, chickpea and pigeonpea–three of its mandate crops (Kumar Rao, 1990, Nambiar *et al.* 1988). Some salient points of research using the ^{15}N isotope dilution method are given below in the context of the present review.

In groundnut, 86–92% of the total N was estimated to be derived from symbiotically-fixed N in a low-N field (Giller *et al.* 1987). Groundnut intercropped with cereals such as maize, millet, and sorghum fixed less N than sole groundnut. There was no significant residual N effect of a postrainy season groundnut crop on a subsequent rainy season millet crop while, a rainy season groundnut crop left residual N, probably in the form of fallen leaves for the following crop.

In chickpea, it was estimated that a single crop could fix up to 40 kg N ha^{-1} in southern and central India. Genotypic differences in extent of nodulation have been observed. The effects of temperature, soil moisture and soil available N levels on N fixation by chickpea have been quantified, showing for example that nodule development and symbiotic activity is severely inhibited when root-zone temperatures exceed 30°C.

In pigeonpea, 90% of N in a medium–duration pigeonpea, grown as a monocrop in a Vertisol, was derived from fixation. In intercropped pigeonpea the proportion fixed was 96% and there was no evidence of immediate benefit to the intercropped sorghum. The benefit to the following maize crop of a medium–duration pigeonpea grown on a Vertisol was estimated at about 40 kg N ha^{-1}, compared to fallowing. Genotypic differences in nodulation of pigeonpea have been confirmed and residual effects on subsequent crops have been found to be greater for high–nodulating than low–nodulating pigeonpea grown on Alfisol.

Quantification of nitrogen derived from N fixation in sole and intercrop pigeonpea

A field experiment was conducted to obtain the N balance sheet for sole crops and intercrops of sorghum (*Sorghum bicolor* (L.) Moench) and pigeonpea (*Cajanus cajan* (L.) Millsp.). Intercropping gave a significant advantage over sole cropping in terms of dry matter production and grain yield. The N fertilizer use efficiency and atmospheric N fixation by pigeonpea were estimated using ^{15}N–labelling and natural abundance methods.

The N fertilizer use efficiency of sorghum was unaltered by the cropping system, while that of the pigeonpea was greatly reduced by intercropping. Although intercropping increased the fractional contribution of fixed N to the pigeonpea, no significant difference was observed between the cropping systems in total symbiotically fixed N (Table 27). There was no evidence of a significant transfer of N from the pigeonpea to the sorghum. This study showed that use of soil N and fertilizer N by pigeonpea was almost the same as that by sorghum in sole cropping, indicating the potential competence of pigeonpea to exploit soil N. However, when N was exhausted by a companion crop in intercropping, the pigeonpea crop increased its dependency on atmospheric N fixation (Tobita *et al.* 1994).

Nitrogen balance sheet for different cropping systems involving legumes

In an experiment conducted on an Alfisol with different cropping systems, a positive nitrogen balance was observed in only one system. Sole pigeonpea grown in rotation with sole castor had a positive balance of 18 kg N ha^{-1} during two years of crop rotation (Table 28). These results show that the legumes also can mine soil N, as cereals do, under certain conditions. However, total N yields from legumes are far higher than cereal plant N yields. Thus in case of grain legumes, where crop residues are removed, a slow decline of, rather than an enhancement in the soil N fertility may occur in comparison to a rapid decline of soil N after a non-fertilized cereal crop (Lee *et al.* 1993).

Natural ^{15}N-abundance technique for estimating N fixation in legumes

Nitrogen accumulation and natural ^{15}N abundance in three legumes (groundnuts, cowpea and soybeans) and in two cereals (sorghum and maize) was investigated in two seasons on Alfisols with and without N fertilization. Using the N uptake and natural ^{15}N abundance of non-nodulating plants for the quantification of N derived from soil and fertilizer, the N derived from atmospheric N was calculated for nodulated plants. Groundnut contained 85% atmosphere-derived N, but this percentage decreased with N fertilizer application. Estimates of atmosphere-derived N by the N difference and ^{15}N abundance technique gave identical results. The proportions of atmosphere-derived N, estimated by the two methods at different stages of groundnut growth, were also similar. Atmosphere-derived N was also estimated in plants grown with 0–200 kg ha^{-1} applied N. Atmosphere-derived N ranged from 42 to 61% for groundnuts, from 33 to 77% for cowpeas, and from 24 to 48% for soybeans, depending on the amount of N applied. The natural ^{15}N abundance of sorghum and maize was very close to that of the non-nodulating groundnut, suggesting that these cereals can be used as reference plants in the estimation of atmosphere-derived N by the natural ^{15}N-abundance method (Yoneyama *et al.* 1990).

Nitrogen requirement at different growth stages of short-duration pigeonpea

The response to N fertilization of a short-duration pigeonpea, ICPL 87, was studied in the field to assess the scope for genetically improving symbiotic N_2 fixation by pigeonpea. The field study was undertaken for three seasons on four soil types (Vertisol, Alfisol, Inceptisol and Entisol). Nitrogen fertilizer was applied to the soil at various growth stages to determine when N becomes most limiting. There was a significant response in grain yield to fertilizer N applied at flowering in the Vertisol but not in the other soils. BNF by short-duration pigeonpea was thus not adequate to meet the N requirements of the crop grown on the Vertisol and therefore there is a need for genetic improvement of the N-fixing ability of these short-duration pigeonpeas when grown on heavy-textured soils (Kumar Rao *et al.* 1995).

Identification of nonnodulating chickpea and pigeonpea

Nonnodulating lines are valuable in assessment of the amount of BNF in a legume. Crop physiologists at ICRISAT have identified a number of lines in chickpea which are indistinguishable from their respective parent accessions for plant growth except for nodulation and nitrogen fixation, and most yielded similarly to their nodulating (Nod^+) accessions when supplied with 50 to 100 kg N ha^{-1}. Recently a large number of pigeonpea lines were screened, plants with low and high nodulation were identified, and progenies of these lines were advanced. After two cycles of pure line selection, the selected lines maintained their relative nodulation ratings. These discoveries should have a major impact on BNF research in future (Rupela, 1992; Rupela and Johansen, 1995).

Selection of high mineral-N tolerant chickpeas

Mineral N is known to suppress BNF. In some legumes as little as 20–30 mg kg^{-1} soil of mineral N can be inhibitory to BNF. Researchers on BNF have tried genetic manipulation of rhizobia in order to have nitrate-tolerant symbiosis. At ICRISAT an alternative approach, that of N–tolerant symbiosis through host plant selection has been tried in chickpea. A large number of chickpea lines have been screened using high soil N (25–30 mg N kg^{-1} soil) in field conditions, and 392 plants representing 85 entries have been selected. Further screening of this selected material is continuing (Rupela and Johansen, 1995).

Effect of high nodulating selection of chickpea cultivar on yield and soil properties

A high–nodulating (HN) chickpea selection from variety ICC 4948 produced only marginally higher grain yield (3.3 to 6.9%, mean of the two N levels) than that of the unselected normal variety and the low–nodulating (LN) selection. The HN selection fixed significantly more atmospheric N at low soil N (as measured by acetylene reduction activity) and also supported increased microbial activity in the rhizosphere. Also, at low soil mineral N level, the microbial flush C:N ratio in the plots of the HN selection was narrower (16.0) than in plots of the LN (24.4) and nonnodulating (20.4) selections. Increased microbial activity, along with a narrower flush C:N ratio in the case of HN selections compared to the LN selection, lead to an increased availability of N for the following sorghum crop which resulted in an extra uptake of 20 kg N ha^{-1} by chickpea and sorghum together. These results indicate the benefits of HN selections of chickpea under low soil N conditions (Rupela *et al.* (submitted for publication)).

Beneficial effects of legumes on crop productivity of succeeding cereals

Despite the negative N balances for grain legumes grown in rotation or as intercrops, many researchers throughout the world have reported benefits of legumes to succeeding non–legume crops. Generally it has been found elsewhere that improvements in cereal yield following monocropped legumes lie mainly in the 0.5 to 3 t ha^{-1} range, representing around 30 to 350% increase over yields in cereal–cereal cropping sequences. In a long–term cropping system rotation experiment on Vertisols conducted since 1983 at IAC, residual effects of legume–based crop rotations were assessed by comparing sorghum growth following a year when a legume was grown with sorghum after a year when only non-legumes were grown. Amongst the treatments, the following are informative—sorghum-safflower sequence, cowpea-pigeonpea intercrop, sorghum-pigeonpea intercrop, and sorghum-chickpea sequence—all followed by sorghum as the next crop in the subsequent year. For a 10-year period, an increase in yield of sorghum following legume was observed. This increase was attributed mainly to the N contribution from the legumes in the crop rotation. The benefit to the following sorghum of the cowpea/pigeonpea (C/PP) intercrop was equivalent to nearly 40 kg N ha^{-1} applied as fertilizer, whereas that of the sorghum/pigeonpea (S/PP) intercrop was about 20 kg N ha^{-1}, and that of the sorghum+chickpea (S+CP) rotation was only about 10 kg N ha^{-1}. The 10-year average grain yield of sorghum was nearly 3.2 t ha^{-1} after C/PP, whereas on the continuous non–legume system (S+SF) it was 1.4 t ha^{-1} (Fig.19). One cannot attribute all the benefits of legumes to N effects only. However, we have observed that mineral N in the soil before planting sorghum is higher in the legume–based cropping system than the non–legume based system.

The N mineralization potential (N_0) of the soils under the pigeonpea–based cropping systems was almost double that of traditional fallow–sorghum. The "active N fraction" (N_0 as a percentage of N_{total}) was 9–17% with the highest values in the soil under pigeonpea–based systems (Wani *et al.* 1995b). Thus higher N availability in legume–based systems might have resulted in higher N uptake and higher grain and biomass yield of sorghum. Research is in progress to quantify the factors other than N, such as soil structural improvement, mycorrhizae, microbial biomass, etc. (Rego and Burford, 1992; Rego and Seeling, 1995; Wani *et al.* 1995a).

Total effects of grain legumes on soil–N fertility and soil organic carbon (C) status

Soils sampled from the above long–term experiment at the start of the experiment in 1983 and again in 1993 have been analyzed. In the fallow–sorghum system, total soil N was decreased by 72 mg g^{-1} soil after ten years. S+SF–S+SF plots also showed decreased total soil N. Both S/PP–S+SF and C/PP–S+SF systems had increased total N in the 0–15 cm layer. In the S+CP–S+SF system, soil N was unchanged. However, soil organic C followed different trends. The non–legume S+SF–S+SF and the chickpea-based S+CP–S+SF system had a decline in soil organic C, while S/PP–S+SF and C/PP–S+SF maintained the soil organic carbon status (Table 29). These results demonstrated that pigeonpea–based cropping systems increased the total soil N substantially and also maintained soil organic C.

Pot experiments with soil from this experiment, and using ^{15}N tracer techniques, indicated that the legume benefits expressed in terms of fertilizer equivalent are slightly overestimated. This study also indicates that there may be some benefits additional to those from N which also increase the biomass and grain yield of the succeeding sorghum crop (Rego and Seeling, 1996; Wani *et al.* 1995a).

Associative N_2–fixation in pearl millet and sorghum

Pearl millet and sorghum are grown on nutritionally poor soils in the semi–arid tropics often without addition of fertilizers. The role of non–symbiotic N fixation in the nutrition of these two cereals has been studied. Wani (1988) reviewed research on development of assay techniques for measurement of biological N fixation, environmental and plant-related factors affecting N fixation, isolation and screening of N fixing bacteria and screening of sorghum and pearl millet genotypes to find out genotypic differences in N fixation. The research results on the response to inoculation in these two cereals were not consistent. Wani *et al.* (1988) concluded that responses to inoculation are mainly attributable to increased plant N uptake which could be the effect of growth–promoting substances secreted by bacteria. Thus the contribution from BNF may be small. Subsequently, Lee *et al.* (1994) recorded that the mean nitrogenase activity (C_2H_2 reduction) in pearl millet throughout the growing period was <0.1% of that in pigeonpea, and that the activity in sorghum was only 1.3% of that in chickpea. Nitrogen balance studies in pots, using pigeonpea as reference, and measurement of natural abundance of ^{15}N ($\delta\ ^{15}N$) using groundnut as reference did not show N gains by these cereals inoculated with N–fixing bacteria.

Fertilizer–N

Uptake kinetics of ammonium and nitrate in legumes and cereals

Influx isotherms were obtained for nitrate and ammonium from three legumes, pigeonpea, chickpea and groundnut, and three cereals, sorghum, pearl millet, and maize. The transition in influx isotherms for both nitrogen sources was found to be within the concentration range (0.05–2.5 mM) tested. There were significant differences in K_m and V_{max} for ammonium between legumes and cereals. The difference in the kinetic properties for nitrate uptake between the two groups of plants only became apparent at the higher concentration tested. Legumes translocated absorbed nitrate and ammonium to shoots more rapidly than cereals. Results showed that there are significant differences in uptake and translocation of ammonium and nitrate between legumes and cereals (Rao *et al.* 1993).

Soil solution nitrogen dynamics

Nitrate concentration in the soil solution extracted by means of ceramic porous cups was found to be highest at the beginning of the cropping season and decreased rapidly thereafter. Only a trace of nitrate was found in soil solution at 50 days after sowing under a sole sorghum crop while under sole pigeonpea detectable amounts were found even up to 70 days after sowing (Adu–Gyamfi *et al.* 1996).

Phosphorus

Behaviour of Phosphorus in Vertisol

Phosphorus deficiency is a major nutritional disorder which often constraints productivity of Vertisols. In collaboration with Central Research Institute for Dryland Agriculture (CRIDA), ICAR, we assessed the P status of these Vertisols and studied the reasons for poor response to P application of dryland crops grown on these soils.

Phosphorus adsorption/desorption studies

Five benchmark locations (Akola, Bijapur, Hyderabad, Solapur, and Kovilpatti) were selected. A high P adsorption capacity (156 $\mu g\ g^{-1}$ soil) was observed for Solapur soil and lowest P adsorption capacity (42 $\mu g\ g^{-1}$ soil) was observed for Kovilpatti soil at 0.2 $\mu g\ ml^{-1}$ of P at equilibrium in solution. In the Vertisol profiles the major (58%) part of the adsorbed P was desorbed by 0.5 M $NaHCO_3$ during two successive desorptions. More P was desorbed during the first desorption than during the second desorption. The adsorption data were fitted well with the Freundlich and modified Freundlich and Dublin equations. The Tempkin equation did not fit well to this data set. The Vertisol samples from Akola were high in clay (73%), and calcium carbonate (13.3%) leading to high P fixation (97% of added P), although 57% of the added P was desorbed. Vertisol of similar origin contained less clay (61%) and calcium carbonate (3.3%). Despite this, 99% of added P was fixed and 57% was desorbed. Soils at Bijapur originated from basalt trap containing 71% clay and high calcium carbonate (18.9%), resulting in 96% fixation of added P. However, 53% of added P was released with desorption. Soils at Kovilpatti originated from granite and had low clay (47%), moderate calcium carbonate (9.5%), had lower P fixation capacity (83%), and high (66%) P desorption capacity.

Role of Vesicular Arbuscular Mycorrhiza (VAM) in P Nutrition

Vertisol

Vesicular arbuscular mycorrhizal fungi form mutualistic associations with most agricultural crops. VAM has been associated with increased plant growth and enhanced accumulation of plant nutrients (mainly P, Zn, Cu, and S) through greater soil exploration by mycorrhizal hyphae. Four benchmark locations were evaluated for native VAM spore numbers in soil and percent root colonization of the crops grown. Vertisol samples from Akola contained far higher numbers of VAM spores (45 g^{-1} soil) than the spore numbers at other locations (9 to 16 g^{-1} soil). Soil samples from a farmer's field at Akola (58 vs 45) and Solapur (16 vs 9) contained significantly more VAM spores than the research farm samples. At Bijapur and Kovilpatti spore numbers were similar from farmer's and research farm samples. At Akola, root colonization by VAM fungi in pigeonpea was higher (37%) for the crop grown on the farmer's field than the pigeonpea grown on the research farm (18%). At Kovilpatti, cowpea roots were colonized by VAM to a greater extent (63%) than the greengram roots (31%). Further, application of P had no significant effect on VAM colonization of chickpea, cowpea, greengram, and pigeonpea at research farm trials. Crop yields of cowpea at Kovilpatti and chickpea at Solapur were not increased significantly due to inoculation with VAM fungi under field conditions. Pot experiment studies using chickpea genotypes grown in Vertisol showed significant responses in terms of increased plant dry matter only in case of long duration genotypes such as ICC 435, ICCV 6, and Rabat. However, no such response to applied P levels was observed in early maturing genotypes such as Annigeri and ICC 640.

Alfisol

VAM spore numbers varied between cropping systems. In an Alfisol, the highest number of VAM spores was under castor followed by pigeonpea, sorghum, and groundnut. Short fallowing between harvesting the crop and sowing of the next year crop reduced the VAM spores from 31 to 16 g^{-1} soil. The deep tillage bare treatment increased mycorrhizal colonization of roots (58%) as compared to 44% in the zero tillage bare treatment. Similar effects of deep tillage on increased VAM colonization of roots were observed in the case of mulch treatment. However, no effect of tillage on treatments receiving FYM was observed (Wani and Lee, 1995).

Phosphorus Management in Postrainy Season Sorghum

An experiment was conducted to determine the feasibility of balance-based fertilizer recommendations in postrainy season sorghum on Vertisols. It is often argued that under the receding moisture conditions of a postrainy crop season, fertilizer application has little affect on yield. A relatively immobile nutrient such as P is mainly concentrated in the plow layer, and this layer dries out quickly. This leaves a relatively short time for the crop to take up the required amount of P. In the experiment, P uptake ceased 75 days after sowing. There was no indication that P uptake was slowed down by drying the surface layer, which occurred earlier than 75 days.

Significant differences in yield and P uptake were observed between the fertilized and non-fertilized treatments. The basis for the final difference in P uptake and yield between fertilized and nonfertilized sorghum was laid in the first week of crop growth. The P influx which is the uptake per unit root length or surface area was nearly equal for both treatments at later stages (Table 30), indicating that plants adapted their P uptake mechanism to low P concentrations in the surrounding soil solution. The main difference occurred within the first three weeks when the influx was 4.6 times higher in the fertilized treatment. This allowed the plants in the fertilized treatment to grow faster and develop a larger root system. At later stages, uptake in the fertilized treatment was still higher than in the non-fertilized treatment but that was only due to the greater root length. The influx was the same. The observed grain yield difference of 1.2 t ha^{-1} between the fertilized and non-fertilized treatment clearly indicates how important sufficient P availability is during the first three weeks, even in the postrainy season, under receding moisture conditions.

Results indicated that fertilizing to replace the amount of P removed by the crop was sufficient to achieve the maximum grain yield of 3.5 t ha^{-1} at a soil test greater than 3 mg P kg^{-1}

(Olsen–P).

There was some indication that organic P was an important source for the nutrition of sorghum under conditions of low P availability. Taking only the inorganic P in soil solution into consideration, the Claassen–Barber nutrient uptake model underestimated P uptake (Fig. 19a). When the organic soil solution P was taken into account the fit of the model improved considerably (Fig. 19b) (ICRISAT, 1995).

Iron Chlorosis in Groundnut on Calcareous Soils in India

Iron chlorosis has been reported as a major production constraint in groundnut grown on calcareous and/or alkaline soils in several parts of India. To quantify yield losses due to Fe chlorosis, on–farm trials at two village sites prone to Fe chlorosis were conducted. The study indicated that Fe chlorosis can cause yield reductions of 32% for pod, 18% for fodder and 25% for total dry matter production. The results also indicated that neither of the two genotypes tested were Fe–efficient. Foliar sprays with $FeSO_4$ were more effective than Fe EDTA for correcting Fe chlorosis. These results have prompted the ICRISAT groundnut breeding program to initiate screening for Fe–efficient genotypes (Potdar and Anders, 1995).

Management of Farmyard Manure (FYM) in India's Semi–Arid Tropics – Farmers Perceptions and Practices:

Farmyard manure is an integral part of livestock–based farming systems and represents a potentially large resource for improving soil fertility. This study was undertaken with the principal objectives of identifying farmers' perceptions and management practices with FYM and determining key factors influencing FYM use.

Farmers perceived FYM to have multiple effects on soil, crop growth, insect pests and plant diseases. The duration of these effects were perceived to be longer than one growing season. Improvement in soil physical properties was the most often cited effect of FYM application. Rainfall, population and composition of livestock, cropping system, and area under irrigation were the greatest influences affecting FYM use.

Inadequate supply of FYM constrains farmers' fertility decisions. Irrigated land is favored over rainfed land for applying FYM and cash crops receive higher fertility inputs compared to food crops. Combined applications of fertilizer and FYM were more common on irrigated crops.

FYM quality varied in the surveyed villages. Nearly 30% of all samples were at risk of promoting N immobilization if applied to soil. The length of time organic materials were left in the dung pit and pits location affected FYM quality. On–farm experiments showed no significant crop response to FYM applications up to 20 t ha^{-1} despite a positive yield response to equivalent N fertilizer applications (Motavalli and Anders, 1991).

Screening of Pigeonpea Genotypes for Salinity Response

Soil salinity can be a major constraint to pigeonpea in the regions where it is predominantly grown. Solution culture experiments were conducted in the greenhouse and controlled environment chamber to assess the extent of genetic variation for salinity tolerance in the germplasm of pigeonpea and its wild relatives. The extent of variation in salinity response among cultivated pigeonpea appeared too limited to warrant genetic enhancement of salinity tolerance. Among the wild relatives of pigeonpea, various species of *Atylosia*, *Rynchosia* and *Dunbaria* showed a wide range of variation in their salinity tolerance.

In continuation of their research, the F_1 hybrids of salt-tolerant *A. albicans*, and salt-sensitive *C. cajan* were screened for salinity tolerance. The results demonstrated the feasibility of transferring salinity tolerance from *A. albicans* to *C. cajan*. The physiological attributes conferring salinity tolerance in *A. albicans* and the F_1 hybrids include Na and Cl retention in the roots and limited translocation to the shoots, high K selectivity and maintenance of transpiration rate under saline conditions (Subbarao *et al.* 1990, 1991).

Nutrient Research at ISC

West African soils have an extremely low supply of mineral nutrients. A lack of volcanic rejuvenation or alluvial deposition has caused the region to undergo various cycles of weathering, erosion, and leaching which leaves the soils poor in many nutrients.

Intensive cropping without restoring fertility depletes the nutrient base of the soils. This results indirectly in damaged soil structure, reduced water infiltration and increased water and wind erosion. Nutrient balances reported elsewhere are negative for many cropping systems with off-take greater than input, indicating that farmers are mining their soils. For example, nutrient mining in Senegal was estimated at 14 kg N, 3.5 kg P and 11.6 kg K ha^{-1} yr^{-1} in 1983, and are projected to be 20 kg N, 3.5 kg P and 16.4 kg K ha^{-1} yr^{-1} by the year 2000. In 1993 alone, from a total of 6.6 million ha of land cultivated in Burkina Faso, soil nutrient mining amounted to a loss of 95,000 tonnes of N, 12,240 tonnes of P and 65,570 tonnes of K (Bationo *et al.* 1995) equivalent to US $159 million of N, P, and K fertilizers. In Mali, it was estimated that farmers extract on average 40% of their agricultural revenue from soil mining. The present food shortage in this area is linked to poor soil fertility as numerous studies have shown that it is the supply of plant nutrients that determine land productivity.

Unlike catastrophes such as drought and locust infestation, soil fertility decline is gradual. To alleviate the food shortage it is urgent to develop sustainable resource management technologies which will enhance food production and preserve the natural resource base.

