SUSTAINABLE AGRICULTURE

Issues, Perspectives and Prospects in Semi Arid Tropics

INDIAN SOCIETY OF AGRONOMY

CONTENTS

Chapter 9	R.F. Follett	Soil Plant Nutrient Research 301 South Howes Street, Fed Building, Ford Collins CO80522 USA
Chapter 10	H.L.S. Tandon Principal Consultant and Director	Fertilizer Development and Consultation Organization, 204-204A Bhanot Corner 1-2 Pamposh Enclave, New Delhi 110 048
Chapter 11	Suresh Chandra Babu	Cornell Food and Nutrition, Policy Program, Cornell University, Ithaca New York 14853 USA
	S.R. Subramanian	Centre for Agriculture and Rural Development, Tamil Nadu Agricultural University, Coimbatore 641 003 India
Chapter 12	I.C. Mahapatra Senior Consultant and Team Leader (SRPP)	Agricultural Finance Consultants Limited, New Delhi, India
Chapter 13	A.A. Jaradat Professor	Department of Agricultural Sciences, Jordan University of Science & Technology, P.O. Box 3030, Irbid, Jordan
Chapter 14	Merle M. Anders Production Agronomist	Research Management Program, International Crops Research Institute for the Semi-Arid Tropics, Patancheru P.O. Andhra Pradesh 502 324, India
Chapter 15	V.D. Mudgal Director	Project Directorate on Cattle, G-123 Shastrinagar, Meerut 250 005, India
Chapter 16	Panjab Singh Director	Indian Grassland and Fodder Research Institute, Jhansi 284 003, India
Chapter 17	Saleem Ahmed Research Associate	Resource Systems Institute, East-West Center, 1777 East-West Road, Honolulu Hawaii 96848, USA
Chapter 18	Martin M. Fogel Professor	School of Renewable Natural Resource University of Arizona, Tucson, Arizona 85721 USA
Chapter 19	John P. Reganold Assistant Professor	Washington State University, Department of Agronomy and Soils, Pullman WA, USA 99164
	Robert I. Papendick	U.S. Department of Agriculture, Agricultural Research Service Pullman, WA, USA 99164

NATURAL RESOURCES MANAGEMENT FOR SUSTAINABLE AGRICULTURE IN THE SUDANO-SAHELIAN ZONE

M.V.K. Sivakumar, C. Renard, M.C. Klaij, B.R. Ntare, L.K. Fussel and A. Batiano

1. INTRODUCTION

The Sudano-Sahelian zone (SSZ) of West Africa extends over several countries from Senegal and Gambia in the west to Chad in the east. With a growing season length varying from 60-150 days, it offers a range of growing conditions, but a large part of the region falls under 120 days of growing season (Sivakumar, 1989a). Subsistence agriculture is the main mode of livelihood in this region since 90% of the population lives in villages. Extended droughts since 1969 and successive crop failures resulted in a decline in the per capita food production. Hence sustainable agriculture to feed the growing populations has become an issue of major concern.

In the SSZ traditional systems of agriculture which thrived for centuries, were based on a delicate balance between crop production and ecological recycling of nutrients through long fallow periods and shifting cultivation. However, with the increasing need to feed the rapidly growing population in the region, fallow periods have virtually disappeared and rangelands were put to cropping bringing more marginal lands under cultivation. These practices have raised critical questions as to how long these areas can be kept productive. The only way to sustain productivity in these areas is through use of a production system which is based on conservation and efficient use of the natural resources. This paper reviews the major constraints of natural resource use for sustainable agriculture in the SSZ and describes several aspects of natural resource management using a case study from the ICRISAT Sahelian Center located at Sadore in Niger.