Nutrient mining by crops, which are increasingly being cultivated on marginal lands, is promoting soil and environmental degradation at an alarming rate. However, for the sub-region, whose rate of fertilizer use is among the lowest in the World, about 10 kg ha^{-1} (compared to 43 kg ha^{-1} Latin

America), the recent devaluation of the CFA franc will further reduce fertilizer use and increase land degradation. The consequences of this scenario on the sub–region's food security and fragile environment will be severe. To halt this trend, alternative practices that also promote higher production per unit area on a sustainable basis are needed. Organic and inorganic fertilizers will play a critical role in this endeavor.

Nitrogen

Nitrogen (N) Fertilizer Sources and Management

The general objective of the N research program has been to improve the efficiency of N fertilizer use in the West African Semi-Arid Tropics environment. The N research has focused on the assessment of N needs of the primary food crops, and the choice of the appropriate fertilizer sources and management techniques required to meet these needs.

In field trials at Sadore, using ^{15}N techniques, there was a strong effect of N source and placement on N uptake by the grain and the stover of pearl millet. Plant uptake of applied N from point-placed calcium ammonium nitrate (CAN) was almost three times that of urea applied in a similar manner. A 57% reduction in fertilizer N uptake by the grain was found when CAN was broadcast rather than point-placed (Table 31).

Early in the growing season, the plant's requirement for N fertilizer is low. However, after stem elongation, crop N needs increase greatly. It is important to apply N in a manner that matches the crop N requirements. If N is applied too early, when the plant cannot use it, N can be lost due to leaching or volatization. Conversely, if N is applied late, it may not be taken up in time to influence grain yield. A ^{15}N experiment on sorghum illustrating this trend was conducted in southern Niger. In this trial, one-half of the N was applied 2 weeks later after planting and the remainder 4 weeks later. Some of the plots received ^{15}N-urea during the first application but received ordinary urea during the second application. The situation was reversed for the remaining plots. Total recovery in the plant plus soil fractions was the same in both treatments and averaged 67% of the N applied for the two treatments. However, the distribution of ^{15}N in the plant and soil differed greatly between N applications. In the basal application, 26% of the fertilizer N was taken up by the plant. The majority of the ^{15}N remained in the stover fraction, and only a small fraction was ultimately translocated to the grain. Conversely, uptake of N in the second split was 33% of that applied, the majority of which was found in the grain at harvest. Thus, the efficiency of the second split in terms of getting N into the grain was more than twice that of the basal application.

The ^{15}N distribution in the soil also differed between treatments. N applied early in the season tended to move deeper into the soil profile. For both treatments, the majority of the ^{15}N was found in the surface 0-15 cm layer (Christianson and Vlek, 1991).

In 1991 and 1992, another ^{15}N-based experiment was conducted in southern Niger to determine the efficiency of N uptake by sorghum from urea, ammonium sulfate, and potassium nitrate. N was applied at the rate of 60 kg N ha^{-1}. It is generally recommended that N-fertilizers be applied to sorghum in two equal splits at 14 days after sowing (DAS) and 42 DAS to maximize N efficiency. Using ^{15}N-labelling made it is possible to determine N-use efficiency from the two splits. The data indicate that N had a strong effect on sorghum, but for both years there was no significant difference between the three sources of N-fertilizers. The values of N derived from fertilizers were always lower for urea than the other two sources. From the values of ^{15}N in the grain and stover, it was concluded that N applied as urea is inferior to the two other sources. Although there was no difference between the three sources in terms of grain and stover production at the rate of 60 kg N ha^{-1} it is assumed that less N fertilizer will be needed from ammonium sulfate and potassium nitrate for optimum crop production. In 1991 N use efficiency (NUE) significantly improved from 44% for urea to 76% for potassium nitrate and in 1992 from 36% for urea to 61% for KNO_3. A high loss of N from urea due to urea hydrolysis, followed by nitrogen volatilization, could be the main reason for the lower values of NUE that are found in sandy soils. In many countries in Francophone Western Africa, most of the nitrogen in the imported complex fertilizers is in the form of NH_4. It is believed that N in the form of NO_3 will be more easily lost by leaching. The results of this research show that fertilizer use efficiency is slightly higher with KNO_3 as compared to $(NH_4)_2SO_4$. There is a need to undertake this type of research in the main agroecological zones and with the most important crops in order to convince the fertilizer importers to change their fertilizer import policies.

A trial was established at Sadore to study the interaction between P and lime on pearl millet. P was applied at 0, 8.7, and 17.5 kg P as single superphosphate (SSP) and lime at 0, 250 and 500 kg ha^{-1} as dolomite. In 1992, ^{15}N-labelled fertilizers were applied to microplots at 30 kg ha^{-1} on control plots for lime and phosphorus, on plots of 500 kg lime per hectare, on plots receiving 17.5 kg P ha^{-1} and on plots receiving 17.5 kg P ha^{-1} plus 500 kg lime ha^{-1}. There was an effect from the application of both P and lime but no evidence of an interaction. Without lime and P application, NUE was only 14% compared with 33% when P was applied. Also the application of lime and fertilizers significantly increased the use of soil N from 11 to 38 kg N ha^{-1} indicating that better root growth improved the use of mineralized soil N by the crop. through leaching.

In 1992, at Bengou, Niger in the Sudanian zone, we studied the interaction between P and N for sorghum production. P was applied at 0, 6.6, 13.2 and 19.7 kg P ha^{-1} and N was applied at 0, 15, 30, 60 and 90 kg ha^{-1}. In order to determine the effect of P application on N use efficiency, ^{15}N-labelled fertilizers were applied to microplots within the 60 kg N ha^{-1} treatments. There was a very strong effect of both N and P on sorghum production but no significant interaction between N and P. Although ^{15}N recovery was not significantly increased with P application of 19.7 P ha^{-1}, as for the case of pearl millet in the Sahelian zone, application of P fertilizers increased the NUE of mineralized soil N which could be lost through leaching.

N Dynamics in Different Cropping Systems

Despite the need to apply chemical fertilizers for high yields, the use of fertilizers in West Africa is limited by lack of capital, inefficient distribution systems, poor communication and other socioeconomic factors. Studies with ^{15}N have shown that uptake efficiency of N in the Sudano–Sahelian zone is low and losses of applied N fertilizers in the order of 58% are common. These losses can be higher under farmer's conditions (Christianson *et al.* 1990). The high losses from N fertilizers and the other factors limiting the increased use of fertilizers make it necessary to look for cheaper ways to improve soil fertility and productivity. One possibility is rotation of cereals with legumes. Legumes are known to increase soil fertility through their N–fixing capacity. Groundnut and cowpea are the most widely grown grain legumes in the Sudano–Sahelian zones. These legumes are often intercropped with pearl millet in the Sahelian zone and with sorghum in the Sudanian zone.

Continuous cropping of pearl millet resulted in lower yields across all N rates than when millet was rotated with cowpea or with groundnut in the different agroecological zones (Bationo *et al.* 1994). Even with 45 kg N ha^{-1}, yield of pearl millet for the continuous monoculture was lower than when no N was applied when cereal followed cowpea or groundnut in a rotation at Tara (Fig. 20).

The positive effect of rotation on cereal yields has usually been attributed to the added N from legumes in the rotation, but also to improvement of soil biological and physical properties, and the ability of some legumes to solubilize occluded P and highly insoluble calcium-bound P by legume root exudates. Other advantages of crop rotation include soil conservation, organic matter restoration, and pest and disease control.

Recovery of N from fertilizer applied to different cropping systems was determined by applying labelled N fertilizers to microplots of pearl millet where millet was grown continuously in rotation with cowpea, in rotation with groundnut, intercropped with cowpea, and intercropped with groundnut. NUE was greater when millet was rotated with cowpea than when grown continuously as a pure crop. At Sadore in 1990 NUE was 20% for continuous pearl millet cultivation and 28% when pearl millet was rotated with cowpea. For both Bengou and Sadore, N derived from the soil was better used in rotation systems than with continuous millet. For example at Bengou in 1990, nitrogen derived from the soil was 39 kg N ha^{-1} in continuous pearl millet cultivation and 62 kg N ha^{-1} when pearl millet is rotated with groundnut.

N-fixation by Cowpea and Groundnut

Previous research has shown the importance of N, P, and organic amendments such as manure, for the improvement of soil productivity in the Sahelian zone. There is increasing evidence of the importance of molybdenum (Mo) for crop production. The availability of Mo decreases with soil pH, and for the acid sandy soil of the Sahel, Mo deficiency could be a problem for crop production. Mo in the soil has been found to be insufficient to meet the Mo requirement for N-fixation of groundnut and cowpea.

Recently, research at the ISC has shown that carbofuran reduced plant parasitic nematode population in the soil and improved the yield of groundnut. In 1991, 1993, and 1994, at Sadoré, we studied the effect of N, P, manures, carbofuran, and Mo on pearl millet, groundnut, and cowpea. The results showed that N, P and manure increased yield and that P is the major constraint to crop production. The yield response to N for legumes indicates that the predominantly sandy soils of the Sahelian zone may be deficient in Mo. There is a positive interaction between P and manure, the effect of manure being less in the presence of P application. This suggests that high yields could be obtained with the combination of smaller quantities of P and manure.

The interaction between N and carbofuran indicated that the response to carbofuran can be obtained only after the addition of N. In cases where the interaction between N and Mo was significant, a greater response to Mo was observed in the presence of N than when N was not applied. This suggest that legumes need a small amount of N as a starter fertilizer. In cases where the interaction between manure and Mo was significant, it was observed that when manure was applied, the yield was less affected with the application of Mo than when manure was not applied. This suggests that manure contains a sufficient amount of Mo as required by the crop or that the increase in soil pH due to manure application will increase Mo availability.

Agricultural productivity could be dramatically increased with the improvement of soil fertility. For example, pearl millet grain yield in 1991 and groundnut fodder yield in 1993 increased five fold with the application of N, P, manure, carbofuran, and Mo. Although N, P, and manure are the most critical for yield enhancement, the application of Mo and carbofuran increased yields up to 70% over the control. The highest yields were obtained when both organic and inorganic fertilizers were applied in combination with control of nematodes.

In 1991, the isotopic dilution method was used to determine the N fixed by cowpea with treatments of Mo, carbofuran, manure, P and a combined treatment which was a mixture of all the amendments. N derived from the air (N_{dfa}) for cowpea varies from 65 to 88%, while for groundnut it varies from 20 to 75%. In the combination treatment cowpea stover fixed up to 89 kg N ha^{-1} whereas for the same treatment, groundnut fixed only 40 kg N ha^{-1}.

Phosphorus

Phosphate Rock (PR)

Although deficiency of P is acute in most of the West African soils, especially the sandy soils, very little P fertilizer is used by farmers due to high cost. Previous research has evaluated the use of the ground form of PR for crop production. A systematic effort has been made to investigate if these PRs could be used for direct application as economical alternatives to more expensive imported water-soluble P fertilizers for certain crops and soils.

The agronomic effectiveness of PR depends on its chemical and mineralogical composition and soil and plant factors. The research program began therefore with the chemical and mineralogical characterization of the different West African PR deposits. This suggested that the agronomic effectiveness of most of the West African PRs would be low. Thus, only Matam (Senegal), Tilemsi (Mali) and Tahoua (Niger) PRs were considered efficiently reactive for direct application.

Meanwhile IFDC developed the " single step" technology for the partial acidulation of phosphate rock. This process increased availability of P in the unreactive PRs (Bationo *et al.* 1990, 1991, Table 32).

A long-term field study was conducted from 1982 to 1993 on a sandy Sahelian soil of Niger to evaluate the agronomic effectiveness and the profitability of various P fertilizers for pearl millet production. The P fertilizers tested were the finely ground PR from Parc-W, PR partially acidulated with H_2SO_4 at 25% and 50% (PAPR25, PAPR50), single superphosphate (SSP) and triple superphosphate (TSP). PR was applied annually (PRA) or once every three years (PRB). The major findings of this study were (i) partial acidulation increased the relative agronomic effectiveness of PR; (ii) relative agronomic effectiveness of TSP was on average 75% of SSP, due to development of sulfur deficiency (iii) for all P sources the residual effectiveness index is at least 50% after three years (iv) application of all P fertilizers was profitable (Table 33).

One of the major constraints to the direct application of PR is the risk of it being blown away due to finer size, and also the need to supplement it with other minerals, such as N, K, S, and eventually micronutrients. For unreactive rocks such as Parc-W PR, the mixture of PR with TSP by compaction (1:1 P ratio from each component plus urea and KCl) can increase the availability of PR in the product. Laboratory and greenhouse studies showed that the Fe_20_3 + $A1_20_3$ contents of PR can significantly hamper the water solubility and agronomic effectiveness of PAPR. In field experiments, it was concluded that Tahoua PAPR was undesirable because of its high Fe_20_3 + $A1_20_3$ contents and resulting low water-soluble P. Some of the water soluble-P in Tahoua PAPR was converted to citrate-insoluble P and thus became less available to the plant. The performance of the compacted products demonstrated that this is an alternative way to produce cost-effective P fertilizers.

Recovery of Fertilizer Phosphorus and Sulfur by Pearl Millet

The ^{35}S and ^{32}P labeled fertilizers and different methods of application were used to compare the recovery of fertilizer P and S from double superphosphate (a mixture of single superphosphate and triple superphosphate, containing both P and S), and compare double superphosphate with triple superphosphate (containing no S) to determine the response of millet to S.

Four types of fertilizer placement were tested: broadcast (B), broadcast and incorporated (BI), broadcast and ridged (BR), and hill-placed (HP). Fertilizers were applied at 8.7 kg P ha^{-1} (Bationo *et al.* 1995).

The broadcast and ridge treatment performed better than the other treatments (B, BI, and HP), but there was no difference between the other placement methods. The P recovery from fertilizer ranged from 10 to 22% in the first year and from 8 to 14% the second year. The lower P recovery in the second year was due to the residual effect of P applied previously. For both years, P recovery was lower when fertilizers were hill-placed (HP) than with the other three methods.

Lime and Mo

The main causes for the low fertility of acidic soils in West Africa are the Al and Mn toxicities and the deficiency or unavailability of P, Ca, Mg and Mo. These factors can act independently or together and can inhibit the survival and functioning of rhizobia, mycorrhizae and other soil microorganisms. Some investigators in the region have noted that the problems of low pH and high Al saturation increased with annual application of mineral fertilizers and that the problems were alleviated or even prevented in treatments containing manure application and mineral fertilizers.

In field studies of lime and P applied as SSP to sandy soils, it has been shown that the application of P and lime led to significant yield increase of legumes crops such as cowpea (Fig. 21). For the acid soils of the Sudanian zone, even with lime application, there is still a strong effect of Mo on cowpea fodder yield indicating that the soils are very deficient in total Mo.

Organic Amendments

In the Sahelian zone, Bationo *et al.* (1993) reported a strong interactive effect of crop residue (CR) application as mulch and fertilizer on pearl millet grain yields. Over the duration of the study, grain yields in the control plots without CR or fertilizers steadily declined. This indicates that the potential for continuous millet production is very limited in the absence of amendments like fertilizer and CR.

For the Sahelian zone, Michels *et al.* (1993) reported that the coverage of millet seedlings by wind blown soil severely hampered millet establishment, reduced subsequent growth and decreased grain yield by almost 50% compared to unburied plants. Michels (1995) showed that, compared to bare plots, CR application of 2000 kg ha^{-1} mulch reduced the amount of soil flux by 46% in 1991 and 48% in 1992.

Although the use of CR as mulch can reduce wind erosion, farmers burn whatever is left of their CR once their needs for fuel, animal feed, or housing and fencing have been fulfilled.

For the Sahelian zone, the optimum level of CR has been shown to be 2 t ha^{-1} (ICRISAT, 1993). McIntire and Fussell (1986) reported that on fields of unfertilized cultivars, grain yield of pearl millet averaged only 236 kg ha^{-1} and mean stover yields barely reached 1300 kg ha^{-1}. In village level studies on CR along a north-south transect in three different agro-ecological zones of Niger, surveys were conducted to assess farm level stover production, household requirements, and residual stover remaining on-farm. Results of these surveys showed that the average amounts of stover removed from the field by a household represent only between 2 to 3.5% of the mean stover production (ICRISAT, 1993). At the onset of the rains cattle grazing had reduced the residual stover on-farm to only 21% to 39% of the mean stover production. Unless stover production is increased at farm-level through the application of plant nutrients, it is unlikely that the recommended levels of CR could be available for use as mulch.

Increased biomass availability at farm-level is also a prerequisite for sustainable land use in the region. On-farm evaluation of CR availability clearly showed that the use of fertilizers allows farmers to increase stover yields. Despite the many competing purposes for which CR are used, the increased CR production led to significantly higher quantities being left behind to act as mulch in the subsequent rainy season (Bationo and Mokwunye, 1991)

The role of animal manures needs further attention. Within the ISC region, animals owned by farmers and pastoralists have traditionally been a source of manure for crops. Arrangements between farmers and pastoralists have provided for increased manure deposition on farmlands, but this practice has declined in many areas for several reasons. Currently there are insufficient animals to provide the manure needed.

Lessons Learned from Long-term Soil Fertility Management Trials

From research at the ICRISAT Sahelian Center, it has been concluded that in the Sahel the low soil fertility is a more limiting factor to crop production than rainfall (Bationo and Mokwunye 1991, Bationo *et al.* 1993).

Long-term experiments with and without chemical fertilizers and organic materials were initiated in the early 1960's by the Research Institute for Tropical Agriculture (IRAT), from which it has been concluded that mineral fertilizers can increase yields in arable farming systems in the Sudanian zone. However, it was found that in the longrun, the use of chemical fertilizers alone would lead to decreasing crop yields.

In the Sahelian zone pearl millet and cowpea yields were significantly increased by both fertilizer and CR application and the highest yields were obtained when fertilizers were combined with crop residue.

In the most years Sudano-Sahelian zone, application of CR alone or with chemical fertilizers failed to significantly increase pearl millet yields. The rate of decomposition of CR was much higher than in the Sahelian zone and likely parallel to the rate of nutrient release. Groundnut pod and fodder yields were significantly increased by both CR and mineral fertilizers in one year. The application of CR increased significantly the organic matter content of soil and the effective cation exchange capacity at the Sahelian site but not at the Sudano-Sahelian site.

For both sites the application of mineral fertilizers alone led to decreasing base saturation, decreasing pH and increasing Al saturation. The apparent contradictory results obtained in the response to CR application suggest that much needs to be done to investigate the mechanisms of CR effects on crop growth in different climates and to monitor more closely the dynamics of organic matter turnover in the different soils.

In addition, cultivation of crops on marginal lands increases soil and environmental degradation. For the Sahelian zone, continuous cultivation reduced in the organic matter levels even with the application of fertilizers. The effective cation exchange capacity (ECEC) is more related to organic matter than to clay indicating that a decrease in organic matter will decrease the ECEC and subsequently the nutrient holding capacity of soils. Soil acidification associated with continuous cultivation is a common phenomenon and application of organic residue is one way to alleviate aluminum toxicity.

Collaboration and Linkages

The following collaboration has existed during the period since 1991:

Government of Japan at IAC–ongoing collaboration in P nutrition of legumes, and N and root dynamics of pigeonpea intercropping.

IFDC at ISC–ongoing collaboration in research on soil fertility and plant nutrition.

NARS (primarily CRIDA, APAU, Maharashtra Agricultural Universities, and CAZRI) in India and CARI in Myanmar, mostly with respect to the ISP1, ISP2 and ISP3 projects, ongoing.

APSRU (Agricultural Production Systems Research Unit of Australia) – initiating collaboration on simulation modelling of farming systems, primarily in the area of farmyard manure and fertilizer management.

University of Hamburg–past collaboration on organic matter turnover.

University of Hohenheim–past collaboration on water relationships and wind erosion.

Future Plans

The primary focus is expected to be on integrated nutrient management, which we understand to mean the management of crop nutrition through the conservation of soil organic matter and inputs of organic materials in combination with balanced inputs of chemical fertilizer.

Following restructuring, the present view of the future relates to the projects. In the case of nutrient management, this means ISP 1 (in Rajasthan in Asia and PS 13 in West Africa), ISP 2 (Alfisols and similar soils in India and Myanmar and PS 14 in West Africa), ISP 3 (Vertisols and similar soils in India, Myanmar and PS 15 and 16 in West Africa) and ISP 4, and strong collaboration with NARS. This signals also a change in research approach from on-station, researcher-driven experiments to on-farm, farmer+researcher-driven experimentation. Multidisciplinary teams (including soil fertility specialists and NARS cooperators) are working in selected villages to identify farmer constraints, and then to discuss possible solutions with farmers. In some cases, farmer-driven experiments will be used to test solutions; in other cases, researcher-driven research, either on-farm or on-station (depending on the nature of this research) will be needed.

For example, in ISP 2 farmer constraints have been identified by PRA techniques in selected villages. On-farm studies have commenced aimed at establishing approximate nutrient balances. Further farmer-driven experimentation would commence in 1996. The research approach would be similar in ISP 1 and ISP 3. A key to this research is close collaboration with genetic resources scientists, agronomists and socioeconomists.

Two long-term experiments continue on Vertisols at IAC. One small plot cropping systems experiment has run for 12 years and is now providing interesting information on soil fertility changes and effects of disease. We suggest continuation with frequent review and see this experiment as even more valuable given the new emphasis on cropping system simulation.

The Vertisol watershed experiment which has run in different forms since 1975 has important soil fertility and crop nutrition implications. Some treatments of interest are essentially unchanged since 1975 and have the potential to provide vital information on long-term soil fertility changes which in turn will be invaluable for modelling. In West Africa, in cooperation with INRAN (Institut National du Recherche Agronomique du, Niger) and the Soil Management CRSP of USA, we have initiated nutrient management studies in a watershed in Tanda, Niger.

Simulation modelling collaboration is seen as important to future activities. Specific contributions are seen in helping the development of APSIM model components for nutrient cycling through animal manures and for P uptake and use. General contributions are initially through participating in testing of APSIM, and later through using APSIM as an aid to on-farm and on-station research.

Table 27. Fractional contribution (%N_{dff}) and amount (N_{dff}) of plant N derived from fertilizer, and fertilizer use efficiency (*FUE*) of sorghum and pigeonpea as sole crop and intercrop cropping systems (cs).

Treatments	Sorghum			Pigeonpea		
	%N_{dff}	N_{dff} (kg ha^{-1})	FUE (%)	% N_{dff}	N_{dff} (kg ha^{-1})	FUE (%)
Sole crop						
N25	8.0	2.8	11.2	1.9	4.5	17.9
N50	17.2	10.5	20.9	3.3	9.2	18.4
N100	27.6	21.5	21.5	12.8	35.2	35.2
Intercrop						
N25	9.9	3.7	14.7	0.5	1.0	4.0
N50	17.7	10.5	21.0	1.1	1.9	3.8
N100	32.1	20.5	20.5	2.4	3.5	3.5
Coefficients of variations (%)						
N	10.3	35.3	24.9	58.2	63.9	51.8
CS	31.1	34.0	27.2	60.2	72.4	59.7
Statistical significance						
N	***	**	NS	*	**	NS
CS	NS	NS	NS	**	**	**
N x CS	NS	NS	NS	*	*	NS

Source: Tobita *et al.* (1994).

Table 28. Nitrogen balance sheet[a] for different cropping systems on an Alfisol, Patancheru, India

Cropping system[b] by year		Import (kg ha^{-1})[c](A)				Export (kg ha^{-1})[c] (B)		Balance (kg ha^{-1}) (A)-(B)
		Fertilizer		Leguminous[d] N_2-fixation		Harvest[e]		
1991	1992	1991	1992	1991	1992	1991	1992[f]	
S/P	C	60	60	0+80	0	88+68	66	-22
C	S/P	60	60	0	0+46	64	93+46	-37
G/P	C	18	60	90+50	0	108+56	72	-18
C	G/P	60	18	0	102+82	65	141+75	-19
P	C	18	60	121	0	115	66	+18

[a]N balance calculated based on main import and export sources of N
[b]S/P = Sorghum intercropped with pigeonpea, C=castor, G/P=groundnut intercropped with pigeonpea, and P=sole pigeonpea
[c]Each value within a binomial corresponds to the crop in intercrop
[d]Including atmosphere-derived N (fixed N) in leguminous roots.
[e]Assumed that groundnut roots were exported by harvest
[f]N contents in mini-plot grown sorghum, pigeonpea, and groundnut were used to calculate total N in the harvest for 1992.
Source: Lee *et al.* (1993).

Table 29. Total N content (μg g^{-1}) and organic C (%) of the 0-15 cm depth of soil under different cropping systems

Rotation[a]	N			C		
	1983	1991	Change	1983	1991	Change
Legumes every year						
S/PP-S/PP	546	686	140	0.56	0.65	0.09
S/PP-S+CP	566	635	69	0.57	0.64	0.07
S+CP-S+CP	536	561	25	0.60	0.48	0.12
Legumes in alternate years						
C/PP-S+SF	543	640	97	0.53	0.58	0.05
S/PP-S+SF	559	610	51	0.56	0.56	0.00
S+CP-S+SF	540	548	8	0.54	0.47	0.07
N0 legume						
S+SF-S+SF	537	513	-24	0.54	0.43	0.11
Standard error ±	19.9	18.0		0.030	0.021	

[a]S/PP = Sorghum/Pigeonpea; S = Sorghum; CP = Chickpea and SF = Safflower.

Table 30. P-influx of sorghum (M 35-1) with P-fertilizer application (P-500: 500 kg P ha^{-1}) and without P-fertilizer application (P-O).

	P-O	P-500
Days after sowing	x 10^{-14} mol cm^{-1} s^{-1}	
0 - 26	0.11	0.47
26 - 40	0.93	0.86
40 - 54	1.21	1.10
54 - 75	1.13	1.80

Table 31. Recovery ^{15}N fertilizer by millet applied at Sadore, Niger, 1985.

N Source[a]	Application method	^{15}N Recovery			
		Grain %	Stover	Soil	Total
CAN	Point incorporated	21.3	16.8	30.0	68.1
CAN	Broadcast incorporated	10.9	10.9	42.9	64.7
Urea	Point incorporated	5.0	6.5	22.0	33.5
Urea	Broadcast incorporated	8.9	6.8	33.2	48.9
Urea	Point surface	5.3	8.6	18.0	31.9
SE		±1.2	±2.0	±1.9	±2.4

[a]CAN = Calcium ammonium nitrate.

Table 32. Agronomic effectiveness of sulfuric acid-based 50% partially acidulated West African phosphate rocks.

Phosphate rock source	Soil order	Crop	Relative agronomic effectiveness (%)
Togo 50% PAPR	Alfisol	Maize	90.0
Togo 50% PAPR	Ultisol	Maize	66.7
Togo 50% PAPR	Oxisol	Maize	108.9
Kodjari 50% PAPR	Alfisol	Maize	84.1
Kodjari 50% PAPR	Alfisol	Sorghum	81.3
Kodjari 50% PAPR	Alfisol	Millet	108.9
Parc W 50% PAPR	Alfisol	Millet	93.4

a. SSP + 100%

Table 33. Relative agronomic effectiveness (RAE)[1] of phosphate rock (PR) over 10 years

P sources[2]	Grain	TDM[3]
PRA	50	48
PRB	46	42
PAPR 25	60	54
PAPR 50	70	71
TSP	75	74
SSP-N	58	56

1. $$\text{RAE} = \frac{\text{Yield of P source - Yield of control}}{\text{Yield of SSP - Yield of control}} \times 100$$

2. PRA = PR applied annually; PRB = PR applied once every three years; PAPR 25 and PAPR 50 = PR acidulated with H_2SO_4 at 25% and 50%, respectively; TSP = Triple superphosphate; SSP-N = Single superphosphate.

3. TDM =Total dry matter yield.

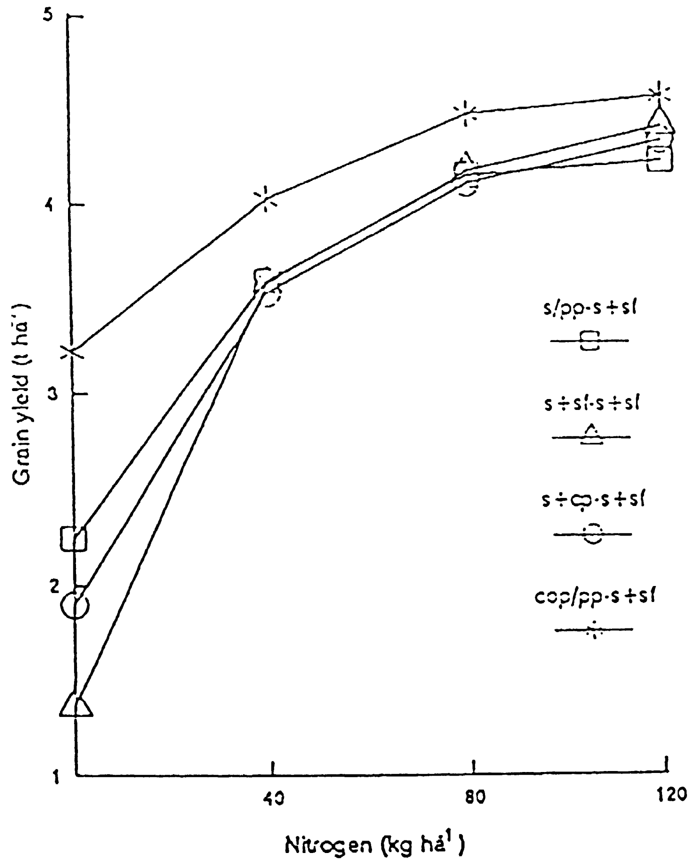

Fig. 18. Mean grain yield of sorghum grown in rainy seasons (1983-92) succeeding different cropping system in previous year. ICRISAT, Patancheru (2 year crop rotation) S - sorghum, PP - pigeonpea, SF - safflower, CP - chickpea, COP - cowpea, / - intercropped, + - sole crop grown during postrainy season.

Source: Rego and Burford (1992).

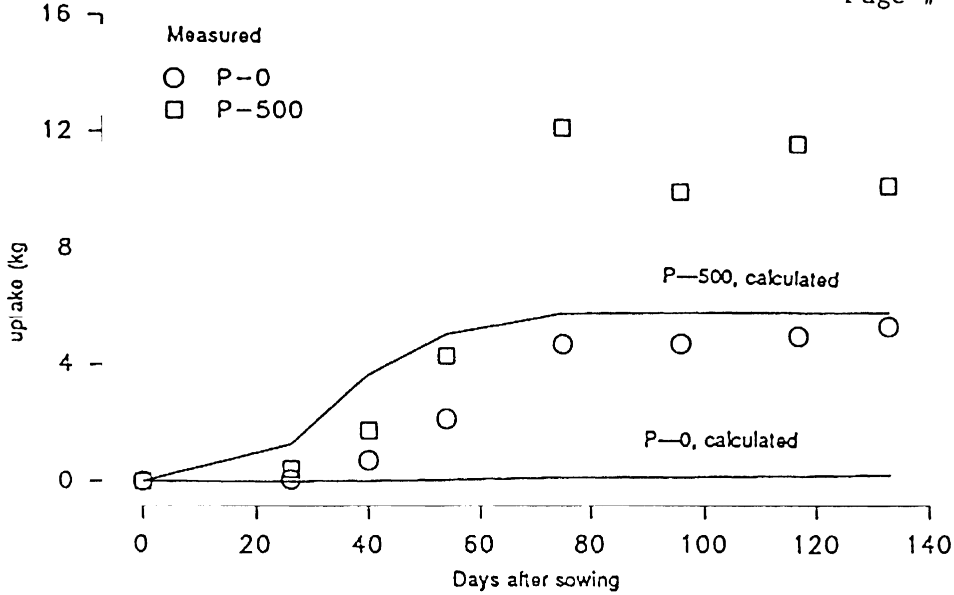

Fig. 19a. Measured and predicted P uptake of sorghum (M 35-1). Phosphate uptake calculated without taking organic P in soil solution into account.

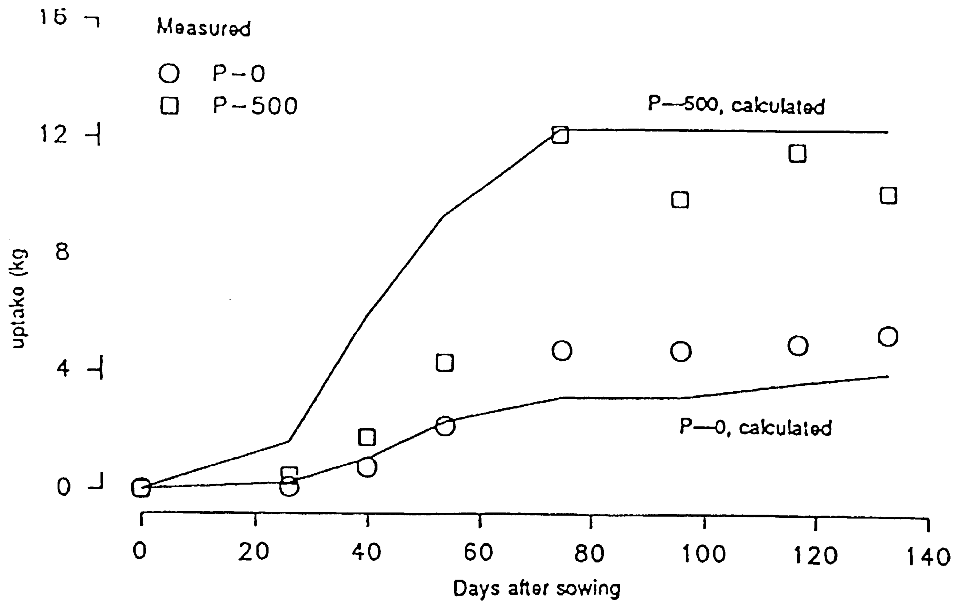

Fig. 19b. Measured and predicted P uptake of sorghum (M 35-1). Phosphate uptake calculated by taking organic P in soil solution into account.

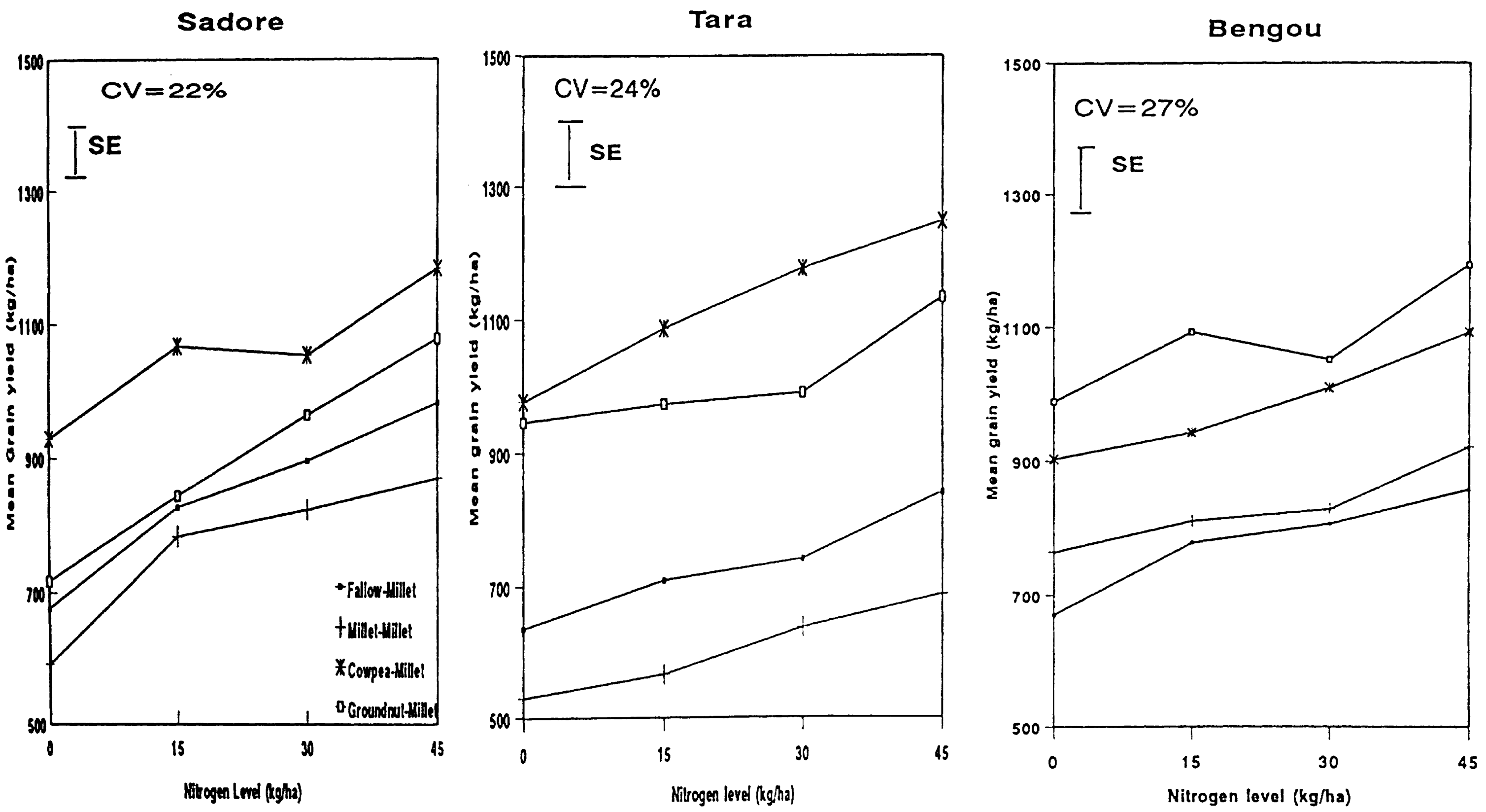

Fig. 20. Effect of nitrogen and cropping systems on pearl millet grain yield at Sadore, Tara and Bengou, Niger, Means over 4 years (1989 to 1992).

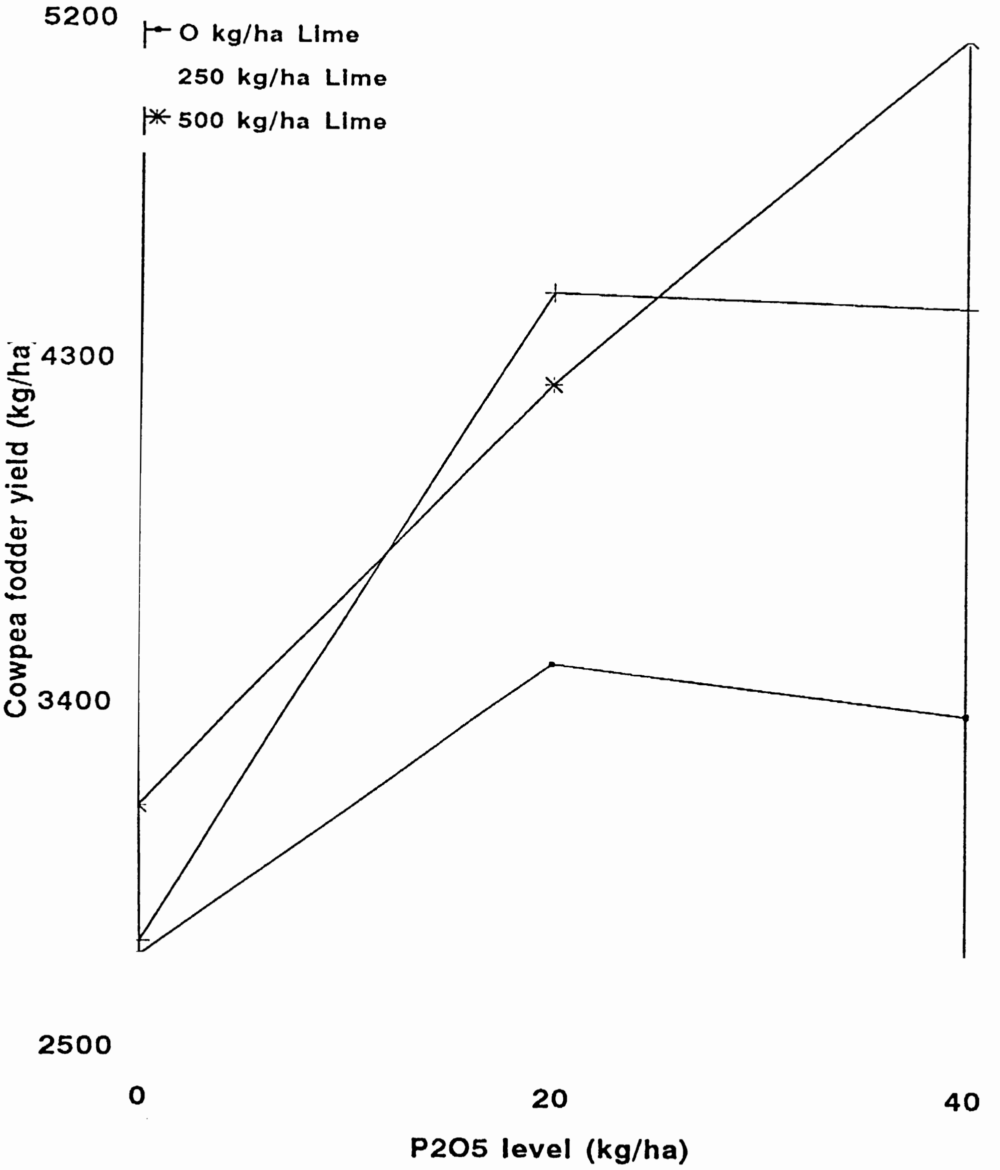

Fig. 21. Phosphorus and lime interaction on cowpea, Sadore, Niger, 1994.

WATER AND NUTRIENT INTERACTIONS

K.K. Lee, W.A. Payne, A. Bationo and M.C. Klaij

Water and nutrients are two major factors that determine crop production. In wet regions or in fertile soils, it may be possible that nutrients alone or water alone dictate crop production. However, in the semi-arid tropics, both water and nutrients limit crop production because most of the soils in this region are deficient in one or more nutrients and receive scarce and erratic rainfall.

It is well known that interactive effects exist between water and nutrient on crop growth, nutrient-use efficiency or water-use efficiency. The research on water x nutrient interaction is essential for increasing and stabilizing crop production, and for maximizing the return from inputs of fertilizer and irrigation. Despite its obvious importance, far fewer studies on this interaction have been conducted at ICRISAT, than those on either nutrient or water alone.

Water x Nutrient Interactions

Vertisol

Biomass and Light

Sorghum (cv SPH 280) was grown in the postrainy-season at IAC with and without irrigation and at 6 levels of nitrogen (N) from zero to 150 kg ha^{-1} applied before sowing. Above-ground biomass was measured weekly. Root biomass was measured every two weeks. Interception of solar radiation was monitored continuously in all treatments.

Leaf expansion was strongly affected both by water and by N (Fig. 22), whereas specific leaf area was almost independent of treatment. In the irrigated treatment, the biomass radiation coefficient (e) for the main growth period was almost independent of N application at 1.3 to 1.4 g MJ^{-1} and was also independent of leaf nitrogen. A decrease of radiation interception with decreasing N was the main source of yield differences. Without irrigation, biomass, yield, e and leaf N were all maximal at 60 kg ha^{-1} N (Rego et al., 1996).

At 33 DAE, root mass was almost independent of N application whether water was applied or not but was somewhat smaller with irrigation. Later, root, leaf, and panicle mass all responded to N and to water but stem mass was unresponsive to N with irrigation. There was evidence of translocation from stem to grain in most treatments. Maximum grain yields were obtained at 90 kg ha^{-1} N in both treatments; 3.9 t ha^{-1} with irrigation and 3.2 t ha^{-1} without.

Water Extraction and Biomass Production

During rainless weather following a monsoon, sorghum (cv SPH 280) was grown either unirrigated or irrigated for 7 weeks after emergence. N was applied at six rates from 0 to 150 kg/ha. Roots were sampled every two weeks to determine biomass and root length density as a function of depth. Every week, soil water content in all treatments was measured gravimetrically to a depth of 0.23 m and with a neutron probe from 0.3 to 1.5 m.

Below 0.45 m, volumetric water content was equal to a negative exponential function of time after roots arrived and the maximum depth of extraction moved downwards at 2 to 5 cm d^{-1}. In the dry treatment, the extraction "front" lagged behind the deepest roots by about 12 days initially but the two fronts eventually converged. Irrigation delayed the descent of the extraction front by about 20 days but thereafter it appeared to descend faster than without irrigation. Averaged over N rates, the time constant of the exponential function was inversely related to the root length density, l_v, increasing with depth from about 14 to 19 d as l_v decreased from 4 to 2.5 km m^{-3} (Singh et al., 1996).

The biomass-water ratio was almost independent of N but increased from a mean of 5.3 g kg^{-1} in the dry treatments to 6.9 g kg^{-1} with irrigation (Fig. 23). When normalized vapour pressure deficit within irrigated and unirrigated plots, the ratios were 13.1 and 13.3 kPa g kg^{-1} respectively.

Growth and Extension of Roots

Effects of fertilizer and irrigation on root development were studied using field-grown sorghum [*Sorghum bicolor* (L.) Moench] (Lee et al., 1996). The total root biomass was affected by fertilizer-nitrogen (N) and irrigation and by their interaction (Table 34). It is the top soil layers that contribute largely to increased root biomass due to fertilizer-N and irrigation. The total root length was not significantly affected by fertilizer-N, but was consistently higher under dry conditions than under irrigated conditions. Spatial distribution of root length did not fit a simple mathematical model such as linear, exponential or logistic curve, except at very young growth stages under irrigated conditions. Except for the top 16-cm layer, the depth at which root length density was maximum shifted to deeper layers as sorghum grew. This may indicate that some roots die after water extraction and that new roots grow at the soil layers where water was available. This specific feature would contribute to the complexity of modelling of root development. Rooting depth was not affected by fertilizer-N, but it was consistently greater under dry conditions than under irrigated conditions. The root depth had a linear relationship with time under dry and irrigated conditions up to the physiological maturity.

Alfisol

Grain Yield and Water Use

A field study was conducted during two postrainy seasons (1983/84 and 1984/85) to examine the yield response of sorghum (cv. CSH 8R) to water use, and to determine the sensitivity of yield to water deficits at three growth stages and at three N application rates. The three growth stages were: emergence to panicle initiation (GS1); panicle initiation to 50% flowering (GS2); and 50% flowering to physiological maturity (GS3).

The four main treatments, consisting of timing and amount of irrigation, were: line source irrigation at all growth stages of sorghum (M_1); line source irrigation at GS1 and GS2, but no irrigation at GS3 (M_2); line source irrigation at GS1 and GS3, but no irrigation at GS2 (M_3); and line at GS2 and GS3, but no irrigation at GS1 (M_4). The N subtreatments were: 40 kg N ha^{-1} (N_1); 80 kg N ha^{-1} (N_2); and 120 kg N ha^{-1} (N_3).