2. MAJOR SOIL AND CLIMATIC CONSTRAINTS FOR SUSTAINABLE AGRICULTURE IN THE SUDANO-SAHELIAN ZONE

2.1 Extreme variability of Rainfall in Time and Space : As is common with the semi-arid tropical regions elsewhere in the world, rainfall in the SSZ is low, variable and undependable. Certain characteristics of rainfall in this zone are as follows :

a) Rainfall in the SSZ is monomodal with the rains concentrated in a short period of 3-4 months. This is followed by a long, dry season for the rest of the year. Agriculture in the SSZ, which is predominantly rainfed, relies heavily on the timely onset of rainfall and its regular distribution through the rainy season.

b) Temporal and spatial variations of rainfall are so large that agricultural systems in the marginal conditions become vulnerable to such variations. Annual rainfall variations at three locations in the SSZ (Fig. 1) illustrates this problem clearly. Years with very high rainfall could be followed quickly by below-average rainfall years. The coefficient of variation (CV) of annual rainfall ranges between 15-30%.

c) Variability in the monthly rainfall is much larger since the rainfall is usually limited to the summer months i.e. May to October. This can be seen from the variation in the monthly and annual rainfall at Filingue, Niger from 1931 to 1988 (Fig. 2).

d) An important feature of the Sudano-Sahelian rainfall is the magnitude and extent of the rainfall deviations. Below normal rainfall could persist for 10-20 years. This can be clearly seen for Filingue (Fig. 2) where rainfall deviations exceeded 50% of the mean rainfall.

e) Rainfall deviations are common over many semi-arid regions of the world. The SSZ of West Africa however, is unique because of the wide spread nature of the rainfall fluctuations. Nicholson (1980) termed this feature as "preferred geographic pattern". For example, the reduction in the mean annual rainfall in Niger after 1969, was a geographical mean pattern, not an isolated or patchy occurrence (Sivakumar, 1989a).

2.2 Diversity of Soils and Problems with Soil Management in Traditional Agriculture : Most climatic zonation schemes are based upon natural vegetation and this is true in the case of SSZ as well. The use of this term dates back to Chevallier (1933) who first used the terms "Sahelian" and "Sudanian", with reference to the natural vegetation patterns. These developed from the north-south movement of the Intertropical Convergence Zone, the principal rain bringing mechanism in West Africa. Later Aubreville (1949) recognized that these climatic zones are essentially transitory in nature and proposed the terms "Sahelo-Saharian", and "Sahelo Sudanian" zones. Afterwards seven different rainfall limits have been proposed for delineating the Sahelian and Sudanian zones (Sivakumar, 1989a).

One of the basic problems with the use of broad climatic zones such as SSZ for sustainable agriculture is that it may convey a sense of homogeneity. In reality, the term SSZ hides a diversity of crop growing environments. Even if there is an agreement on the rainfall limits that could be used, water availability for crop growth should take into account not just rainfall, but potential evapotranspiration and soil types as well.

From the point of sustainability therefore, it is important to recognize the diversity of soils in the SSZ. Major soil types and their extent in the SSZ, computed from the soils map of Africa (FAO-UNESCOM 1977), are shown in Table-1.

Aeronosols and Luvisol are the two major soil types in the SSZ accounting for 56% of the total area. There are important differences in the physical and chemical characteristics of these soils as described by Sivakumar (1989b).

2.2.1 Poor management of soil fertility : Aeronosols are low in organic matter, N and P. The soils are very sandy, and the organic matter and cation exchange capacity of these soils is low. With the reduced ratio of the length of fallows to cropping years in the SSZ, soil fertility has been declining. According to Mudahar (1986), average use of fertilizers in the sorghum and millet growing countries of West Africa was only 5 kg/ha. In the absence of added manure or fertilizers on these poor soils, the rapid decline in the productivity under conditions of continuous cropping threatens sustainable agriculture in this region.

2.2.2 Limited, untimely soil management practices : Rainfall intensities in the SSZ are much greater in the temperate and subtropical zones and pose special problems in agricuitural management and soil conservation. Although appropriate soil and water management practices are crucial for making efficient use of the limited rainfall, at the farm level soil management practices are virtually unknown. In a major part of the millet growing region in the SSZ, use of animal traction for preparatory cultivation is not common and the soils are seldom plowed (Spencer and Sivakumar, 1987). On soils that are hard and crusty, non-adoption of soil tillage results in low infiltration rates and runoff, and in low water use efficiencies. Perrier (1986) in Burkina Faso estimated the surface runoff losses to vary from 40 to 80% of the annual rainfall.