To account for variation in grain yield (Y), or relative grain yield (ratio of actual to maximum observed grain yield, Y/Ym) in terms of seasonal water use (ET) at different crop growth stages, or relative water use (ratio of actual to maximum water use, ET/ETm), Y and Y/Ym were regressed against ET and ET/ETm at different growth stages. Total seasonal water use accounted for 70% to 80% of the variation in sorghum grain yield with different nitrogen application rates (Table 35). This improved to 84 to 88% when ET or ET/ETm was considered separately for GS1, GS2, and GS3. A decline in relative yield (Y/Ym) with decrease in relative water use (ET/ETm) at a particular growth stage is an accurate measure of crop sensitivity to water deficit. The coefficients of equations 10, 11 and 12 are therefore a measure of the sensitivity of crop growth stages to drought. It is clear that crop sensitivity to drought depends upon both the amount of N fertilizer applied, and crop growth stage. At a low N application rate (N_1 level) the crop is most sensitive to water deficit at GS1. This is possibly due to poor root development in dry soil. At higher N application rates (N_2 and N_3 levels), the relative crop sensitivity at GS2 and GS3 increased, and that of GS1 decreased. At higher fertility, the greater yield sensitivity of GS2 to drought compared with GS3 is due to the reduction in seed number per panicle rather than seed mass.

Water x Nutrient Interactions

Alfisol

Water and Nitrogen Response

Two experiments were conducted on an Alfisol during the dry seasons of 1985 and 1986 to study the response of pearl millet (BJ 104) to amounts of nitrogen (N) and drought treatments imposed at different phenological stages. The drought treatments were: adequate water supply throughout the season (M1); drought during growth stage 2(GS2), i.e., from panicle initiation to anthesis (M2); and drought during growth stage 3(GS3), i.e., from anthesis to physiological maturity (M3). Sub-plots in each drought treatment received four levels of N in 1985 and six in 1986.

The pattern of response of pearl millet to water and N was similar in both years (Table 36). Drought stress in GS2 reduced grain yield and total dry matter (TDM), but the effect of drought was more pronounced for TDM. In the M2 treatment, there was no response to N beyond 40 kg ha^{-1} in 1985, and 100 kg ha^{-1} in 1986. Drought stress in GS3 reduced grain yield at all N levels in both years, more so in 1986. The yield reduction was mainly because of a smaller contribution by tillers. Another reason was that drought stress in GS3 reduced the grain-filling period by about 1 week in both years and at all N levels. Though grain yield did not increase with N in M3, the TDM did. Thus in both years, drought reduced the harvest index when applied in GS3 but increased it when applied in GS2.

The smaller grain yield and TDM in the 1986 M3 treatment compared to the 1985 treatment suggests that the drought may have been more intense in 1986. Another general observation is that both grain yields and TDM were smaller in summer-season crops than in rainy-season crops. Though N, radiation, and water supply were not limiting in the M1 treatment, higher saturation deficits and air temperatures inevitably increase the demand for water and this may restrict crop growth and development.

Sandy Soil

Fertilizer Application and Water Use Efficiency

Some information relevant to the effect of fertilizer on water use efficiency in West Africa can be drawn from two experiments, the long-term Baobab experiment and the long-term rotation experiment conducted at ISC.

Fertilization increased seasonal crop water use (ET) modestly (Table 37), but due to the high response of pearl millet, its water use efficiency increased drastically from 5.4 to 14.4 kg mm^{-1} in 1986. Measured crop water use by in experiment 2 was similar in 1986 and 1987, but water use efficiency in 1987 was much lower than in 1986, i.e., due to insect attacks and poor stand (more soil evaporation or transpiration by weeds). This also happened for cowpeas. In conclusion, water does not seem to be the primary limiting factor, and fertilization is prerequisite to increase crop production in this Sahelian soil, provided that crop-stands are adequate and that weeds are controlled.

Effect of Rainfall on Nitrogen Response

The efficiency of N fertilizer depends on the rainfall received by the crop. If optimal rainfall is received during the entire growing season, the response to N will be strong. Conversely, in years of poor precipitation, no N response will be obtained because crop growth will be limited by low soil moisture and therefore N demand will be limited. In extreme drought conditions, such as those of 1984 in the Sahel, N application may actually diminish yields. Fertilized plants are larger early in the season and rapidly deplete soil water reserves. By the time of crop maturity, insufficient water is left for grain filling, and thus yields are depressed. In contrast, unfertilized plants grow more slowly and will leave more water in the soil for grain filling.

These trends were evident in experiments conducted in Niger. On the basis of these trials, the following model was developed relating grain yield at harvest to mid-season rainfall (45 days from mid-July to end of August).

$$Y_i = \gamma_0 + \gamma_1 R_p + \gamma_2 N_i + \gamma_3 N_i^2 + \gamma_4 N_i \,.\, R_p + \varepsilon_i$$

where,

Y_i	is the grain or stover yield at the i^{th} lever of N fertilizer and p^{th} rainfall amount
γ_1	is the parameter for a rainfall effect during the critical period
γ_2 and γ_3	represent the parameters for the effect of the 1^{th} level of nitrogen
γ_4	is the interaction between rainfall and nitrogen levels
ε_i	is the random error with normal properties
N_i	is the N rate ka N ha^{-1}
R_p	is total rainfall received in a 45-day period from mid-July to end of August.

This model predicts that N response in dry years (e.g., 1984) will be very limited, and there will be no benefit of N fertilizer use (Fig. 24). However, in a year of average mid-season rainfall, use of 30 kg N in the presence of adequate P will result in a yield increase of 430 kg grain (14 kg grain kg^{-1} N). In a year of optimal rainfall, it is essential to use N to gain maximum yields, and use of 30 kg urea-N will result in a fertilizer efficiency of 25 kg grain kg^{-1} N (Christianson and Vlek, 1991).

Subsurface Drip Irrigation for Measuring Transpiration Ratios

A subsurface drip irrigation system was evaluated as a field method of measuring transpiration ratios (TR), the ratio of plant dry matter to transpiration of two pearl millet varieties grown under contrasting levels of water and nutrient availability. The system permits a reliable method of comparing TRs so long as growth conditions are favorable enough to a lower limit of about 1 g kPa kg^{-1}. (Payne, Gérard, and Klaij. 1995a).

Phosphorus and Water Interactions on Sandy Soils

Several publications have resulted from this study. Briefly the main findings are: TR varies inversely with plant phosphorus(P)-use efficiency (PUE) when defined in the classic sense (g dry matter mg^{-1} P uptake). P root uptake efficiency (mg shoot P g^{-1} root dry matter) is less sensitive to ontogeny, soil P availability, and water stress, and is positively correlated with both TR and yield (Payne, Hossner, Onken and Wendt, 1995b).

In the case of P deficiency, the response of TR appears to be mostly related to rates of stomatal exchange of CO_2 and H_2O. Improved plant P status increases the slope of the relation of photosynthesis to stomatal conductance, and decreases leaf internal CO_2 concentration. This implies that P deficiency reduces photosynthesis through metabolic dysfunction rather than through stomatal control (Payne, Drew, Hossner, and Lascano, 1996).

Growth analysis experiments have quantified the increase in whole plant growth and organ rates in pearl millet due to increased soil P in the presence and absence of water stress. (Payne, Lascano, Hossner, Wendt, and Onken, 1991).

Increased root growth due to P application is associated with greater rooting depth and therefore seasonal water supply, as well as greater soil water extraction from soil layers during dry spells. (Payne, Brück, Sattelmacher, Shetty, and Renard, 1996).

Environmental Effects on Transpiration Ratio

Research has also shown several environmental effects upon transpiration ratio (TR). We have reported results from container and field experiments that TR varies with ontogeny and genotype, increases with N and P availability, and decreases with water availability and Striga attack (Boukar, Hess and Payne, 1996).

Future Plans

Sandy Soil

Evaluate Strategies for Improved Management of Soil Nutrient and Water Resources in Pearl Millet-based Cropping Systems (ISP1, Activity 2a, PS1)

Almost all the studies on water x nutrient interaction have been carried out on on-station experiments at IAC or ISC. In future, we will move towards on-farm participatory research.

The main objectives are: (i) to use data from on-station and on-farm research to better understand the water and nutrient dynamics of pearl millet-based production systems, and to develop the capacity to stimulate these systems, and (ii) to involve farmers, extension officers, and researchers in using on-farm experimentation and simulation modelling to evaluate options for improved soil nutrient and water management.

One of the planned experiments under this activity is a water balance and fertilizer experiment using pearl millet cultivars at Rajasthan. Nutrient treatments are 0, 20 and 40 N kg ha^{-1}. The different soil profile water will be measured and used as different levels of available water.

Alfisol

Measuring and Modeling Water Balance in Traditional and Improved Systems to Explore Options for Increased Resource-Use Efficiency and Improved Management (ISP2, Activity 2b, PS 9)

The main objectives here are: (i) to study the groundnut productivity and resource use efficiency under traditional management; (ii) quantify components of water balance under traditional management; and (iii) assess the scope for improving resource (light, water and nutrients) use efficiency.

All the measurements will be taken in farmers' fields in Anantapur district. Different levels of nutrient will be different farmers' nutrient applications ranging from 6 to 16 kg N ha^{-1}, 4 to 13 kg P ha^{-1} and 2 to 3 kg K ha^{-1}. Variation in yearly rainfall will provide different levels of available water.

Assessment of the Rates of Degeneration of Soil Structure in a Low-Input Cereal-based System (ISP2, Activity 3.2, PS 4)

This activity is based on the experiment at RM 19 site in IAC that was conducted as QDPI/ICRISAT project. The objective was to examine the effects of different soil surface managements on runoff and soil loss, and was not designed to study water x nutrient interaction. However, this experiment was redesigned in 1995 to include low fertility treatment (20 kg N ha^{-1}) and high fertility treatment (90 kg N ha^{-1}). If variation in yearly rainfall is used as different levels of available water, this experiment will enable us to study the effect of water x nutrient on crop growth, and soil physical, chemical and biological properties.

Vertisol

Study Genotypes, Cropping Systems, Water and Nutrient Management Practices including Assessment of Farmers' Practices (ISP3, Activity A2, PS 7)

The original objectives were: (i) to evaluate the effects of different cropping systems and their rotations on long-term soil fertility with special emphasis on soil nitrogen; (ii) to estimate the long-term N requirements of different cropping systems and their rotations for maintaining optimum crop production. It was not planned to study water x nutrient interaction. However, this activity will be restructured to examine water x nutrient interactions using rainfall data in different years as this experiment has different fertility treatments.

Table 34. Root biomass as a function of soil depth at the time of maximum total root biomass, 93 DAE.

	N-level				SE[2]		
	0N		150N				
Depth (m)	Dry	Irri-gated	Dry	Irri-gated	Irri-gated[3]	Nitro-gen[4]	Irri-gated[5]* Nitrogen[5]
	$g\ m^{-2}$						
0.05	26.9 (34)	31.9 (36)	41.3 (40)	69.7 (41)	0.43	4.43 **	7.05
0.16	6.0 (8)	10.5 (12)	8.5 (8)	16.1 (10)	0.70 *	0.98 !	1.44
0.30	5.6 (7)	8.2 (9)	6.3 (6)	7.8 (5)	0.40 !	0.80	1.11
0.45	4.4 (6)	4.4 (5)	5.3 (5)	6.6 (4)	0.37	0.39 !	0.63
0.60	5.2 (7)	3.9 (4)	3.6 (3)	8.6 (5)	0.77	0.88	1.38
0.75	5.6 (7)	4.8 (5)	4.0 (4)	8.4 (5)	0.37 *	1.54	2.01
0.90	3.3 (4)	4.4 (5)	2.5 (2)	7.7 (5)	0.58	0.91	1.31
1.05	3.4 (4)	3.9 (4)	4.1 (4)	8.1 (5)	0.29	0.63	0.87
1.20	3.5 (4)	5.0 (6)	6.1 (6)	9.1 (5)	0.19 !	0.79	1.04
1.35	3.1 (4)	4.3 (5)	4.6 (4)	8.6 (5)	0.34	0.98	1.31
1.50	4.0 (5)	4.3 (5)	4.2 (4)	8.9 (5)	0.40	0.92 !	1.25
1.65	3.7 (5)	1.9 (2)	5.1 (5)	4.5 (3)	0.26	0.73 !	0.98
1.80	1.8 (2)	0.7 (1)	4.4 (4)	3.6 (2)	0.38 !	0.73 *	1.01
1.95	1.7 (2)	0.2 (0)	3.3 (3)	1.7 (1)	0.70	0.51 !	0.96
Total	78.1(100)	88.6(100)	103.3(100)	169.3(100)	6.31 !	7.96 ***	12.08 !

[1]The values in parentheses are percent of total root biomass.
[2]Standard error or means calculated from all treatments in this study; !, *, ** and *** significant at P = 0.1, 0.05, 0.01 and 0.001 respectively.
[3]For irrigation effect comparison.
[4]For N-fertilizer effect comparison.
[5]For interactive effects of irrigation and fertilizer-N comparison.

Table 35. Functions explaining variation in sorghum grain yield (Y, kg ha^{-1}) or relative grain yield (Y/Ym) to seasonal water use (ET, mm) or relative water use (ET/ETm). Analysis of 2-year pooled data, ICRISAT Center, postrainy-seasons 1983/84 and 1984/85.*

Function number	Nitrogen level	Function	r^2 or R^2	rse
1	N1	Y = 457 + 11.0 ET	0.80	540
2	N2	Y = 290 + 13.06 ET	0.70	785
3	N3	Y = -112 + 15.7 ET	0.75	816
4	N1	$Y = 1571-13.9\ (ET)_1 + 7.5\ (ET)_2 + 15.3\ (ET)_3$	0.84	478
5	N2	$Y = 2407-52.8\ (ET)_1 + 22.2\ (ET)_2 + 14.3\ (ET)_3$	0.86	538
6	N3	$Y = 2866-58.5\ (ET)1 + 17.1\ (ET)_2 + 20.7\ (ET)_3$	0.88	559
7	N1	$Y = 1339-431\ (ET/ETm)_1 + 1152\ (ET/ETm)_2 + 3014\ (ET/ETm)_3$	0.81	522
8	N2	$Y = 2158-2591\ (ET/ETm)_1 + 2943\ (ET/ETm)_2 + 3310\ (ET/ETm)_3$	0.86	540
9	N3	$Y = 3168-3699\ (ET/ETm)_1 + 2503\ (ET/ETm)_2 + 4773\ (ET/ETm)_3$	0.83	658
10	N1	$\log Y/Ym = 1.012 \log (ET/ETm) + 0.40 \log (ET/ETm)_2 + 0.19 \log (ET/eTm)_3$	0.66	0.21
11	N2	$\log Y/Ym = 0.193 \log (ET/ETm)_1 + 0.55 \log ET/ETm)_2 + 0.33 \log (ET/ETm)_3$	0.83	0.16
12	N3	$\log Y/Ym = -0.274 \log (ET/ETm)_1 + 0.51 \log (ET/ETm)_2 + 0.47 \log (ET/ETm)_3$	0.84	0.16

*See the text for relative grain yield, relative water use and nitrogen level. Subscrips 1, 2 and 3 refer to growth stages of GS1, GS2 and GS3, respectively.

Table 36. Response to drought and N of grain yield and total dry matter (main stems + tillers) (t ha^{-1}) of a pearl millet cultivar (BJ 104) on an Alfisol, ICRISAT Center, postrainy-season 1985 and 1986.*

Nitrogen	Grain yield			Total dry matter			Storer		
(kg ha^{-1})	M1	M2	M3	M1	M2	M3	M1	M2	M3
1985									
0	1.43	1.90	1.47	3.77	3.75	3.23	2.34	1.85	1.76
40	2.14	2.42	1.46	4.71	5.13	3.72	2.57	2.71	2.26
80	2.31	2.32	1.44	5.65	4.81	4.04	3.34	2.49	2.60
120	2.60	2.32	1.55	6.20	5.20	4.47	3.60	2.89	2.92
SE_1[1]		±0.16			±0.29				
SE_2[2]		±0.11			±0.23				
1986									
0	1.32	1.28	0.60	3.03	2.56	2.16	1.71	1.28	1.56
25	1.74	1.63	0.83	4.35	3.44	2.41	2.61	1.81	1.58
50	2.04	1.65	0.86	4.78	3.48	2.69	2.74	1.83	1.83
75	2.36	1.67	1.00	5.78	3.70	3.12	3.42	2.03	2.12
100	2.26	2.19	0.85	5.58	4.58	2.69	3.32	2.39	1.84
125	2.43	2.02	0.81	5.67	4.62	3.01	3.24	2.60	2.20
SE_1[1]		±0.14			±0.30				
SE_2[2]		±0.10			±0.23				

* See the text 1.3 for M1, M2 and M3.

1. SE_1 = SE for comparing drought treatment at the same or at different levels of N.
2. SE_2 = SE for comparing N levels at the drought treatment.

Table 37. Effect of fertilizer on water use efficiency. Results from two experiments, ICRISAT Sahelian Center, rainy seasons 1986 and 1987.

		Evapotranspiration (mm)	Drainage (mm)	Rainfall (mm)	Total biomass (kg ha^{-1})	Water use (ET) efficiency kg mm^{-1} ha^{-1}
Experiment 1						
1986 Pearl millet	no fertilizer	211	207	440	1140	5.4
1986 Pearl millet	fertilizer	268	147	440	3850	14.4
Experiment 2						
1986 Pearl millet	fertilizer	298	105	431	4030	13.5
1987 Pearl millet	fertilizer	303	65	361	2170	7.2
1986 Cowpea	fertilizer	276	115	339	3760	13.6
1987 Cowpea	fertilizer	265	57	319	660	2.5

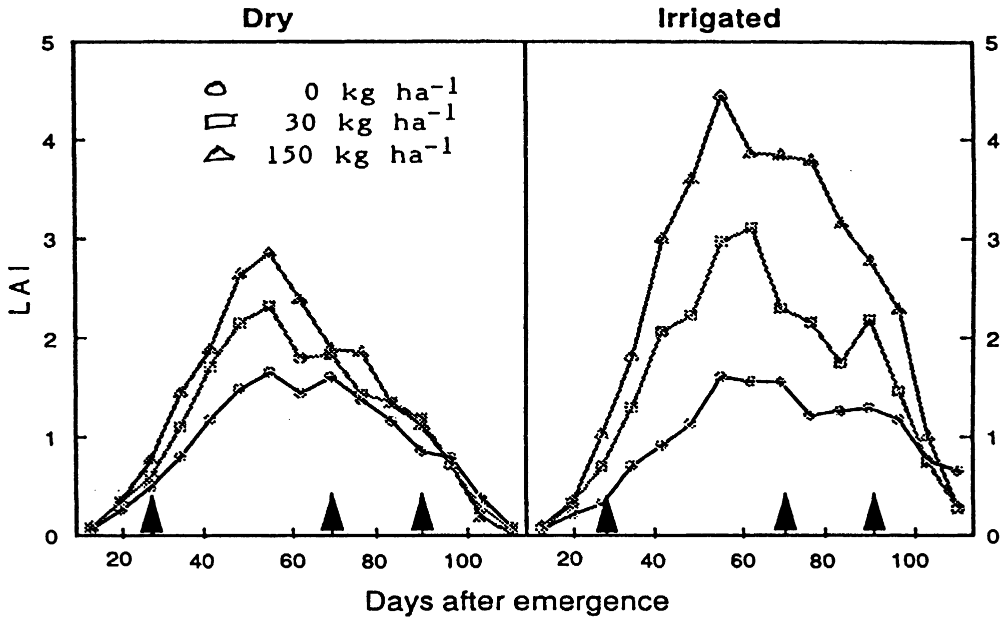

Fig. 22. Leaf area index as a function of time and N application (kg ha^{-1}).

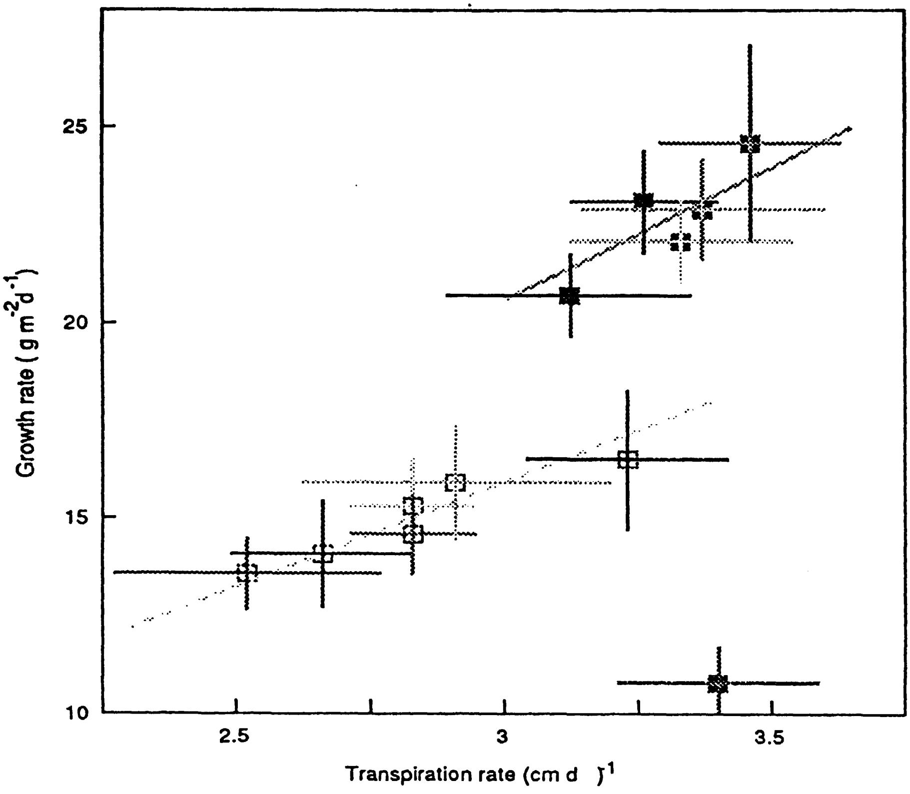

Fig. 23. Mean crop growth rate for each N level estimated from 41 to 82 DAE plotted as a function of mean transpiration rate for the same period for the unirrigated (□) and irrigated (■) treatments. Lines correspond to mean biomass/water ratios of 5.31 (+0.13) g.kg^{-1} and 6.82 (+0.17) for unirrigated and irrigated treatments respectively.

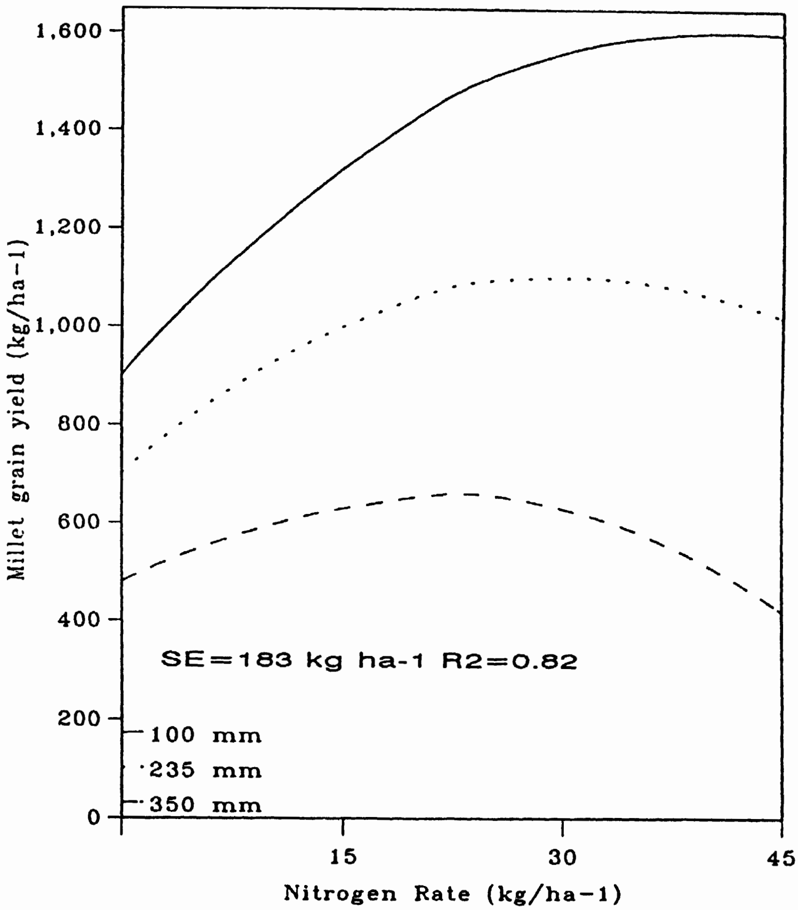

Fig. 24. Millet grain yields as affected by N rate and midseason rain at Sadore, Niger.