2.3 High Temperatures and Wind Erosion lead to Problems of Crop Establishment : Environmental conditions during the stage of crop establishment in the SSZ, specially in the low rainfall areas, are usually harsh since the sowing rains follow a long and hot dry season. Air temperatures in the SSZ are usually higher because of the high radiation load. From south to north temperatures increase and rainfall decreases. From the analysis of the frequency distribution of air temperatures, Sivakumar (1989a) showed that mean maximum temperatures could exceed 40 °C at the time of sowing and that absolute temperatures could be much higher. During the dry season, and in dry spells during crop establishment, when the surface soil is bare and dry, the fields are susceptible to wind erosion. Moving sand particularly affects crop establishment by damaging the seedlings by "sand blasting" and burying. In addition, during seedling establishment period, soil temperature at a depth of 5 cm can reach 42 °C on a sunny day following rain (Klaij and Serafini, 1988). Under these conditions, seedling death is quite common leading to sub-optimal plant stands and replanting over large areas.

3. NATURAL RESOURCE MANAGEMENT FOR SUSTAINABLE AGRICULTURE - A CASE STUDY AT THE ICRISAT SAHELIAN CENTER, SADORE, NIGER

Effective and stable soil and crop management practices in the drought-prone SSZ can be developed with an understanding of the environment and its variability. Several aspects of natural resource management for sustainable agriculture have been described using a case study at ISC.

3.1 Analysis of Rainfall Data for Deriving Effective Cropping Strategies

3.1.1 Coping with uncertainties of rainfall : As described earlier, rainfall variability in the SSZ is high and one has to cope with a high degree of uncertainty in the rainfall patterns from year to year. Historical rainfall data could be analyzed for detection of any predictors of this uncertainty and for evaluating cropping risks. Even at locations such as Niamey with low average annual rainfall (560 mm), years with more favourable rainfall distribution do occur (Fig. 1) and it is necessary to strive for product-maximizing strategies in such years. Hence any predictors that could help in early identification of the rainy season potential will be important in designing appropriate strategies for increased food production in the SSZ.

From an analysis of parameters such as the onset of rains and the length of the growing season for 58 locations in Niger and Burkina Faso which fall in the SSZ, Sivakumar (1988) showed that the date of onset of rains is an useful predictor of the rainy season potential. This is based on the finding that the onset of rains is much more variable than the ending of rains. At Niamey, the standard deviation (s.d.) for the average date of onset of rains (12 June) is 18 days while the s.d. for the average date of ending of rains (27 September) is 12 days. Therefore, an early onset of rains offers the probability of a longer growing season while delayed onset results in a considerably shorter growing season. Hence the potential of the growing season can be assessed with reference to the date of onset of rains. This is illustrated in Table-2 for Niamey, Niger (database 1904-1988). If the onset of rains occurs 20 days early i.e., by 24 May, there is a 71% probability that the growing season will exceed 120 days. On the other hand, if the rains are delayed till beginning of July, there is only a 15% probability that the growing season will exceed 100 days.

The above analysis suggests that it is possible to cope with uncertainties of rainfall in the SSZ by formulating alternatives that can be offered to farmers, based on the date of onset of rains in a given year. Aspects of application of this strategy are discussed under agronomic management in this paper.

3.1.2 **Understanding the nature of Intra-seasonal droughts** : Although the date of onset of rains provides an idea regarding the potential of the growing season, questions still remain on the nature of distribution of rainfall with the growing season. When are droughts most likely to occur with in the growing season and what is the expected length of the droughts? Long term daily rainfall data could be analyzed to answer such questions. Sivakumar (1988c) used the specific definition of onset of rains for each year as the sowing date and computed the length of dry spells (or days until the next day with rainfall greater than a defined threshold value) and the percentage frequencies of dry spell lengths for 150 locations in the SSZ.

The length of dry spells for Ouagadougou, Burkina Faso, at 50, and 90% probability levels for 10 and 20 mm rainfall thresholds are shown in Figure 3. The choice of the probability levels reflects the degree of certainty with which the dry spell lengths can be determined. For example, at 50 DAS for the 10 mm rainfall threshold, 50% of the dry spells will end after 3.2 days (Fig. 3a) while 90% of the dry spells will end after 8.5 days (Fig. 3b). Length of dry spells between 50 DAS and 90 DAS are markedly reduced.

This is more evident at the 90 % probability level than at the 50% level. The predicted length of dry spells increases with time after 100 DAS.

The implications of the above analysis is that in terms of crop phenology, dry spells from the stages of emergence of panicle initiation (up to 30 DAS) and grain filling last longer than those during panicle initiation to flowering (30-60 DAS).

3.2 Understanding the sandy soils and their management

3.2.1 Soil physical properties : Measurement of the physical and chemical properties of soils help understand the soil resources and their constraints and in evolving strategies for their management. According to the U.S. system of classification the predominant soil series at the ISC are classified as a Psammentic Paleustalf (West et al., 1984), corresponding to "Sol ferrigineus tropicaux" in the french system. The total sand content is around 90%, of which 85% fall within Chepil's classification (quoted by Zachar, 1982) of soil textural ranges with a very high (0.1 - 0.15 mm), to high (0.05 - 0.1 mm and 0.15 - 0.50 mm) potential for wind erodability. The dominant clay mineral is kaolinite. The clay content of the topsoil is about 5% gradually increasing to 6-8% at a depth of 1.5 m. As a result these soils are weakly structured.

The soil surface is generally flat and smooth with a negligible rainfall surface storage capacity. A weak crust may be present. The soil surface horizon is yellowish red to about a depth of 30 cm. The Bt horizon consists of weakly structured red sand to depths exceeding 2 m. Soil bulk densities of the top soil range from 1.40 to 1.70 Mg m^{-3} corresponding to a porosity of 36% to 43%. The densities at the higher end of this range may hamper root development through mechanical resistance. Sub soil bulk densities are somewhat lower.

Rainfall simulation runs on untilled initially dry 1.5 x 1.5 m plots (3-4% slope) demonstrated sustained infiltration rates of 100 mm $hour^{-1}$ for over 2 hours (Klaij and Hoogmoed, 1989). The saturated hydraulic conductivity is very high at 150-200 cm day^{-1}. As a consequence these soils have a rapid internal drainage, with soil moisture contents reverting quickly to field capacity after a rain. Actual runoff on untilled plots cropped with pearl millet (plot size 6 x 24 m, 3-4% slope) was 1.5% at most from 1984 to 1987.

The available soil moisture, ranging between 0.07 - 0.10 g cm^{-3}, increases slightly with depth as the clay content increases. Macro porosity, the air filled pore space at field capacity, is very high ensuring good aeration levels.

3.2.2 Soil Chemical properties : One striking feature of soils of SSZ is their inherent low fertility (Table-3), which is expressed through their low levels of organic matter, total nitrogen and effective cation exchange capacity (CEC), The low CEC could be attributed to the low clay contents as well as the kaolinitic mineralogy of the soils.

Several investigations have shown that phosphorus (P) constitutes the major constraint to food production in the SSZ. Total P contents range from 25 to 349 mg P kg^{-1} with an average of 110 mg P kg^{-1} (Bationo et al 1989b), but these soils can be considered as having relatively low P fixing capacity. Only a small amount of P fertilizer is required to satisfy the crop needs, due to the low P buffering capacity associated with these soils.

3.3.3 Tillage, fertilizer application, crop establishment and yield : Roughening the soil surface by tillage helps minimizing wind erosion effects. On similar sandy soils, modifications in the soil surface such as ridging may reduce soil losses due to wind erosion by as much as 85% (Fryrear, 1984). Modest amounts of crop residues, covering as little as 20% of the soil surface (0.6 t of corn stalks) reduced soil losses by 57% (Fryrear, 1985). These are important aspects in minimizing wind erosion damage during crop establishment.

However, tillage in dry conditions must be avoided, it requires excessive energy and it results in a loose cohesionless top soil which is even more susceptible to wind erosion. But in a moist top soil, tillage is easy and produces a reasonably stable soil surface (Hoogmoed and Klaij, 1989). As explained earlier, reductions in bulk density and soil surface modifications resulting from tillage do not have an important impact on infiltration. However, reduced bulk density from tillage does not result in enhanced rooting, greater access to soil moisture, increased fertilizer uptake, and therefore higher yields (Charreau and Nicou, 1971; Chopart, 1983). These yield advantages are most pronounced in dry years (Pieri, 1985).