SIMULATION MODELLING

Piara Singh, G. Alagarswamy, P. Pathak, and K.P.C. Rao

The characteristic distribution of the natural resources (soils and climate) in the dry semi-arid tropical areas promotes strongly location specificity of crop growing environments. Because of the large variation in environments, each location will need a different set of management options, to increase and sustain productivity and to protect or improve the resource base. Simulation models which can predict crop response to soil and crop management, and their effect on resource use and conservation, can be used to evaluate management options. These models can also be used to interpolate or extrapolate research results between environments both in time and space to evaluate the productivity and sustainability issues. Since 1982, research at ICRISAT has been done to test and validate soil water balance, crop growth, and soil management models. Some of the models have been used to assess natural resource availability and potential productivity of environments and to evaluate the long-term effect of soil management options on productivity and sustainability of resource base. The progress made to date has been described in the following sections.

Soil Water Balance and Hydrological Modelling

Fechter *et al.* (1991) evaluated the SWATRER soil water balance and the CERES-Millet growth models for millet during the 1989 growing seasons at Tara, Niger. A field experiment was carried out to validate the soil water balance and plant growth subroutines. The required minimum data sets for the plant and soil components were either field determined or obtained from literature. Soil water content, leaf area index (LAI), and dry matter (DM) were measured weekly. Good agreement between simulated and measured soil water content was obtained with SWATRER. The CERES-Millet model consistently overestimated soil water content by 5% throughout the growing season and also overestimated LAI, DM, and yield. The SWATRER model showed good promise for evaluating water and fertilizer management strategies. Bley *et al.* (1991) used three seasons (1986-1988) data of field experiments conducted at Niamey, Niger, to test the SWATRER model. They then carried out long-term crop water balance simulations for Gao in Mali and for Tilaberi, Niamey, and Gaya in Niger. Based on their analysis, they constructed a risk-probability map for millet production in southwest Niger. They concluded that in large parts of the southwestern Niger the crop water supply in general cannot be considered as the most limiting factor in millet production.

Pathak *et al.* (1989) developed a runoff model for small watersheds based on a modified curve number technique and on a soil moisture accounting procedure. Soil characteristics which have strong influence on runoff such as cracking and land smoothing were represented. The model needs simple inputs which are normally available and the outputs are daily runoff and soil moisture. The model has four input parameters which are estimated through calibration using measured runoff and soil moisture content data. The validity of the model was tested using the hydrological data collected from small Vertisol watersheds at ICRISAT Asia Center, Patancheru.

The agreement between measured and simulated daily, monthly, and annual runoff was good. The root mean square error values between the measured and simulated annual, monthly, and daily runoff from a Vertisol watershed were 5.2, 3.1, and 1.6 mm respectively (Table 38). The modified model and the moisture accounting procedure simulated quite accurately runoff for high, low, as well as normal rainfall years in the semi-arid tropical environment.

Sorghum Model—SORGF

Multilocation Experiments

Multilocation experiments were conducted at 9 locations in India (11-31°N) to test and validate the sorghum model SORGF. These locations were Hisar, Rahuri, Coimbatore, Ludhiana, Delhi, Pune, Solapur, Patancheru, and Parbhani. The mean annual rainfall at these locations ranged from 446 mm to 902 mm. Standard data sets on crop, climate, and soils were collected from these experiments. Based upon the initial testing, the phenology, light interception, soil water balance, dry matter production and partitioning subroutines of the model were modified. As a result of these revisions (Huda, 1987) the prediction of the model improved (r^2 = 0.52 to 0.86). The model was then applied for the following aspects of crop production :

Predicting Sorghum Grain Yields

Simulated yields were compared with independent data of observed sorghum grain yield (cv. CSH 6) from the rainy seasons of 1978 to 1984 at ICRISAT Asia Center, Patancheru. Simulated yields were within the range of 1 to 9% of the observed yields in six years, when observed yields ranged from 4.9 to 6.2 t ha^{-1} and within 16% for one year when the yield was 6.6 t ha^{-1}.

Grain yields were also simulated using actual weather data from sowing to flowering and average weather data (based on 10 years data from 1974 to 1983 at ICRISAT Asia Center, Patancheru) from flowering to physiological maturity. Simulated yields using these data, were within 2 to 13% of the observed grain yields. This exercise illustrated that the model can be used to predict yields ahead of harvesting.

Assessing the Impact of Drought

The revised SORGF model was tested by comparing the simulated and observed response of 2 sorghum cultivars (CSH 8 and M 35-1) to drought-stress in 2 post-rainy seasons (1979/80 and 1980/81). The experiment was conducted in an Alfisol (85 mm available water holding capacity) at ICRISAT Asia Center, patancheru, with 2 cultivars and 2 water treatments (irrigated and drought-stressed).

Grain yields from the irrigated treatment were 3.8 t ha^{-1} for CSH 8 and 2.1 t ha^{-1} for M 35-1 in the first year, while these were 6.1 t ha^{-1} for CSH 8 and 3.9 t ha^{-1} for M 35-1 in the second year. Grain yields from the drought-stressed treatment were 2.1 t ha^{-1} for CSH 8 and 1.3 t ha^{-1} for M

35-1 in the first year, while these were 2.5 t ha^{-1} for CSH 8 and 1.7 t ha^{-1} for M 35-1 in the second year. Differences in grain yields between the two years were due to different sowing dates and irrigation schedule. The correlation coefficient between observed and simulated grain yield data pooled over the 2 water treatments, 2 cultivars, and 2 years was 0.84 (Fig. 25). A comparison between the observed and simulated percent reduction in grain yield due to drought-stress showed that the model was capable of simulating the impact of drought-stress on sorghum grain yield.

Simulating the Response of Sorghum to Plant Density

This experiment was conducted on a medium deep Vertisol (150 mm available water holding capacity) at ICRISAT Asia Center, Patancheru, with 5 levels of plant density ranging from 40,000 to 200,000 plants ha^{-1}. Sorghum was sown on 21 June 1983, and was grown under rainfed conditions (rainfall June to October, 1021 mm).

Cultivars tested produced similar grain yields up to a density of 120,000 plants ha^{-1}, but above this, CSH 6 gave higher grain yield than SPV 351. Simulated grain yields for CSH 6 were higher than SPV 351 at each plant density. Maximum grain yields were observed at 160,000 plants ha^{-1} for both cultivars (5.3 t ha^{-1} CSH 6, and 4.5 t ha^{-1} SPV 351). Further increase in plant density did not increase grain yield in CSH 6 but decreased grain yield in SPV 351. Simulated grain yields in both cultivars increased with increasing plant density and were between 3 and 15% of the observed data. The correlation coefficient between observed and simulated grain yield was 0.91 (Fig. 26).

Screening Environments for Sorghum Production and Input Response

The revised SORGF model was used to compute the probabilities of simulated sorghum grain yield for 4 locations in India using climatic data from 1941 to 1970. Mean annual rainfall for these locations is 527 mm in Anantapur, 792 mm in Patancheru, 889 mm in Dharwar, and 1001 mm in Indore. Available water holding capacity of soils was 50 mm in Anantapur, and 150 mm in the other three locations. Simulated sorghum grain yields under adequate management (e.g., timely field operations, high yielding cultivar, recommended doses of nutrients and adequate plant protection measures) in 70% of the years were more than 2.2 t ha^{-1} for Anantapur, 4.5 t ha^{-1} for Patancheru, 5.5 t ha^{-1} for Dharwar, and 6.2 t ha^{-1} for Indore. Agroclimatic environments of Indore can be more profitably utilized by growing high value crops such as soybean and by adopting cropping systems (intercrop, sequential) capable of harnessing better soil water availability of this location. Agroclimatic environments of Patancheru and Dharwar are suitable for growing sorghum based cropping systems.

The probabilities of N-fertilizer requirements for these locations were simulated following the approach of Huda *et al.* (1985a). Given that a total uptake of 20 kg N ha^{-1} was required to produce 1.0 t ha^{-1} sorghum grain yield, N-uptake from unfertilized plot was 30 kg ha^{-1}. Based on the simulated sorghum yields, the N-fertilizer requirements in 70% of the years would have been at least 15 kg ha^{-1} in Anantapur, 60 kg ha^{-1} for Patancheru, 80 kg ha^{-1} for Dharwar, and 95 kg ha^{-1} for Indore.

Sorghum Model—RESCAP

Monteith *et al.* (1989) developed the resource capture (RESCAP) model for sorghum to predict sorghum crop growth and yield for the water limiting and nonlimiting environments of the semi-arid tropics. RESCAP places equal emphasis on the role of leaves in relation to the interception of light, and to the role of roots in relation to the uptake of water. The model is based upon two assumptions, which are well supported by field evidence. The assumptions are (1) the amount of dry matter produced per unit of radiation intercepted by foliage is effectively constant during vegetative growth when water is not limiting; and (2) the amount of dry matter produced per unit of water transpired is inversely proportional to mean saturation deficit constant whether water is limiting or not. According to Monteith *et al.* (1989), building a model around these conservative quantities keeps the model structure simple and is equivalent to the use of constants in physical models. This model was tested against the data set available at ICRISAT and it performed very well.

Applications of the CERES Sorghum Model

Characterization of Yield Gap for Sorghum

The difference between the agroecological potential of a crop and the yields that farmers realize in a given region is termed as "yield gap". It is a popular way of characterizing the "untapped" potential and defining the opportunity that can be exploited if all constraints are removed. We estimated the agroecological potential of sorghum crop in selected bench mark locations in the major sorghum growing agroecological (AE) subregions of peninsular India. The difference between the potential yield and farm level yield in these locations constituted the "yield gap". We used Geographical Information System (GIS) to extend the yield gap data of the benchmark location (from a point data) to the whole AE (on a spatial basis) where the benchmark location is situated (Virmani and Alagarswamy, 1993).

In the rainy season AE subregions, even though rainfall is adequate and improved sorghum cultivars are used by farmers, the yield gap was large. As a first step, research in these AE subregions should be directed to explore the causes for existence of such large yield gap before launching any research program.

The yield gap is < 1 t ha^{-1} in the core postrainy season AE subregion (Fig. 27). Potential yield estimates demonstrate that even the improved technology coupled with any improved cultivars might not change the existing low yield in these subregions as long as water resources are not properly developed.

Nitrogen Dynamics for Sorghum Production in the Indian SAT

The productivity in SAT agricultural system is influenced by both the temporal and spatial variability of rainfall. Because of the risks involved for dependable crop production and the increased cost of fertilizers, dry land farmers do not generally use fertilizers. However, the conservatism about the fertilizer use in the SAT is changing progressively. We have used CERES Sorghum model and risk analysis procedures to quantify climatic risks to sorghum production and risks involved to the use of N fertilizer in various areas of Indian SAT (Godwin *et al.* 1988; Alagarswamy *et al.* 1990).

A 25-year simulation study indicated that in wetter environments fertilizer use efficiency is often limited by losses of N associated with leaching of N. Where leaching losses were high, there was an advantage to splitting of fertilizer application. In drier environments the recovery of applied fertilizer was low in general and the median recovery was approximately 25%. Comparison of N fertilizer use strategies for shallow alfisols indicated that in one out of four years there is no response to applied fertilizer above 30 kg ha^{-1}. Even under similar soil series, risks associated with fertilizer application were variable and related to variable moisture environments.

In fertile vertisols (initial mineral N content 36 kg ha^{-1}; available water storage capacity 172 mm) a basal application of 30 kg N ha^{-1} could boost yields to over 4.5 t ha^{-1}, indicating a response of 53 kg grain per kg of fertilizer N applied. Economic response (1 kg N produced 5 kg grain) is obtained up to 90 kg N ha^{-1}. In alfisols, a much higher level of N fertilizer was required to obtain comparable higher yields. The efficiency of fertilizer N utilization (ratio of kg N to kg additional grain produced) in alfisols was much lower compared to vertisol. The results indicated that the practice of applying 30 kg N ha^{-1} at sowing can safely be extended to sorghum growing areas in the vertisols where annual rainfall exceeds 700 mm.

Quantification of Climatic Risks to Sorghum Production

The primary production areas of sorghum [*Sorghum bicolor* (L.) Moench] in India lie on the Deccan Plateau in India. This region is characterized by a semi-arid tropical climate. The seasonal rainfall is 500-900 mm and the length of growing season (LGS) is 110 - 150 d. Typically, sorghum is grown on tropical Alfisols, Vertic soils, and Vertisols having an available water holding capacity ranging between 100 and 150 mm. To increase crop yield, application of (N) fertilizer is essential. However, N-response is highly variable and dependent on the amount and distribution of rainfall, and on the moisture holding characteristics of the soil.

We used the CERES-Sorghum model to quantify climatic risks involved in N-fertilizer management at four selected locations in the Deccan Plateau. The simulated results showed that yields were extremely variable when no N-fertilizer was applied. Even though the crop almost failed in the unfertilized treatment in some of the years, there was a guaranteed minimum yield in those years when 30 kg N ha^{-1} was applied. Fertilizer application reduced the grain yield variation and increased yield stability (Alagarswamy and Virmani, 1994).

Substantial response to applied N up to 60 kg N ha^{-1} was noted from the cumulative distribution function (CDF) curves for gross returns. At the Hyderabad location, where a relatively dependable seasonal rainfall occurs, the spread in the CDF curve was narrow indicating that risks associated with N-fertilizer application seem to be minimal. On the contrary, at other locations (Akola, Parbhani, and Pune) where seasonal rainfall is less dependable, the spread in the CDF curves for a similar N-level was much wider, indicating an increased risk level. The gross and net returns at Hyderabad and Akola were maximized between 60 and 90 kg N ha^{-1}. This maximum is supported by results from N- response field studies conducted in Vertisols at Hyderabad, indicating a maximization of grain yield at about 90 kg N ha^{-1}. This analysis shows the use of crop simulation models coupled with long-term weather data offer the possibility of evaluating various management strategies to sustain agriculture.

Pearl Millet Modelling

Because of the similarity in some of the growth and development processes of pearl millet and sorghum, a model for simulating growth and yield of pearl millet was developed following an approach similar to that of SORGF (Huda *et al.* 1994 and Huda, 1987). In the SORGF model, sorghum was described as a single-culm plant and the leaf area was calculated from the input data on total number of leaves and maximum area for each leaf. Pearl millet generally produces more tillers than sorghum and this is a major difference in the growth of sorghum and pearl millet. Thus, it would be very difficult to get input data of the total number of leaves and the maximum area for each leaf in pearl millet to calculate leaf area. The SORGF model simulates growth and yield of a single plant while in the pearl millet model, an approach to simulate growth and yield over a unit area was used. The input data and the subroutines used in pearl millet model are briefly described.

Input Data

Climatic, soil and location data requirements of the pearl millet model are similar to that of SORGF. For plant data, maximum leaf area index (LAI) is used instead of total number of leaves, and maximum area of each leaf.

Phenology

Huda *et al.* (1984) studied the duration of three growth stages--emergence to panicle initiation (GS1), panicle initiation to flowering (GS2), and flowering to physiological maturity (GS3) for pearl millet cultivar BJ 104. Mean growing degree days (GDD) values using a base temperature of 7°C were 350 for GS1, 470 for GS2 and 570 for GS3. The coefficient of variation was 29%

for GS1, 14% in GS2, and 9% for GS3. Since pearl millet has a quantitative short-day response, the duration of GS1 increased with increasing daylength. When daylength correction was introduced in the model variability in GS1 was reduced to 10%.

Leaf Area Development

An approach different from that of SORGF was used in the pearl millet model to simulate daily progression of leaf area. Potential maximum LAI (measured or assumed at flowering) was given as input data. Huda *et al.* (1984) reported that leaf area development in pearl millet (cv. BJ 104 was slower than in sorghum (cv. CSH 6) in GS1 and only 10% of the maximum LAI was achieved at panicle initiation. LAI increased linearly from 10% to 100% from panicle initiation to flowering, LAI remained 100% for about a week after flowering; then it decreased to 50% linearly at physiological maturity.

Light Interception and Soil Water

The subroutines on light interception and soil water from the revised SORGF model were used.

Dry Matter Production and its Partitioning

Jarwal (1984) reported that 2.2 g of dry matter was produced for each MJ of radiation intercepted. Ong and Monteith (1985) reported the amount of dry matter produced per unit of intercepted radiation appeared to be conservative at about 2.4 g MJ^{-1}. These relationships were used in the pearl millet model to calculate potential dry matter accumulation. Net dry matter accumulation was calculated using the water-stress coefficients calculated from the soil water availability. Partitioning of total dry matter to leaf, culm, head and grain at different growth stages were based on empirical data.

Testing of Pearl Millet Model

Simulated grain yields were compared with independent data of observed grain yields of pearl millet (cv. BJ 104) from the rainy seasons of 1978, and 1980 to 1984. Simulated yields differed in the range of 2 to 12% of the observed yields in 5 years, when observed yields ranged from 2.2 to 2.9 t ha^{-1}, and was within 46% in one year when the yield was 1.7 t ha^{-1}. Observed grain yield in 1980 was very low because 190 mm rainfall in two days (19 and 20 August) which coincided with flowering.

Groundnut Model—PNUTGRO

Multilocation Experiments and Model Validation

We have investigated the groundnut model (PNUTGRO) developed by the University of Florida and the IBSNAT project for testing and validating it for the SAT environment (Boote *et al.* 1992). A program of cooperation was developed with scientists in India located at Ludhiana, Hisar, Rajendranagar, Anantapur, Coimbatore, and Bhavanisagar. The collaborators conducted experiments on groundnut that included a common cultivar Robut 33-1 at all locations in addition to other cultivars and management treatments of local importance. Minimum data set on crop, climate, and soil were collected according to the IBSNAT format. Changes were made in various subroutines to improve the predictability of phenology and growth. Using the data sets from several years the model was calibrated for genetic-coefficients of cultivars Robut 33-1 and TMV 2. It also determined their phenology and growth, as well as for soil physical parameters influencing the soil water balance. The model was validated for cv. Robut 33-1 against independent data sets obtained from field experiments conducted during the later years. The model predicted the occurrence of flowering and podding within ±5 days of observed values at locations where growth stages were recorded more frequently. Predictions of growth stages beyond podding were less accurate because of difficulties associated with the indeterminate nature of the crop and to record growth stages after pod growth has started in the soil. Changes in vegetative growth stages, total dry matter accumulation, growth of pods and seeds, and soil moisture were predicted accurately by the model. Predicted pod yields were significantly correlated (r^2=0.90) with observed data. These results indicate that under biotic stress-free situations, the model PNUTGRO can be used to predict groundnut yields in different environments as determined by season, sowing date, and moisture regimes (Piara Singh *et al.* 1994).

Predicting Responses to Plant Population and Row-Spacing

Field experiments were conducted during the 1987, 1991, and 1992 rainy seasons at Patancheru, Andhra Pradesh, India, to collect data to test and validate the hedgerow version of the groundnut model PNUTGRO for predicting crop response to row spacing and plant population. The model was calibrated using the crop growth and phenology data of groundnut (cv. Robut 33-1) obtained from the 1987 and 1991 rainy season experiments. In these experiments groundnut was grown at plant populations ranging from 5 to 45 plants m^{-2} with and without irrigation. Changes were made in the cultivar specific coefficients related to light penetration into the canopy and dry matter production. The model was validated against independent data obtained from a 1992 rainy season experiment. In 1992, groundnut was grown at plant populations ranging from 10 to 40 plants m^{-2} and at row spacings of 20, 30, and 60 cm. The model predicted the occurrence of vegetative and reproductive stages, canopy development, total dry matter production and its partitioning to pods and seeds accurately. Maximum LAI observed during the season was significantly correlated with simulated values (r^2=0.95). In spite of some incidence of diseases and pests, the correlation between simulated and observed pod yield was significant (r^2=0.61). It is concluded from this study that the hedgerow version of the groundnut model PNUTGRO can be used to quantify groundnut growth and yields as influenced by plant population and row-spacing (Piara Singh *et al.* 1994).

Genetic Coefficients of Promising Genotypes

In addition to the testing and validation of the model to the environmental factors, we have conducted several field experiments at Patancheru site to develop the genetic coefficients of promising cultivars. These cultivars vary in days to maturity, growth habit, and other plant traits. These cultivars are TMV 2, ICGS 76, JL 24, CG 49, ICGS 44, ICGS 65, ICGS 21, ICCG 91129, ICCG 91123, ICCG 91116, ICCG 93382, ICCG 93397, and ICCG 91124. Model predictions on the of these cultivars need to be tested across environments.

Analysis of Risk and Production Potentials

We used the groundnut model PNUTGRO to quantify the groundnut production potential of 8 locations as influenced by water availability and plant population at two levels of soil quality factor (PHFAC3). Soil quality factor is a measure of overall soil fertility, including the influence of soil pests and diseases. The value of PHFAC3 ranges from 0 to 1.0 and it is an index of the rate at which the crop would grow in an environment provided water availability is not a limiting factor. The sites selected varied in the amount and pattern of rainfall. Anantapur, Hebbal, and Coimbatore have bimodal rainfall, while other sites have unimodal rainfall. Rainfall at Anand, Patancheru, and Hebbal is more assured and the growing season is longer than the other sites. Patancheru and Hebbal have cooler temperatures during the season compared to the other locations.

Solar radiation levels are high at Ludhiana, Anand, and Solapur. Soils at Ludhiana and Anand are deeper while those at other locations are shallower. Using soil survey information on soil profile characteristics of the locations and the DSSAT (Decision Support System for Agrotechnology Transfer) Program of the IBSNAT (International Benchmark Sites for Agrotechnology Transfer) Project, soils file on characteristics for determining soil water balance was created.

Crop yields were simulated assuming PHFAC3=1.0 i.e., soil fertility is optimum and it is not a limiting factor for crop growth, and PHFAC3=0.7, i.e., soil fertility is suboptimal and has limiting influence on crop growth. However under actual field situation, the fertility factor may vary between 0 and 1.0 for example, with our present version of the PNUTGRO model we have determined by calibration that PHFAC3 equals 1.0 for Anand, 1.0 for Patancheru, 0.77 for Anantapur, and 0.62 for Coimbatore. Therefore, this analysis is focused more on the climatic potential and crop yield sensitivity to changes in soil quality, water availability (irrigated and rainfed), and plant population levels (15 and 30 plants m^{-2}).