At the ISC several tillage methods have been evaluated in combination with addition of phosphorus fertilizers in terms of plant establishment and crop yields. Tillage and crop row-orientation in this experiment was perpendicular to the prevailing direction of erosive winds which usually accompany storms in the beginning of the season. We compared the effects of plowing to a depth of 15 cm, ridging (75 cm between ridges, ridge height 15 cm) without other primary tillage, "sandfighting", (increasing the surface roughness by creating small depressions and clods), and a treatment without primary tillage referred to as no-till for their effect on millet production over a 2 year period.

The treatments were permanently assigned to plots, and were compared with or without the addition of chemical fertilizers: 17 kg P ha^{-1} pre-sowing and a split application of 40 kg N ha^{-1} at 3 and 6 weeks after sowing. The tillage treatments were carried out at the beginning of the rainy season with the first rainfall exceeding 10 mm. Tractor drawn equipment was used to ensure maximum seed placement precision (depth) and repeatability over the years. Thirteen thousand millet hills ha^{-1} were planted in rows 75 cm apart. Plowing and ridging with soil moisture at field capacity reduced soil bulk densities in the 0-15 cm layer to 1.22 mg m^{-3}, thus increasing total soil porosity to 54%. Reconsolidation due to raindrop impact during the season proved to be a slow process. Penetrometer measurements confirmed the persistence of reduced bulk density through much of the season, two months after plowing, soil resistance was still 50% lower than in untilled soil.

Agronomic results show the important interaction effect of pre-sowing cultivation and fertilizer application. Plowing and ridging improved plant stands and yields more when they were combined with fertilizer use. The response to fertilizer was moderate in the absence of primary tillage and on "sandfought" plots (Table-4). As ridging without other primary tillage requires considerably less time and energy than plowing, it seems o be the most appropriate technique in helping establishing a pearl millet crop.

The soil management measures described are effective on a field scale protecting the land and limiting wind erosion damage. Ideally these tactical measures ought to be part of a comprehensive soil protection strategy, in which crop rotations, the (partial) return of crop residues, and wind breaks are likely to play an important role.

4. MANAGEMENT OF SUSTAINABLE MILLET-BASED SYSTEMS

4.1 Cultivar choice : There is scope to develop more productive and stable millet cropping systems with the increasing availability of new cultivars with a different plant type and maturity cycle shorter than the traditional cultivars. Such systems must have the stability typical of tradition systems. Matching the cultivars phenology to season length is very important in providing this stability. Cultivars should reach maturity before available soil moisture is exhausted. Given the rainfall variability in the Sudano-Sahelian zone and the high probability of intra-season droughts, early maturing pearl millet varieties are most likely to produce an acceptable yield in most years. For example, in a variety trial conducted at the ISC over five years and under adequate soil fertility, the early maturing improved cultivar (CIVT) outyielded the local cultivar ('Heini Keri') in four out of five years. The choice of the early variety (90-day cycle) resulted in a mean increase in grain yield of 16% across the five years when compared with the late maturing local cultivar (110-day cycle).

Early maturity is desirable for two reasons. Firstly, with a shorter growing season and the high probability of drought, both at the start and end of the rainy period (Sivakumar, 1989b), earlier varieties help to avoid this moisture stress. Further-more, earlier millet varieties, such as CIVT and ICH412 (90-day cycle) use less moisture than traditional cultivars of 110-day duration such as Local Sadore (Fig. 4a). With the higher grain yields the earlier maturing varieties, water-use efficiencies are markedly improved (Fig. 4b). Secondly, there is much more flexibility in selecting a more favourable planting time. Both of these advantages result in a much lower chance of crop failure and, thus, a more stable cropping system.

4.2 Cropping System Choice : Intercropping and relay cropping systems offer alternative cropping strategies to sole crop systems for maximizing water use efficiency in conditions where season length and rainfall incidence are highly variable.