We used Robut 33-1 as a test cultivar to quantify yields in response to management factors. The simulated results showed that under no water stress situation, Ludhiana, Solapur, and Bangalore have the highest production potential when soil fertility is optimal and plant population is 30 plants m^{-2} (Table 39). High production potential at Ludhiana and Solapur is attribution to the high radiation regime at these locations, while at Hebbal it is because of low temperatures which caused extension of the crop growth duration resulting in greater yields. Sensitivity of yields to the change in soil fertility factor was much greater than to the change in plant population. This is because of greater compensation ability of groundnut plants when plant population levels are below optimum. Patancheru, Anand, Anantapur, Coimbatore, and Pune have relatively low yield potential because of frequent cloud cover and low radiation levels. Response to other management factors followed the similar trend. Simulated yields under rainfed situation are directly related to the amount and distribution of rainfall at these locations. At Patancheru, Anand, Coimbatore, and Bangalore, the modeled yields ranged from 3.3 to 3.6 t ha^{-1}. Although the mean yields were high at Coimbatore and Bangalore, the standard deviation in yields was also high because of more variability in rainfall at these two locations. At other sites, the yields were low as well as the variability in yields was also high which is directly linked to the amount and variability in rainfall at these sites. Response to plant population and fertility factor followed a similar trend as in the irrigated situation.

The above analysis has distinguished the locations in terms of their production potentials and yield reductions caused by weather and management factors. Sites with assured rainfall need more attention for managing soil (soil fertility), whereas sites with low rainfall would need more attention for managing water and its use efficiency. Physiologically, low plant population does not cause more reduction in groundnut yields. But this is rarely observed under field situations as the outbreak of diseases and pests causes greater yield reductions at low than at high plant population. Thus maintaining high plant population provides resilience to the crop against biotic stresses and possibly reduce soil erosion. This suggests that if groundnut crop can be well protected from diseases and pests, we can still expect high groundnut yields even at suboptimal plant population levels. However to provide resilience to the crop against yield reducers it would be worthwhile to maintain high plant population. In future we plan to extend this analysis to other locations in India where groundnut is grown.

Chickpea Model—CHIKPGRO

Model Development and Validation

A chickpea growth and development model (CHIKPGRO) has been developed by adapting the source-code of the hedgerow-version of the groundnut model PNUTGRO (Piara Singh and Virmani 1996). To start with, chickpea crop-specific parameters were incorporated in the crop parameters input file to make it chickpea crop-specific. Changes were also made in various subroutines determining vegetative and reproductive development, crop growth, and allocation of assimilates to different plant organs to simulate chickpea crop growth under water limiting and non-limiting situations. Using the experimental data of the 1984 and 1986 seasons, the model was calibrated for cultivar-specific parameters of cvs. Annigeri and JG 74. We determined their growth and development and for soil parameters needed for the estimation of the water balance of the root-zone. The model was validated against data obtained from the 1985, 1987, 1992, and 1993 season experiments. The model predicted flowering, pod-initiation, beginning of seed growth, and physiological maturity within ±5 days of the observed values, except under too wet situations when the actual seed growth and physiological maturity of chickpea occurred later than the simulated dates. Leaf area index, total dry matter production (TDM) and its allocation to various plant organs under irrigated and water stressed situations were also predicted satisfactorily by the model. Soil moisture dynamics in the root-zone of chickpea was also predicted accurately. Predicted TDM and seed yields of cvs. Annigeri and JG 74 at harvest were significantly correlated with observed data (r^2=0.89 for TDM, and r^2=0.82 for seed) (Fig. 28). These results on model performance show that CHIKPGRO can be used to predict potential and water-limited yields of chickpea at a location.

Genetic Coefficients

In addition to the development of the chickpea model (CHIKPGRO), we have also conducted experiments to collect the required data on growth and development of promising chickpea cultivars to develop their genetic coefficients for use by the model. These cultivars are Annigeri, ICCV 88202, ICCC 32, ICCC 42, ICCV 2, and ICCV 10. We have developed the genetic coefficients of these cultivars by model calibration. Future work will be on using the data to predict cultivar performance in different environments.

RESCAP—Chickpea

Model Development and Validation

Based upon the principles of RESCAP-Sorghum model, Piara Singh *et al.* (1990) developed the RESCAP-Chickpea model to predict potential and water-limited yields of chickpea in the SAT environment. The model was calibrated against the 1985 and 1987 measurements on cultivars Annigeri and JG 74, and then used to predict biomass, seed yield, and evapotranspiration (ET) for other seasons. A total of 27 independent data sets for seasons from 1978 to 1986 were available for testing the performance of the model. Simulated total dry matter was strongly correlated (r^2 = 0.87, $P<0.01$) with observed yields. Similarly simulated seed yields and ET were well correlated with observations (r^2 = 0.72 for seed yield and r^2 = 0.91 for ET). These correlations suggest that the model could be used more widely to assess water requirements and the associated chickpea biomass and seed yields in response to soil water availability and supplemental irrigation.

Predicting Response to Irrigation Schedule

The model was further used to assess yield responses of chickpea (cv. Annigeri) to irrigation schedules, and to soil water availability on a Vertisol for 11 postrainy seasons using the 1978 to 1989 climatic data at Patancheru. In response to irrigation, a maximum seed yield of 2.2 t ha^{-1} with a coefficient of variation (CV) of 21.4% was obtained when the (modeled) crop was given 5 cm of irrigation at vegetative, flowering, and pod-filling stages. Total biomass production with three irrigations was 5.0 t ha^{-1} with a CV of 9.2%. On the average, the crop used 30.5 cm of water to produce 5.0 tons of biomass per hectare. With two irrigations each of 5 cm, the best strategy was to irrigate the crop during flowering and pod-filling to obtain higher and stable yields over the years. The mean seed yield was 2.2 t ha^{-1} with a CV of 13.3%. With one irrigation, the crop could be irrigated either during flowering or pod-filling to increase yields, but the yields were more stable when the crop was irrigated during pod-filling. Non-irrigated yield was 1.4 t ha^{-1} with a CV of 13.3%. The response of chickpea to available soil water at emergence (ASW) was also examined. On average 2.9 t ha^{-1} of dry matter and 1.4 t ha^{-1} of seed were produced when the soil profile was full (20 cm ASW) at emergence. As expected, the yields declined and yield stability decreased with the decrease in soil water availability. When ASW was only 50% of its maximum value, only 0.6 t ha^{-1} of dry matter and 0.3 t ha^{-1} of seed yield could be produced. The crop was unable to extract water deeper in the profile because of restricted root growth. It is clear that the model is sensitive to water availability and could be used to assess yield response to soil water availability, rainfall, and supplemental irrigation.

Pigeonpea Model

Model Development

The pigeonpea model is an adaptation of a crop model for groundnut, PNUTGRO, developed at the University of Florida. The model needs the same input data as the PNUTGRO. The model then calculates phenology, actual daily evapotranspiration, photosynthesis, above- and below-ground biomass production and the development of pods. In our initial work, we retained the framework of PNUTGRO while focusing on crop growth under nonlimiting situations of soil moisture and nutrients. Field experiments to calibrate and validate the pigeonpea model were conducted under conditions of adequate available water and nutrients. The PNUTGRO root development subroutine was modified to reflect experimentally-observed root-shoot ratios that decreased from about 40% early in the season to 10-15% late in the season. We expect the root growth subroutine to undergo further substantial modification, as the 'perennial' characteristics of pigeonpea influence growth, distribution and activity of the root system, particularly in medium- and long-duration types.

Pigeonpea photosynthetic activity is concentrated in newly formed leaves. It gradually decreases in older leaves. Therefore, newly formed assimilates are distributed over (new) leaves, stem, and pods. As the pods develop, C and N assimilates in the older leaves are mobilized and transported to the pods. This results in the senescence of the older leaves and ultimately in their shedding. The pod development subroutine was modified by shutting-off the 'pegging' subroutine. The subroutine describing photosynthesis was changed to incorporate the effect of ageing of leaves on assimilation because the process of senescence (of leaves) is of little importance to groundnut, but is critical in pigeonpea. The process of senescence is driven by inherent (genetic) factors and by the development of the pods. We believe that further research is necessary in this area.

Model Validation and Future Work

With these modifications, the PGNPEA model was developed to describe the development of leaf area, biomass production and pods of pigeonpea under conditions of nonlimiting water and nutrients. Preliminary validation results showed that under the experimental conditions, the model describes the growth of the crop in the vegetative and early pod-fill stages fairly well. We are not yet able to model the late pod-fill stage accurately.

The model needs to be developed further, in particular, with regard to the soil moisture and root subroutines, if we wish to predict the response of pigeonpea to different ecological environments. The model also needs to be refined and tested with regard to the effects of photoperiod and temperature on phenology. Associated with this is the need to further develop the senescence and assimilate partitioning (accumulation, mobilization) subroutines. Discrepancies have been observed between predicted and measured growth and leaf senescence once active pod-fill begins. The mobilization and relocation of assimilates from older leaves is probably more than has been assumed hitherto, and the decline in N concentration in the leaves is not linear. The partitioning of N constituents could be studied using ^{15}N labeled fertilizers. Other areas in which the model could be further developed include the dynamics of nitrogen and phosphorus in soils and drought stress impacts.

Model Application

Virmani *et al.* (1995) evaluated the potential for introducing Extra-short duration (ESD) and short duration (SD) pigeonpea types into new agroecological environments or for intensifying its production in existing systems. This ex-ante analysis using crop growth simulation model could indicate (a) new agroecological environments where existing genotypes might fit well, (b) crop characteristics required to fit particular environments, and (c) yield gaps between potential and present levels of production. The possibility of extending the ESD and SD pigeonpeas in rainfed environments where the effective length of growing season is short, was examined. It was suggested that the ESD and SD pigeonpeas could find a niche as sole crops in areas with a seasonal rainfall of 500-1000 mm. The expected yield is 1.5-2.0 t ha^{-1}. The SD types need about 1400°C d and 750°C d during vegetative and reproductive phases respectively. The crop could, therefore, fit into regions where pigeonpeas are not currently grown, and replace crops such as maize which have similar agroclimatic requirements. A maize-pigeonpea rotation, which may be most sustainable may emerge, as the areas under ESD and SD genotypes extend in peninsular, central and northern Indian rainfed regions.

Modelling of Soil Management Effects—PERFECT Model

Several models available, such as CREAMS, EPIC, and CERES family models, simulate runoff as a function of rainfall and soil water content only. The model PERFECT (Productivity, Erosion, Runoff Functions to Evaluate Conservation Techniques), developed by Queensland Department of Primary Industries, Australia, includes effects of crop and surface cover and runoff is calculated as a function rainfall, soil water content, crop cover and surface cover. The surface cover and on-farm management algorithms of PERFECT were modified to simulate the management options relevant to Indian farming systems. The modified version is referred as PERFECT-IND.

Runoff algorithm of PERFECT-IND is based on a modified form of the USDA curve number (CN) procedure. In this version the effects of cover and tillage on curve number are incorporated as follows:

$$CN_{(cov)} = CN_{(bare)} - (C_1 \times COVER)$$

Where $CN_{(cov)}$ is the value of CN adjusted for surface cover, $CN_{(bare)}$ is the CN for soil with no cover, C_1 is the reduction in CN for each 1% of cover and COVER is the surface cover (%).

$$CN_{(til)} = CN_{(cov)} + C_2(\Sigma Rain/C_3 - 1)(\Sigma Rain<=C_3)$$

Where $CN_{(til)}$ is the value of CN adjusted for effect of tillage, C_2 is the maximum reduction in CN due to tillage, C_3 is the cumulative rainfall required to remove tillage effects and ΣRain is the cumulative rainfall since tillage.

The model simulates cover and runoff after tillage and adjusts the CN on a daily basis. Temporal changes in the surface cover are simulated by the functions that relate weight of surface amendment to percent cover (Table 40). The model also includes decay rates of the amendments and adjusts the cover function by calculating the amount of residue left. The decay functions are obtained from the studies of soil biologists in this experiment.

CNs for this soil were obtained from the rainfall runoff data collected both from natural events and simulator data. The curve number for bare soil is 94 and drops by 35 units when there is 100% cover. Similarly for shallow tillage the curve number is reduced by 5 units and for deep tillage by 10 units. These curve numbers will revert back to that of bare situation with a cumulative rainfall since tillage of 200 mm for shallow tillage and 400 mm for deep tillage. A separate calibration for CNs for perennials was made using the runoff data from those plots.

PERFECT-IND contains some new functions to simulate the farm management operations. They include:

1. Allowing the user to define dates, amount and type of amendment application
2. Permitting the user to specify deep or shallow tillage operations
3. Functions to simulate in-crop tillage operations
4. Removing all above ground biomass at harvest
5. Criteria for selecting tillage and planting operations

Results of the model validation showed that PERFECT-IND explained between 71 and 91% of the variation in daily runoff volumes. The model also provided accurate predictions of average annual runoff ranging from 33 to 217 mm for the 15 soil management systems studied under this project.

Cooperation with NARS and International Agencies

ICRISAT scientists collaborated with the national and international institutes in the development, testing, and validation of water balance, crop simulation, and soil management models for the semi-arid tropical environment. Collaborative projects were developed with the national institutes to conduct field experiments to collect minimum data sets required for testing and validation of models. As most of the crop models were developed in environments other than that of SAT, these required model calibration and adaptation to the semi-arid tropical conditions. Based upon the results obtained, appropriate changes were make in various routines of the models to improve their predictability. The scientists from the national programs were provided training in the management of databases and model applications in their environments. To study and model the soil erosion and productivity relationships of Alfisols, the QDPI scientists from Australia were placed at the IAC Center for a period of five years to strengthen this activity. Some of the important linkages were as follows :

- Sorghum and pearl millet modelling (CERES Models)
  - Michigan State University, USA
  - International Fertilizer Development Center, Muscle Shoals, USA
  - IBSNAT Project, University of Hawai, USA

- Groundnut modelling (PNUTGRO)
  - University of Florida, USA
  - IBSNAT Project, University of Hawai, USA
  - Punjab Agricultural University, India
  - Haryana Agricultural University, India
  - Gujarat Agricultural University, India
  - Andhra Pradesh Agricultural University, India
  - Tamil Nadu Agricultural University, India

- Chickpea modelling (CHIKPGRO)
  - University of Florida, USA

- Pigeonpea modelling
  - University of Florida, USA

- Modelling of soil management effects (PERFECT Model) on runoff, soil erosion, and crop productivity
  - Queensland Department of Primary Industries (QDPI), Australia

Water balance modelling
- Michigan State University, USA
- Central Research Institute for Dryland Agriculture (CRIDA), India
- India Meteorological Department, India
- National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), India

Applications of soil water balance and crop models
- International Institute of Applied Systems Analysis, Laxenburg, Austria

Future Plans

Simulation modelling will receive greater emphasis in the new research projects developed by ICRISAT. Simulation models of cropping systems and soil management will be used to evaluate management options and to transfer technologies to other agroecologies. To strengthen this work, a special ICRISAT/APSRU/ACIAR collaborative project entitled "Collaboration on Agricultural/Resource Modelling and Applications in the Semi-arid Tropics (CARMASAT)" has been developed for application of systems simulation modelling in SAT. With this ICRISAT will be entering a phase of development which features simulation of production systems which will include simulation of cropping systems and soil management effects on resource base, sustainability and productivity. CARMASAT will support the use of APSIM in a wide range of projects across ICRISAT locations. System models of ICASA will also be employed to address some specific issues of the projects.

In the Integrated System Project 1 (ISP1) the millet-based systems in Asia and Africa will be investigated for nutrient and water balance effects on crop productivity and sustainability.

In the Integrated System Project 2 (ISP2) simulation models will be used to quantify water and nutrient balances to address the sustainability issues of the sorghum and a groundnut-based systems in Asia and Africa. Nutrient balances will be quantified to find out the reasons for the lack of adoption of fertilizer recommendations in southern and eastern Africa.

In the Integrated System Project 3 (ISP3) models will be used to evaluate the opportunities for double cropping on Vertisols and Vertic Inceptisols, quantify nutrient and soil water availabilities, and yield gap analysis. Soil management models such as PERFECT will be used to evaluate soil water conservation practices and to assess land degradation.

In the Integrated System Project 4 (ISP4) water balance and crop models will be used to quantify soil water availability and potential productivity of legumes in the rice-wheat system. Nutrient availability models will be used to monitor and predict temporal changes in availability of nutrients in the rice-wheat system and to quantify the residual effect of legumes to guide fertilizer use and to evaluate the sustainability effects of legumes.

Table 38. Comparison of measured and simulated annual runoff for Vertisol watershed at ICRIAT Center, Patancheru, India.

Watershed	Land treatments	Year	Rainfall (mm)	Measured runoff (mm)	Simulated runoff (mm)
BW1	BBF* system at	1978	1091	270	264
	0.6% slope	1979	616	72	76
		1980	728	116	112
BW2	BBF system at	1977	566	0	0
	0.6% slope	1978	1080	186	187
	with farmers'	1979	615	38	48
	field bunds	1980	692	66	69
BW3A	BBF system at	1976	644	51	46
	0.4% slope	1977	562	0	1
		1978	1092	196	202

* BBF = Broadbed and furrow

Table 39. Yield estimates of groundnut (Robut 33-1) at various levels of soil fertility factor and plant population in irrigated and rainfed situations at selected locations in India.

Location	Plant population (plants m^{-2})	Soil fertility factor (PHFAC3)[1]	Pod yield ($t\ ha^{-1}$) ± Standard deviation	
			Irrigated	Rainfed
Ludhiana	30	1.0	5.1 ± 0.52	1.8 ± 1.24
	15	1.0	4.9 ± 0.51	1.4 ± 1.32
	30	0.7	2.9 ± 0.30	0.79 ± 0.69
	15	0.7	2.6 ± 0.28	0.69 ± 0.60
Patancheru (Hyderabad)	30	1.0	4.5 ± 0.22	3.6 ± 0.79
	15	1.0	4.3 ± 0.22	3.3 ± 0.76
	30	0.7	2.3 ± 0.15	1.7 ± 0.43
	15	0.7	1.9 ± 0.16	1.3 ± 0.33
Anand	30	1.0	4.7 ± 0.18	3.5 ± 0.84
	15	1.0	4.5 ± 0.19	3.4 ± 0.78
	30	0.7	2.6 ± 0.13	1.9 ± 0.39
	15	0.7	2.2 ± 0.14	1.6 ± 0.27
Anantapur	30	1.0	4.9 ± 0.14	1.5 ± 1.81
	15	1.0	4.7 ± 0.40	1.3 ± 1.73
	30	0.7	2.7 ± 0.09	0.75 ± 0.95
	15	0.7	2.3 ± 0.10	0.59 ± 0.79
Coimbatore	30	1.0	4.7 ± 0.33	3.7 ± 1.39
	15	1.0	4.4 ± 0.29	3.6 ± 0.99
	30	0.7	2.3 ± 0.17	1.9 ± 0.52
	15	0.7	1.9 ± 0.15	1.6 ± 0.34
Pune	30	1.0	4.8 ± 0.21	1.9 ± 1.5
	15	1.0	4.4 ± 0.22	1.6 ± 1.3
	30	0.7	2.3 ± 0.14	0.72 ± 0.64
	15	0.7	1.8 ± 0.13	0.54 ± 0.47
Bangalore	30	1.0	5.7 ± 0.38	3.3 ± 2.0
	15	1.0	5.2 ± 0.37	3.1 ± 1.9
	30	0.7	2.9 ± 0.29	1.6 ± 1.0
	15	0.7	2.3 ± 0.27	1.4 ± 0.86
Solapur	30	1.0	5.2 ± 0.31	0.23 ± 0.45

1. 1.0 = Soil fertility is optimum and it is not a limiting factor for crop growth and 0.7 = Soil fertility is suboptimal and has limiting influence on crop growth.

Table 40. Relation between percent cover and cover weight for different treatments.

Amendment type	Percent cover for residue weight (t ha^{-1})			
	0.5	1.0	2.5	5.0
Sorghum	17.4	36.1	74.3	96.6
Castor	6.8	13.2	22.1	38.7
Millet	13.9	30.5	69.1	91.9
Rice straw	47.5	92.2	98.8	100.0
Maize	13.7	18.7	47.3	96.5
Groundnut	26.2	46.2	94.7	100.0
Pigeonpea	7.1	11.0	21.9	39.8
FYM	13.0	21.0	30.9	32.8

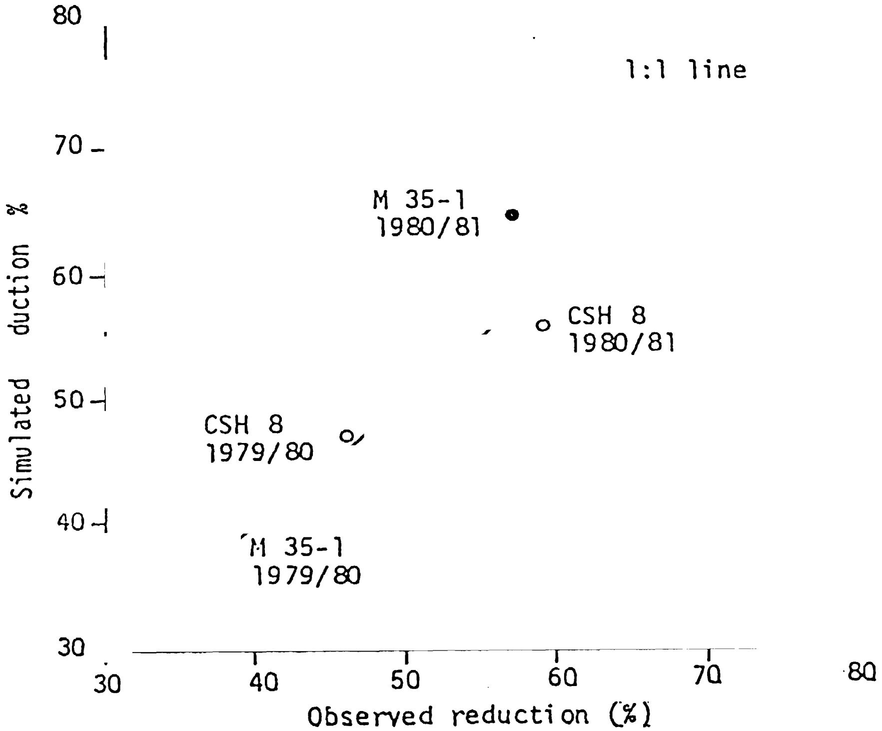

Fig. 25. Comparison between observed and simulated reduction in sorghum grain yield due to drought-stress for two sorghum cultivars in 2 postrainy seasons at ICRISAT Center, Patancheru.