Intercropping of cereal and legumes is a common practice by farmers in the semi-arid zone of West Africa (Fussell and Serafini, 1985). This system has been developed under conditions involving both risk and constraints which limit crop production. Farmers use this system as a response to scarcity of resources and to lower risks and labor requirements (Norman, 1974; Matlon, 1980). The parity and, often, superiority of intercropping over sole crop in terms of insurance from risk, better resource-use and higher returns has been highlighted (Willey, 1979; Francis, 1981; Fussell and Serafini, 1985). From the results of recent research in the Sudano-Sahelian zone it has been concluded that millet/cowpea intercropping generally improves and stabilizes yields Fussell and Serafini, 1987; Ntare et al, 1989).

Traditional millet cropping systems, however, are expected to change as improved germplasm of cereals and legumes, as well as other new technologies, become available, and as increasing population pressure demands more intensive land use and greater productivity from farm labor. Millet/cowpea intercropping experiments conducted at the ISC since 1984, are demonstrating the importance of cowpea plant types in improving the cropping system. Early maturing (60-70 days) erect cultivars are less competitive with pearl millet than full season cultivars (Table-5). Yield advantages of up to 60% have been recorded. Millet yields were not greatly affected by the presence of early maturing cowpeas, where soil fertility and moisture were adequate (i.e. >500 mm of seasonal rainfall, 40 kg P_2O_5 ha^{-1} added). Earlier shorter statured millets than the local cultivars have been shown to also enhance cowpea hay and grain production, further improving the productivity of the system (L.K. Fussell, personal communication).

Other changes may include a gradual change from the traditional mixtures of cereals and legumes towards more structured and potentially more productive cropping systems. These may involve sole cropping in some cases, or strip cropping which preserves the multiple crop output of the traditional system but in a more structured fashion, or possible various forms of relay cropping. Any of these may be suited to realizing the yield potentials of improved germplasm and other new technologies (including AT and use of agricultural chemicals), which can both be more profitable and alleviate the land-use pressure of traditional systems.

In years with early onset of rains, a complementary system to intercropping is the relay cropping of millet with cowpea for hay. This strategy assumes that the farmers' aim is to harvest a test at ISC, Sivakumar (1989d) showed that when the onset of rains occurs early, it is possible to establish a second crop of cowpea for hay. Cowpea enables effective use of the September rains, a large part of which would otherwise have evaporated because of the poor water holding capacity of the soils at

ISC and provides valuable hay (and possibly grain if rains continue in October) to the farmer.

Though sole crop cowpea is not a traditional system in the Sudano-Sahelian zone, it still holds promise.. Millet grows best on land previously cropped with cowpeas or groundnuts (Pieri, 1985), although it is not clear if the increased yields are due to residual effect of N from the legume of residual fertilizer P not used by the legume. There is evidence of a combined residual effect from cowpea and groundnuts (Fig. 5). The role of legumes such as cowpea and groundnuts in the soil N-economy and fertility maintenance cannot be over emphasized. At ISC, researchers have began to quantify the beneficial rotational effects of the cowpeas on millet. As cowpea is becoming popular as a cash crop in the region, it is feasible and desirable to use purchased inputs, such as fertilizers and pesticides, on sole cowpea which will result in greater millet yield the following season (ICRISAT, 1988). This is one way of intensifying the cropping systems while sustaining and maintaining the stability.

4.3 Agronomic management : Traditionally, pearl millet is sown after the first rainfall of more than 10 mm on inherently low fertility soils. Millet densities are low (3000-7000 hills ha^{-1}), an appropriate strategy in the absence of added fertilizer, as there is little or no response to higher densities on these poor soils (Fig. 6). However, the use of fertilizers warrants a concomitant change in plant type and increase in millet densities (Fig. 6) and even intercropped cowpea densities (Fussel et al, 1987). Improved millet varieties have been shown to be more responsive to higher soil fertility and plant densities than the traditional varieties hills at low densities (1000-5000 hill ha^{-1}), 2-4 weeks later. In this system, the competitive effects of cowpea on millet yields necessiates a rather low cowpea density. However, both cowpea grain and fodder are salable products and this should off-set the loss in millet yields due to intercropping at higher fertilities and plant densities. Furthermore, increasing the density of an early maturing cowpea has been shown not to reduce millet yields below that of traditional cowpea/millet intercrop (Ntare, 1990 in press).