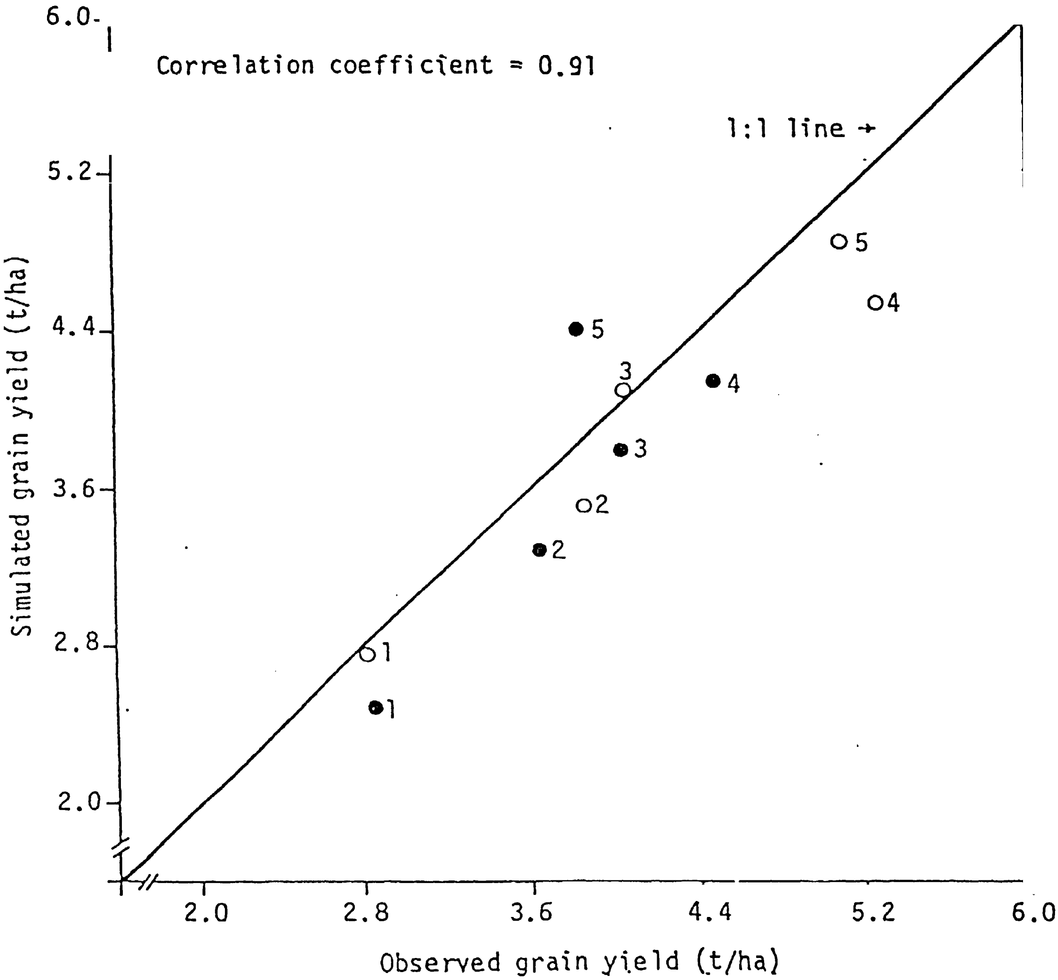

Fig. 26. Observed and simulated grain yield of two sorghum cultivars (o = CSH 6, • = SPV 351) under 5 levels of plant density (1 to 5 denotes lowest to highest plant density) in 1983 rainy season at ICRISAT Center, Patancheru.

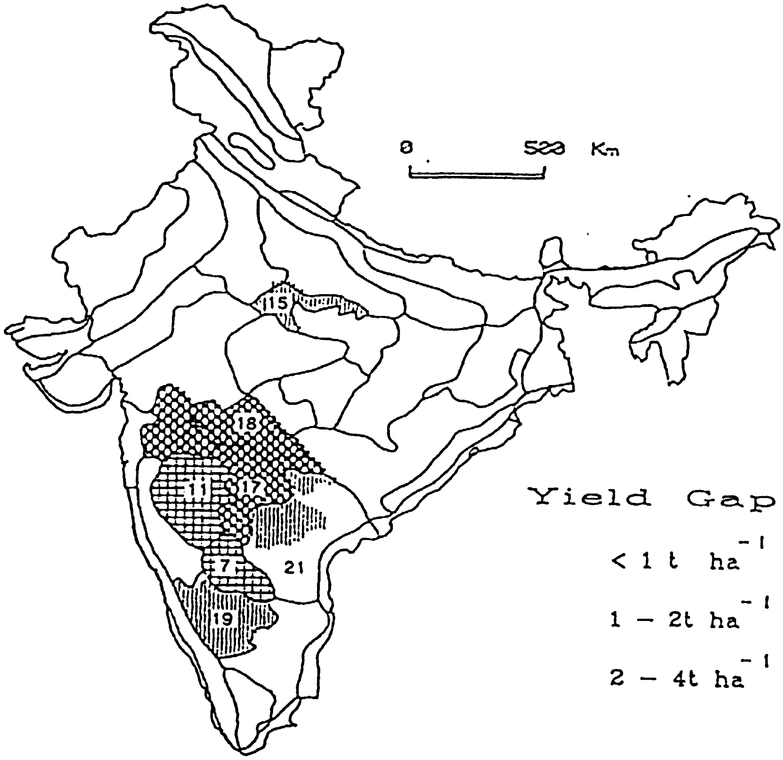

Fig. 27. Yield gap analysis of sorghum production for selected agroecological subregions.

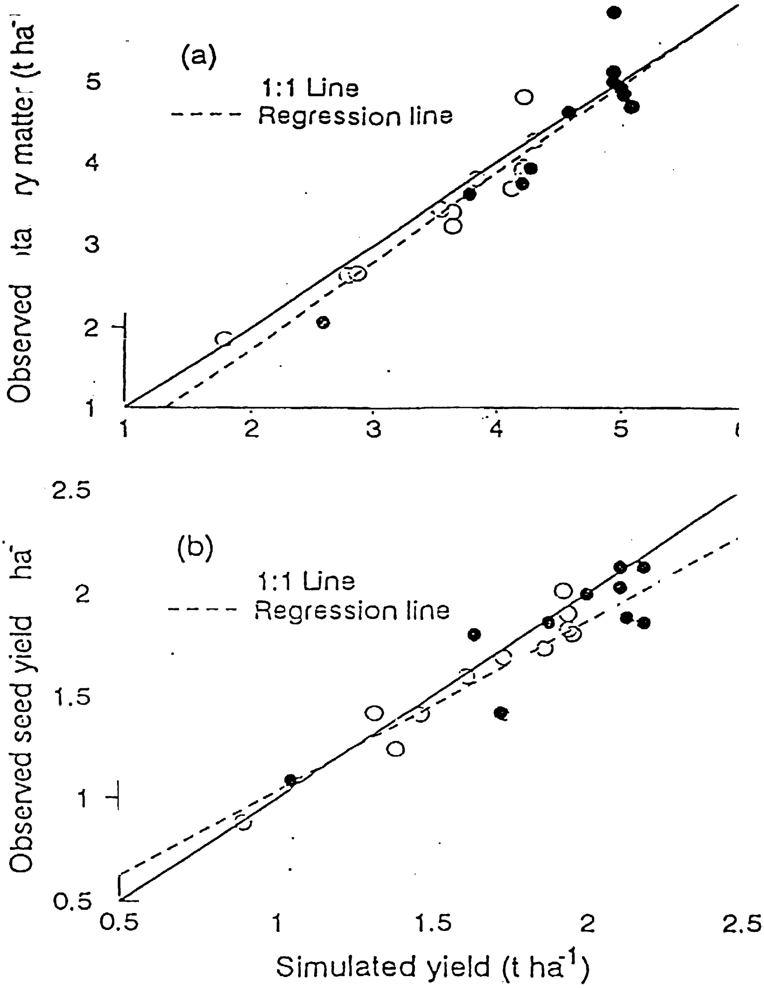

Fig. 28. Simulated versus observed (a) total dry matter (TDM),a nd (b) seed yields of cvs. Annigeri (o) and JG 74 (•). For TDM: y = -0.41 (±0.0331) + 1.07 (±0.08), r^2 = 0.89, rmse = 0.336; For seed yield: y = 0.21 (±0.149) + 0.83 (±0.08) x, r^2 = 0.82, rmse = 0.138.

SOCIOECONOMIC STUDIES

S. Kolavalli, M.L. Whitaker, J. Baidu-Forson and D.D. Rohrbach

The focus of socioeconomic aspects of soil, water, and nutrient management research has been closely tied to the priorities of ICRISAT's agronomic and soil science research. Three major themes can be identified: assessment of technologies for improved management of soil, water, and nutrient resources and identification of adoption constraints; common property issues; and degradation and sustainability of agriculture. Over the years the focus has shifted from the former to latter.

1970's and early 1980's: Assessing Technologies for Improved Management of Soil, Water, and Nutrient Resources and Identification of Adoption Constraints

Initially the central objective of ICRISAT's work in India on improved resource management was the development of technologies which made better use of available water. Noting that on the Vertisols of central India only a relatively small portion of rainfall was used in crop production, research focused on development of strategies to better exploit available water. The main objective of the land and water management research was to identify criteria for new varieties, cropping systems and crop management technologies which increased long-term rainfall-use efficiency while contributing to runoff control and erosion protection. Traditional solutions such as contour bunding, fallowing, and other traditional methods to cope with excess moisture were considered to be ineffective. Although bunds are efficient for soil conservation, their disadvantages were thought to outweigh any advantage. They were also rejected because no substantial yield benefits from moisture conservation were obtained from contour bunds under most conditions.

Watershed-based resource development approach included a)control and management of water where it falls, b) controlled and safe removal of excess water and where possible c) the use of supplemental water for rainfed agriculture. Ponds were tested to store runoff from the watersheds. Broad beds built along the mild grade which could last for a few years were found to be superior to ridges and furrows. They were one of the basic components of a 'Vertisol technology' package. The technology was tested in watersheds on site and in farmers' fields. A cooperative on-farm project was initiated in 1978 to adapt, test and measure the performance of prospective land and water management technologies.

The early work in SEPD focused on the assessment of Vertisol technology components. Information from experiments on-site and on farmers' fields was used in cost benefit analyses and modelling. In addition to work on constraints to adoption, related studies were conducted including studies on fertilizer use by farmers and constraints to double cropping.

The research during this phase related to:

- methodologies for assessing the impact of new technology on SAT agriculture
- economic assessment of soil, crop, and water management and improved watershed based technologies .
- role of social organization in small watershed development potential for water harvesting and supplementary irrigation
- credit requirements of new technology
- constraints to double cropping
- rainfall probabilities and risks of farming
- fertilizer use in SAT

A study based on on-farm testing of Vertisol technology showed that although yields increased somewhat, profits were not significantly higher; and costs were three times higher compared to traditional technology (Sarin and Ryan, 1983). The benefits from broad beds were not significant particularly when the same production technology was adopted on both broad beds and traditional leveled fields. The study emphasized the need to develop more cost effective technologies and also the need to adopt the total package to get attractive returns. The experiments on site yielded fairly high returns when all components of the technology (the use of fertilizers, soil and crop management, variety and water management) were adopted. The benefits were however lower on Vertic Inceptisols and on Alfisols. An ex-ante evaluation using a whole farm model to see the potential performance of technology showed that availability of credit would be key to adoption (Ghodake and Lalitha, 1986). Double cropping was found to be very profitable; sowing an extra crop on Vertisols generated more than seven times the profits of the traditional rainy-season fallow, postrainy season cropping pattern.

Simulation models which used derived rainfall runoff relationships were used to evaluate economic potential for postrainy season pigeonpea. A runoff simulation model was developed for Alfisols to assess the probability of having a viable amount of runoff available in December. It indicated that there would be sufficient water and that return on investment would be adequate (Krishna Gopal and Ryan, 1983). The benefits from storage of water and irrigation on Alfisols were studied. The results suggested that it would be difficult to justify water harvesting and supplementary irrigation for rainy season, low value upland crops like sorghum.

The need for farmers to work together in adopting watershed technologies was recognized to be a limitation of the technology. Consolidated holdings were thought to be conducive to introduction of watershed based technologies as they may not require group action to implement. The work on collective management of wells also suggested that individuals will work together when the benefits include additional returns to compensate for the transaction costs involved in organization (Doherty, 1982).

Another study focused on the minimum needs for an assessment of impact of improved technologies on agriculture (Ryan, 1975). It suggested methods to account for the effect of uncontrollable variables and emphasized the need to document the distribution of benefits from technology adoption particularly as it could be adopted only by those who have access to resources. It also emphasized the importance of operational research on farmers' fields in providing immediate feedback to scientists.

In the mid to late seventies greater attention was given to soil nutrients . The research focus was on soil fertility management and fertilization of important crops and cropping systems and investigation of seasonal changes in nutrient status under different management systems. As most SAT soils are unable to supply sufficient nitrogen and phosphorus for optimum plant growth, there was concern that deficiency of these nutrients is likely to become more pronounced as cropping intensities increase and new varieties with higher yield potential and nutrient requirement are introduced (Jha and Sarin, 1984).

The soil fertility and chemistry program gave increased attention to nutrient requirements of new agronomic developments. Our studies showed that nearly 60 per cent of the fertilizers was consumed in irrigated districts or those with more than 25 per cent the cultivated area irrigated. Lack of fertilizer response in traditional varieties and the lack of irrigation were considered to be primarily responsible for relatively low levels of fertilizer use in SAT (Jha and Sarin, 1980).

A soil fertility program in West Africa initiated in 1982, was directed at identifying optimal levels of nutrient N and P for pearl millet. Different sources of P were evaluated. In some cases the net gains from the application of P alone exceeded the net gains from combined application of N and P. The study suggested that application of N to pearl millet in sandy soils of the Sahel may not be profitable. It also indicated that small quantities of natural phosphate rock applied more frequently are more profitable than large quantity added at extended intervals. (Bationo *et al.* 1994).

Late 1980's: Common property issues

Work on common property was initiated in the mid eighties in India. Additional studies on the economics of Vertisol technology were motivated by concerns regarding poor adoption. This phase was also characterized by greater interest in understanding farmer decision-making, management capabilities, and knowledge systems, and rural institutions (Jodha, 1985).

Research during this period related to:

- contribution of common property resources, their decline, and consequence for the poor
- credit requirements of Vertisol technology

- tank irrigation in India

- small scale irrigation in Alfisol watersheds and water management options for rainfed agriculture

- constraints to double cropping

- economics of Vertisol technology and socioeconomic aspects of technology transfer

- indigenous soil classification

Research on common property resources (CPRs) highlighted their role in providing employment and income to the poor, the changes in their management, and their consequences for the poor. The study revealed that CPRs provided significant employment and income to rural poor and that the area of CPRs had been declining (Jodha, 1986).

The work on irrigation examined the variability in area irrigated by tanks and rice production in comparison to non-irrigated crops such as sorghum. It indicated that food production was becoming unstable because of instability in area irrigated by tanks. The instability was attributed to lack of maintenance, siltation, poor water control systems and shifts in rainfall patterns (von Oppen, 1988; Virmani, 1991).

Various options for managing water under different rainfall and soil water holding capacities were evaluated. Strategies were suggested for different conditions. Improved tank management and a system of runoff and erosion controlling land management practices were examined as useful concepts for improved watershed management (von Oppen and Subba Rao, 1987). A stochastic linear programming model was developed to assess the impact of composite watershed management on SAT agriculture (von Oppen *et al.* 1986).

Constraints to double cropping were examined. They found that farmers who were producing their subsistence crop in rabi season were reluctant to raise a kharif crop in the lands allocated for these crops (Foster, 1988). Indigenous soil classification was examined (Dvorak, 1988).

Lab analysis of soil samples generally supported farmers way of thinking about soils. The system adopted by farmers was at times better suited than formal systems adopted by scientists to stratify soils into groups for analysis.

Constraints to adoption of Vertisol technology were examined. The development costs of improved technology were estimated. It was felt that there is a need to increase credit supply to facilitate adoption. It also emphasized the need for adoption of the total package to get full benefits of the technology (Walker *et al.* 1989). Doubts were also raised as to whether the existing delivery system in India was capable of transferring this technology which was a package. Improved technology also tended to cause peak labor periods to widen. It also emphasized the need for adoption of the total package to get full benefits of the technology (Ryan *et al.* 1989).

1990's: Degradation and Sustainability of Agriculture

Although double-cropping, a key component of Vertisol technology, yielded higher returns through better utilization of moisture, it had the potential of depleting soil fertility. Experiments on site indicated that double-cropping on deep vertisols will require additional nutrient inputs for both rainy season and post-rainy season crops. Maintenance of soil fertility and sustainability of soil productivity became a research question. There were doubts as to whether introduction of legumes will influence soil nitrogen status.

Resource management also was given a broader definition. The objective of the resource management program was stated as "finding ways in which farmers of the semi-arid tropics can use the scarce resources of the region more efficiently and without making them even scarce by damaging the environment". The word sustainability appeared in the annual report in which the central problem was defined as being maintaining or increasing yield by using renewable resources such as rainfall more efficiently without degrading resources such as soil. Emphasis was put on long-term improvement of soil fertility, management of rain where it falls, and systems which maximize yields when inputs are constrained. Study to quantity relationship between erosion and crop productivity began on site.

The socioeconomic studies conducted during this stage reflects this concern. The research was related to:

- sustainability of alternative cropping systems
- farmer fertilizer practices
- soil fertility management
- crop rotation in traditional farming systems
- soil and water conservation practices of farmers
- adoption of watershed technologies
- investigation of individual discount rates
- perception and management of FYM

- modeling agroecological environments to identify priority area for soil conservation sustainable management of grazing land in Rajasthan

A spread sheet model was developed to make comparisons of total factor productivity across cropping systems and over time to quantify the productivity and sustainability of alternative cropping systems, The model was tested with data from long term trials conducted at the site. The attempt highlighted the need for long term experimentation if sustainability is to be understood (Binswanger *et al.* 1980).

The studies in south India also showed that farmers have developed effective practices for conserving soil and water on dry lands. Economic factors determine not only the design of soil and water conservation technologies but also their adoption patterns. In another study , discount rates of individuals in two villages were measured using experimental games . The results of both the games and the questions revealed that the discount rates were significantly above the highest interest rates paid by respondents indicating the presence of binding credit constraints.

Surveys were conducted in two locations typical of Sahelian environments to assess technological, socioeconomic and institutional factors relevant to wind erosion control. The specific objectives were to identify relative priorities accorded to specific wind erosion control techniques, examine constraints to adoption of highly-rated methods of control and the policies needed to facilitate adoption of wind erosion control techniques. The study found widespread recognition of the importance of human factors in exposing soils to wind erosion. Increasing demographic pressure and deforestation were perceived as very important factors in promoting soil exposure to erosion. Low cost, technologies based on indigenous know-how and locally available raw materials were perceived to be very important to adoption of erosion control technologies.

The fertilizer practices study showed that fertilizer applications by farmers was heavily biased towards nitrogen. Farmers added farm yard manure as a soil amendment and not as a substitute for fertilizers.

A study based on on-farm experiments conducted in Niger evaluated the response of pearl millet to application of P and N and crop rotation. Relative agronomic efficiency and net gains from fertilizer amendments were estimated for cereal-legume rotations in sandy soils of the Sahel. Economic analysis supported the results suggested by RAEs. The analysis of annual financial returns showed that it is better to apply P annually.

On-going work includes:

- the potential for inclusion of legumes in rice-wheat systems to maintain soil productivity

- farmer perceptions of soil and water conservation technologies and farmer practices the extent of soil degradation and its impact on yields

- farmer nutrient management practices and perceptions

- strategies to improve soil water and nutrient management in millet-based systems of Rajasthan

Agenda for the Future

The research objectives in the area of SWNM are to develop technologies and policies for improved management of soil, water, and nutrient resources for enhanced productivity and sustainability of drylands in the SAT. SAT farmers manage the use of their soil, water, and nutrient resources through crop and soil management practices which include crop rotations and mixtures, use of manure and penning of animals, limited use of fertilizers, response farming, bunding and other soil conservation structures. Under the pressure of rapidly increasing population and food demand, farmers are intensifying crop production. Most small-scale farmers living in this climatic zone presently have low incentive to invest scarce capital in soil productivity. Consequently, with cropping intensification, cropland productivity is declining due to soil erosion and the mining of soil fertility. Not enough is understood about how farming systems are changing; how farmers are managing the changes particularly with respect to soil, water, and nutrient resources; and what constraints and opportunities may exist for improving farmers' management strategies to enhance and sustain farm productivity. Economists will work with agronomists, soils scientists, and farmers in exploring the possible implications of alternative crop and soil management strategies for managing soil, water, and nutrient resources through on-farm and on-station studies and simulation modelling.

The focus will be on:

- understanding degradation caused by movement of soil and depletion of organic matter caused primarily by intensive cultivation, and its effect on crop productivity understanding why farmers do or do not invest in soil fertility inputs and soil conservation to maintain or improve soil productivity

- identifying opportunities for better management of limited soil, water, and nutrient resources to enhance and sustain farm productivity

Issues include:

- The nature and the extent of soil degradation due to soil movement; impact of degradation on productivity; technologies to arrest degradation; farmers' perceptions of degradation, its effects on productivity and the means to alleviate it; and finally the need for state intervention.

- The nature and the extent of nutrient mining under various cropping systems;

- Economic viability of practices which help to increase production without depleting soil resources; constraints faced by farmers in adopting such practices.

- The nature of constraints to investments in improving soil productivity; farmers' objective functions, risk preferences, discount rates; fertilizer availability; costs of degradation and benefits of improved management at the farm level; lack of information.

- The role of institutions in influencing decisions on resource management.

In all these areas, the thrust is on documenting 'what farmers do' and on understanding 'why farmers do what they do' so that we can identify the constraints and opportunities for improved management options. What ought to be done is also not well known to us. Evaluation of options for managing soil, water, and nutrient resources is especially difficult in this climatic zone because of the temporal and spatial variability in rainfall. Simulation models offer a potential means of alleviating this difficulty if the models can simulate sufficiently well the important interactions of environment with management interventions. Cropping systems models are being adapted and tested with farm-level data to simulate growth and yield of important crops; runoff and soil erosion; long-term trends in soil organic matter; soil dynamics, and supply to plants of water, N, and P; effects of residues, manure and fertilisers; interactions of crops in mixtures and sequences; and conditional crop and soil management actions. Cropping systems models will strengthen experimentation on the effects of degradation on crop productivity. The models will allow researchers to explore a wider range of options for arresting or reversing degradation processes and improving soil water and nutrient management than would be feasible in field experiments, through simulated experimentation. Cropping systems and economic models will be used in farm case studies to explore ways to improve management of soil water and nutrients through "What if?" analysis and discussions on important issues. The farm case studies will be supplemented by work on institutions and their effects on the possibilities for improving individual farmers' resource management.

A more precise definition of sustainability for agriculture will be developed and a set of indicators of sustainable agriculture will be identified which can be relatively easily measured using local knowledge systems. These indicators would be grounded in factors that scientists associate with 'unsustainability' (soil fertility status, groundwater status, loss of topsoil, loss of vegetation, ...) but applied with observable measures that local farmers associate with 'unsustainability'.

The indicators could be used in prioritizing research or in assessing impact of technologies.

ON-FARM TESTING AND EVALUATION

A. Bationo and J.Baidu-Forson

Introduction

A review of the state of the art of the agronomic research concluded that on-station research has developed a considerable amount of promising results but very few of these technologies have reached the small farmers. It is recognized that most of the technologies developed on-station are not built on indigenous practices and local socioeconomics realities. Farmers' priorities and perceptions also have not always been appreciated. Therefore, on-farm research will involve researchers, farmers, extension agents, non-governmental agencies, policy makers at the design, implementation and evaluation stages. In this way, the technologies generated have a better chance of adoption by the farmers.

On-farm research reported here was conducted in West Africa and identifies some technologies to be tested on-farm under farmer managed trials knowing that a particular farm management practice is often less effective in the hand of the farmer than it is in on-station or on-farm researcher managed trials. Experimental farm input packages should therefore be tested under farmer's conditions to allow the scientists to observe transfer of techniques to the farmers' field and to determine associated management practices to be adopted in order to ensure good economic return.

The specific objectives of the on-farm research activities were:

- To assess farmers' perception of the different technologies proposed.
- To identify the farmers' management practices which affect the performance of the different technologies.
- To evaluate the profitability of the different technologies.
- To identify the constraints to technology adoption and means to alleviate them.
- To assess in impact of technology adoption.

The farmer managed trials were carried at Gobery (Niger) from 1986 to 1995 and from 1995, two new sites were selected at Karabedji and Banizoumbou (Niger). The village of Gobery is situated at 120 km southeast of the capital Niamey, Niger. The average annual rainfall of about 600 mm. Rainfall is highly variable, undependable and end of season drought is a common phenomenon. The soils of the study area are sandy paleustalfs. Banizoumbou and Karabedji are located at 80 and 50 km distance from Niamey with average rainfall of 400 mm and 500 mm respectively.

Previous agronomic data from on-station research clearly indicated that crop production can be a function of both climate and soil conditions. However it has been concluded that in the Sahel, the low soil fertility is a more limiting factor to crop production than rainfall. On-station research has also established that phosphorus is the most limiting nutrient to crop production in the Sahel and response to nitrogen can be substantial when both moisture and phosphorus are non-limiting. Intensive cropping, without restoring, depletes the nutrient base of the soils. The continuous soil nutrient mining in Niger in 1993 was estimated at 16 kg N ha^{-1}, 5 kg P_2O_5 ha^{-1} and 8 kg K_2O ha^{-1}. This phenomenon results in reduced soil fertility, damaged soil structure increased water and wind erosion. Nutrient mining by crops which are increasingly being cultivated on marginal lands is promoting soil and environmental degradation at an alarming rate.

The research program on integrated nutrient management started in 1982 and after three years of on-station research, the program identified some technologies to be tested on-farm under researchers' managed and farmers' managed trials knowing that a particular farm management practice is often less effective in the hands of the farmer than it is in research on-station managed plot.

Among the different technologies tested since 1985 in Gobery, are phosphorus fertilizers sources, water soluble P-fertilizers, phosphate rock (PR) and partially acidulated phosphate rock (PAPR), planting density, legume-cereals rotations, and application of crop residue as mulch.

Evaluation of nitrogen and phosphorus fertilizers and planting density for pearl millet production in Niger

From 1986 to 1988 a study was conducted with 20 farmers in Gobery, Niger to assess the response of pearl millet [*pennisetum glaucum* (L.) R. Br] to phosphorus and nitrogen fertilizers under farmers' conditions. In each field, treatments included control, single superphosphate only (SSP), SSP plus nitrogen broadcast or hill placed (SSP+N) and partially acidulated phosphate rock from Parc-W in Niger plus nitrogen (PAPR + N), N and P were applied at 30 kg N ha^{-1} and 30 kg P_2O_5 ha^{-1}. Farmers were allowed to plant, weed, etc., as they wished and they planted at densities ranging from 2,000 to 12,000 pockets per hectare.

In the comparison of the five treatments over 3 years, millet showed a significant response to fertilizer, and annual application of 30 kg P_2O_5 ha^{-1} without supplemental nitrogen resulted in yield increases of 125% (Table 41). Treatments that received nitrogen in addition to phosphate showed a 181% increase over controls. No significant difference was found between PAPR and SSP, nor was a difference found between SSP plus N broadcast and SSP plus N hill placed. However, crop response to fertilizer use was strongly affected by the cropping density chosen by the individual farmers (Bationo et al. 1992).

Averaged over all fertilized treatments and all years, crop density was shown to have a highly significant effect on millet yield. When farmers in the lower density quartile planted at less than

3,500 pockets per hectare, yield was very low (317 kg ha^{-1}) and no response was found to fertilizer use. However, for each 1,500 pocket ha^{-1} increase of approximately 200 kg grain ha^{-1}.

The strong effect of density on yield was evident in all treatments. In the absence of fertilizer inputs, increasing density from 2,000 to 7,000 pockets per hectare (the highest density achieved without fertilizer) increased yield by approximately 450 kg. Over the density range of 2,000 to 12,000 pockets/ha that was found in the fertilized plots, addition of P alone increased yield 490 kg ha^{-1} above that of the control to give a yield benefit of 16 kg grain/kg P_2O_5. However, increasing density did not greatly enhance the yield response to phosphorus. The response to N+P relative to P only or control treatments was highly dependent on crop density. At densities below 3,000 pockets ha^{-1} no response to P+N was found. However, as density was increased to 10,000 pockets ha^{-1} and N demand rose, a millet response of an additional 333 kg grain over the P only treatment was predicted.

Phosphate fertilizer applied in 1986 continued to have a significant residual effect on crop growth in 1987 and 1988. Annual residual response to fertilizer was found in the low density plots, yields in the high density plots averaged 100 kg grain per hectare higher than controls. A significant residual effect, in terms of increasing plant density, and therefore yield was also found for 2 years after phosphate application though no such effect was noted with nitrogen.

A significant effect of fertilizer use on plant density at harvest was noted in all years. Even though each farmer planted at the same density in the control and fertilized plots, average densities at harvest in 1986 for the fertilized treatments were 40% higher than found in the control plots. Similar trends were noted in 1987 and 1988, suggesting that P fertilizer use had the additional effect of increasing the survival rate of plants. These results illustrate the role that fertilizer use can have on early crop development and crop survival. Fertilizer promotes rapid early shoot and root growth and thus enables the plant to better withstand early drought stress. In addition, improved vigor reduces the extent of injury caused by moving soil in the sandstorms that may precede major rainfall events in the Sahel.

It is evident that fertilizer use efficiency, and therefore the profitability of its use in farmers' fields, depends significantly on crop density, which, in turn, determines the millet response. Once this is set, the profit realized by the farmer depends on two ratios: the ratio of the value of the additional grain produced to the cost of the fertilizer inputs necessary to achieve this yield (value: cost ratio) and the ratio of the costs of a kilogram of fertilizer to the value of the kilogram of millet (price ratio). These ratios will vary with government pricing policy and market prices. Based on the yield model described and on the density reduction without fertilizer, the value: cost ratio for fertilizer use depends on both the price ratio and planting density. A value: cost ratio of 2 has been chosen by FAO as the economic limit above which a farmer will likely adopt a crop management practice. In such a case a farmer would achieve a return of 100% on a fertilizer investment.

When millet prices are high and/or P fertilizer is inexpensive (price ratio of 3.5 or less), the model indicates that use of 30 kg P_2O_5 is profitable at any density in excess of 1,000 pockets ha^{-1}

and would result in a value: cost > 2. As the price ratio increases, profitability of P use is limited and when it reaches 6, even very high densities will not make P fertilizer by itself a viable option.

Because of phosphate plus nitrogen is more expensive than phosphate alone and the effect of N is not as strong as that of P at low density, a very favorable P+N pricing must be in effect before their use at low density will result in acceptable value: cost ratios. Thus, the farmer must use high densities to maximize the benefit of his inputs. Figure 29 indicates that in no case P+N (30 kg/ha as P_2O_5 and N) will be profitable at a density of 1,000 pockets ha^{-1} and only at 3,000 pockets ha^{-1}, P+N will fertilizer show profitability at a price ratio of 4 or lower. However, as the price ratio increases to 10, P+N fertilizer use can still exceed a value: cost of 2 if crop densities are kept high enough.

Evaluation of water soluble phosphorus and nitrogen fertilizers, phosphate rock from Tahoua (PRT) and rotation of cereal with legumes

Phosphorus (P) deficiency is a major constraint to crop production in West Africa. The use of P fertilizers at the farm-level is limited by supply and the high cost of imported fertilizers. Therefore, the availability of cheaper but efficient sources of fertility amendments would be helpful to farmers. Phosphorus rock deposits, that can provide cheaper source of P, exist in some Sahelian countries. On-station research showed that finely-ground phosphate rock of Tahoua (PRT) can be 82% to 91% as effective as single superphosphate (SSP), when used for pearl millet (*Pennisetum glaucum* (L.) Br.) production (Bationo et al. 1990).

Nitrogen (N) uptake by pearl millet crop on sandy Sahelian soils is between 20% and 37% of the total N that is applied whereas N losses that occur are about 25% to 53% (Christianson et al. 1991). Nitrogen fertilizer is an important but costly and more risky input than P in millet production. The fixation of N by legumes in cereal-legume rotations could reduce the risk of financial losses associated with N application in the unpredictable production environment that characterizes the Sahel. The most important legumes in the Sahel are cowpea (*Vigna unguiculata* (L.) Walp) and groundnut (*Arachis hypogaea* L.) Sahelian farmers sow cowpea at very low density as an intercrop with pearl millet.

A farmer-managed fertilizer and rotation trial was conducted between 1990 to 1992 at Gobery. Relative agronomic efficiency (RAE) and partial budgets are used to show the efficiency and profitability of applications of P from PRT, N from urea and cowpea-millet rotations.

Phosphorus was broadcast on the soil surface before planting. There was split-application of N (15 kg/ha per split), from urea. The first split was applied at about two to three weeks after planting (WAP) while the remaining equal amount was applied at about five WAP. Local millet and improved cowpea (cv TN5-78) varieties were planted in the treatments. The timing and frequency of field operations were at the discretion of farmers.

The RAEs were calculated for P from PRT, the addition of N and rotation. The test and reference treatments have the same characteristics with the exception the effect being studied. The control yield is either the traditional continuous sole millet or the continuous sole cowpea depending on the crop grown in the reference and test treatments.

Both annual application of P from SSP and the residual effect of single P application significantly increased yields of pearl millet grain and total dry matter, compared to yields of the continuous millet with no fertilizer application that is traditionally practised by Sahelian farmers. Although the results show two-year residual effect on dry matter, there was no evidence of significant yield gains when P application interval exceeded one year.

Relative efficiencies of 50% or less observed for P from PRT, were much lower than the results of earlier researcher-managed trials that showed RAEs of between 82% and 91%. Similarly, the relative efficiencies of PRT in cowpea cultivation were less than 80%. In the researcher-managed trials, a rotor-tiller was used to incorporate PRT into the soil. However, in the farmer-managed trials, PRT was broadcast because farmers lacked the tillage equipment. Therefore, the observed lower RAEs may be due to the methods of PRT application and their relative effects on losses of pulverized PRT to blowing wind. It is possible to reduce losses pulverized PRT if phosphate rock is applied in granulated form. However, granulation is likely to decrease rapid release of P and thus increase cost of PRT that can be realized from millet production when PRT is granulated or compacted.

The addition of N to P from SSP produced higher RAEs, particularly when there was increasing reliance on residual P. Millet-cowpea rotations also showed consistently high RAEs for a millet crop that followed a pure cowpea crop. This is consistent with earlier millet-cowpea rotation results which showed that improvements in soil fertility by a sole cowpea crop are of benefit to the succeeding pearl millet crop. It was not clear from earlier studies whether the increased millet yields were due to the residual effect of N from the legume or the residual P. However, the compared sizes of RAEs for millet after sole cowpea in 1992 and the application of N suggest that the beneficial effect of a preceding sole cowpea crop on subsequent millet yields could be attributed to residual N effect. Therefore, in view of the high losses associated with N fertilizer application and its cost, millet-cowpea rotations could provide a less risky fertility improvement substitute for farmers in the Sahel. However, preference for staple millet grain, the need for insecticidal sprays to improve grain yields and the non-availability or cost of spraying equipment and insecticides might discourage farmers from cultivating sole cowpea in alternate years. The cultivation of pure cowpea might encounter fewer adoption constraints where there is a strong market for cowpea fodder, eliminating the need to spray, and there are well-established local market opportunities for exchange of fodder for millet grain.

Farmers make net financial gains if P from SSP is applied either annually or at least once every three years. Although costs are reduced when residual effect of P from SSP is used for millet production in two consecutive years, three-year net gains over the more costly annual application of P from SSP were significant. The use of N in addition to P application significantly improves net gains. Comparisons of millet-cowpea rotation treatments show that it is better to apply P annually instead of relying on the residual effect of P for two consecutive years. However, the low three-year net gains suggest that exploitation of benefits from residual P effect should be limited to one year.

Comparisons of treatments in which the same quantities of P from PRT and P from SSP were applied show that it is better to apply SSP. This is due to the low RAEs for P from PRT. However, where SSP is unavailable, farmers should apply indigenous PRT instead of continuing the current practice of continuous cropping without fertilizer application.

Comparisons of the traditional continuous millet treatment with each of the other treatments show that three-year net gains increase with frequency of cowpea cultivation. This is because cowpea grain and fodder prices are higher than millet grain and stover prices. However, the cultivation of cowpea requires higher amounts of labor, particularly for harvesting. The increased gross returns generated by the cultivation of cowpea are not high enough to compensate for the increased use of labor. Therefore, returns to labor are invariably reduced.

Evaluation of crop residue, water soluble phosphorus and nitrogen fertilizers, phosphate rock from Tahoua and rotation of cereal with legumes

Poor soil fertility and low use of organic and inorganic fertilizers are the greatest constraints to increasing agricultural productivity of farming systems in the West African semi-arid tropics (WASAT). Results from long-term field experiments showed that the use of mineral fertilizers alone in the long-run leads to decreasing base saturation, decreasing pH and increasing aluminum (Al) toxicity in soils which might be limiting crop yields. The soil fertility in intensified farming in the WASAT can only be maintained through efficient recycling of organic material such as millet crop residue (CR) or manure in combination with mineral fertilizers and using rotations with legumes such as groundnut and cowpea. The mechanism responsible for the positive effects of CR on crop yields are multiple. They include local conditions such as rainfall, wind speed, soil type, and temperature regime. Thus, at some sites an increase in available phosphorus (P) or potassium (K) may be the most important mechanism while at other sites, the protection against sand coverage and water erosion, a loosening of the upper soil layers, soil microbiological effects or a decrease of soil surface temperature and soil resistance may be dominant. In mixed crop-livestock systems, the issue of competing uses for CR needs to be addressed to understand the current mechanisms of resource allocation by farmers and to design economically and ecologically sound alternatives which ensure the sustainability of current farming systems at a higher output level. The complementary effects between livestock and crop production in the Sahel also suggests that research efforts should not only take into account ways to increase crop biomass at the farm level, but also to increase the quantity and quality of fodder. (Bationo et al. 1993)

Application of fertilizer and crop residue increased plant establishment at harvest, grain and total dry matter yield but the addition of SSP hill placed at the rate of 200 g $hill^{-1}$ was not significant. In 1995, phosphate rock from Tahoua was added to plot receiving the hill placement of SSP and both grain and total dry matter yield were improved as compared to the application of PRT alone.

It may be concluded that when cowpea is rotated with cowpea there is no more need to apply nitrogen to pearl millet.

As already indicated, Karabedji and Banizoumbou were selected from 1995 as additional sites for testing our technologies. Both water soluble P fertilizers, phosphate rock and hill placement of 200 g P $hill^{-1}$ as SSP positively affected millet density at harvest, grain, and total dry matter yields.

Assessment of the impact of the on-farm testing and evaluation of technologies

As a result of this research, farmers in Gobery increased their yield of millet by an average of 250% in the tests plots. Fertilizers consumption increased in Gobery from less than 2 units of single superphosphate (SSP) in 1982 to more than 115 units of SSP, urea, and compound NPK fertilizers in 1988. This figure has continued to grow and over 150 units of fertilizers were used during the 1994 cropping season. in 1994, 86 households of the total 136 planted a portion of their fields into pure cowpea for rotation with pearl millet. The introduction of cowpea as cash crop will allow the farmers to purchase inputs such as fertilizers. Use of millet straw as mulch and as source of plant nutrients has become a common practice. The use of rotations involving sole-crop cowpea and millet is gaining momentum. The cowpea serves as a source of biologically fixed nitrogen for the millet crop. Although the on-farm research involved only 30 farmers, today, over 98% of the farmland in Gobery is fertilized. Even though very little of the increased millet production was sold during the first few years of this program, farmers felt more food secure and used a greater proportion of their off-season income to purchase fertilizers. Perhaps more significantly in terms of soil fertility maintenance, farmers who applied fertilizers increased crop residue production which was used as fuel, fodder, and also to protect soil from wind erosion and improve fertility.

The on-farm trials have underscored two important lessons. First, the use of fertilizers is more efficient, profitable and environmentally sustainable when placed within an integrated system of sound management practices. These practices include use of organic materials and improved seed varieties; proper planting density and planting time; and split applications of nitrogen fertilizer. Because management practices are crucial to crop performance, research scientists, extension personnel and farmers must jointly develop and promote agricultural technologies. Further, farmers' needs, beliefs, preferences, and constraints as understood, defined, and articulated by farmers themselves must be built into the research and development agenda from the beginning. Second, phosphate rocks indigenous to West Africa can meet the phosphate needs of crops in the region. Researchers believe that sustainable use and management of West African natural resources can help reverse declining agricultural production, reduce soil degradation and desertification and alleviate rural poverty. African farmers have long recognized the need to improve soil fertility to maintain food production. However, the cost of imported fertilizers is beyond the reach of most resource-limited farmers. Most fertilizers are purchased with scarce foreign exchange. The devaluation of the currencies in all West African countries has reduced their ability to buy fertilizers. The focus on using indigenous phosphate rock as a cardinal axis of a national soil fertility management strategy as source of plant nutrients and as soil amendment has given national leaders new hope for regional food security.

Table 41. Millet grain yields by treatment (mean of 3 years).

Treatment	Yield ($kg\ ha^{-1}$)
Control	261
SSP only	586
SSP + N hill placed	700
SSP + N broadcast	751
PAPR + N broadcast	752
$LSD_{0.05}$	84

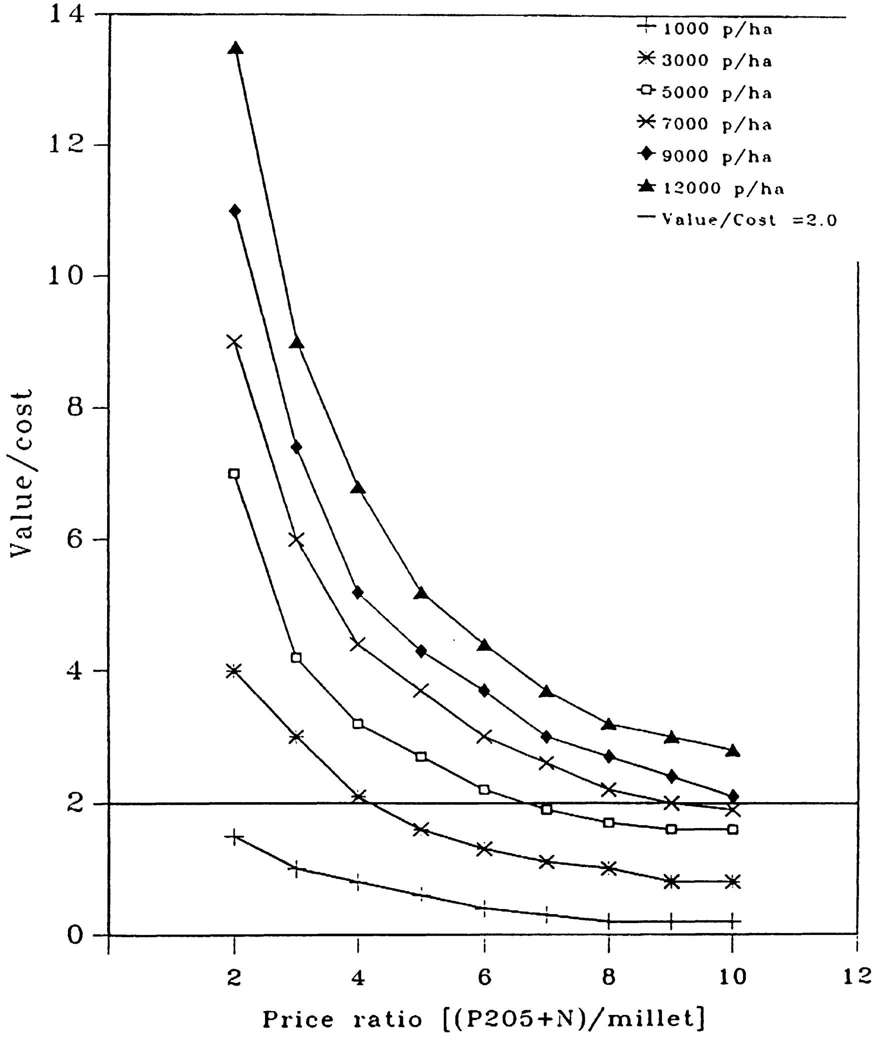

Fig. 29. Effect of price ratio and planting density on value cost ratio where farmers use both P (30 kg P_2O_5 ha^{-1}) and (30 kg N ha^{-1}) fertilizers.

Acronyms

APAU	Andhra Pradesh Agricultural University, Hyderabad, Andhra Pradesh, India
APSRU	Agricultural Production Systems Resource Unit
BBF	Broadbed and furrow
BNF	Biological nitrogen fixation
CARMASAT	Collaboration on Agricultural/Resource Modeling and Applications in the Semi-Arid Tropics
CCS	Conditional cropping system
CDF	Cumulative distribution function
CHIKPGRO	Chickpea simulation model
CN	Curve number
CPR	Common property resource
CR	Crop residue
CRIDA	Central Research Institute for Dryland Agriculture (ICAR), Hyderabad, Andhra Pradesh, India
D	Drainage
DSSAT	Decision Support System for Agrotechnology Transfer
DUET	Crop growth simulation model
EARSAM	Eastern African Research Network on Sorghum and Millet
E_S	Soil evaporation
ESD	Extra-short duration
ET	Evapotranspiration/water use
ET_A	Actual water use

ET_M	Maximum water use
FAI	Fertilizer Association of India
FAO	Food and Agriculture Organization
FEER	Fond de l'ean et de 'lequipment rural
FYM	Farm yard manure
GDD	Growing degree days
GIS	Geographic Information System
GS1	Growth stage 1
GS2	Growth stage 2
GS3	Growth stage 3
IAC	ICRISAT Asia Center
IBSNAT	International Benchmark Sites for Agrotechnology Transfe
ICAR	Indian Council of Agricultural Research
ICARDA	International Center for Agricultural Research in the Dry Areas.
IH	Institute of Hydrology
IIASA	International Institute for Applied Systems Analysis, Vienna
IIPR	Indian Institute of Pulses Research (ICAR), Kanpur, India
IITA	International Institute of Tropical Agriculture
ILRI	International Livestock Research Institute
ISC	ICRISAT Sahelian Center
ISP	Integrated System Project
ISU	Iowa State University

ISU	Intercrack structural units
K	Potassium
$K(\theta)$	Unsaturated hydraulic conductivity
KSU	Kansas State University
LAI	Leaf area index
M_o	Molybdenum
N	Nitrogen
NARS	National Agricultural Research System
NBSS&LUP	National Bureau of Soil Survey and Land Use Planning (ICAR), Nagpur, India
P	Phosphate
PAPR	Partially acidulated rock phosphate
PERFECT	Productivity Erosion Runoff Function to Evaluate Conservation Techniques
PGNPEA	Pigeonpea simulation model
PHFAC3	Soil quality factor
PNUTGRO	Groundnut simulation model
PRT	Phosphate rock from Tahona
PS	Production system
QDPI	Queensland Department of Primary Industries
RAE	Relative agronomic efficiency
RESCAP	Resource capture model
RUE	Radiation use efficiency
SD	Short duration

SEPD	Socioeconomics and Policy Division
SORGF	Sorghum growth simulation model
SSP	Single superphosphate
SWATRER	Water balance model
TDM	Total dry matter
TE	Transpiration efficiency
UNDP	United Nationals Development Program
USDA	United States Department of Agriculture
VAM	Vesicular Arbuscular Mycorrhiza
VASI	Vietnam Agriculture Sciences Institute, Hanoi, Vietnam
WAP	Weeks after planting
WASAT	West African Semi-Arid Tropics
WATBAL	Water balance model
WMO	World Meteorological Organization
WTC	Water Technology Center, Indian Agricultural Research Institute, New Delhi, India
Y	Yield
Y_M	Maximum yield
Z_M	Maximum depth of probe measurement

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