Cowpea is sown 2-4 weeks after millet under traditional practices. Millet/cowpea intercropping research conducted at ISC has shown that thee grain yield from early maturing cowpeas is substantially increased when sown with or shortly after millet without the intercrop adversely affecting millet yield (Ntare and Fussel, 1988). Planted in this way cowpea grain and fodder yields were higher in paired rows than single alternating rows, whereas millet yields were similar to those produced under sole crop.

4.4 <u>Use of fertilizers on the sandy soils</u> : Soil fertility limitation is recognized as the major constraint to increase productivity in the SSZ and it is widely speculated that the severity of this constraint is increasing because fallow periods are decreasing due to population pressures. Although lack of moisture limits crop production, research results showed that soil fertility is a more serious problem than rainfall (Bationo et al 1989b). Table-6 shows that millet yields can be increased three folds if the soil fertility can be improved.

Crop response to nitrogen (N) in the SSZ depends upon the genetic potential of the plant as modified by agroclimatic and farm management factors. Thus nitrogen management tends to be site-specific and several studies have shown that only in the presence of adequate P will the response to other fertilizers be found (Traore, 1974). Christianson et al (1988) found that millet response to N was most affected by mid-season rainfall over a six week yield sensitive period corresponding to millet stem elongation and anthesis. In the past, few studies using ^{15}N labelled fertilizer to assess the fate and efficiency of fertilizer N in millet production were reported. Christianson et al (1988) found that total plant uptake of N was low (20-37%) and losses were severe (25-53%). The majority of N remaining in the soils was found in the 0-15 cm layer and the mechanism of N loss is believed to have been ammonia volatilization.

Farmers in the SSZ use very low densities when growing millet in order to reduce the risk of crop loss due to low moisture availability (Dancette, 1983). Bationo et al (1989a) found that farmers will gain high benefit from N input by increasing planting density without increasing risk.

Use of commercial P fertilizers in the SSZ is limited due to the high cost of imported fertilizers but several countries in this region are known to have phosphate deposits. Direct application of indigenous phosphate rock (PR) can be an economic alternative to the use of imported, more expensive commercial fertilizers and would allow savings of much needed foreign exchange. The effectiveness of PR depends upon its chemical and mineralogical composition, and soil factors. According to the classification for direct application of PR proposed by Diamond (1979), the PR available from Tahoua in Niger, is medium in its reactivity. By acidulating PR with only a portion of sulfuric or phosphoric acid required to fully convert the insoluble phosphate to water soluble phosphate monohydrate (Schultz, 1986), the solubility of PR can be increased. Field trials conducted at ISC showed that acidulation of PR up to 50%, can increase its agronomic effectiveness and increase the crop yields (Fig. 7). Use of a limited quantity of fertilizer ensues better plant stand, increases the water use efficiency and crop yields. With continuous cultivation, sulphur deficiency becomes evident as can be seen from the differential response to single superphosphate and triple superphosphate which contains sulphur (Fig. 7). Vlek (1985) pointed out that it is impossible to assess the seriousness of micronutrient deficiencies in SSZ on the basis of the available data.

4.5 Use of crop residues for water and fertility management : Traditionally, soil fertility in SSZ has been maintained through shifting cultivation, and farmers abandoned lands to fallow as productivity declined. Pichot et al (1981) have shown that addition of mineral fertilizers alone with removal of crop residue can result in yield decline with time. Addition of crop residue can delay this soil degradation. In an experiment at ISC addition of crop residues has improved the yields but the highest yield was obtained with a combination of organic and inorganic amendments (Table-7). Chemical properties measured after four years of addition of crop residues showed that crop residues have dramatically reduced the soil exchangeable acidity. Crop residues are not commonly used for the maintenance of soil fertility in the SSZ. The problem is not one of stover quality, but rather its availability because the straw is used as fuel, animal feed, and as housing and fencing material and little is left to be returned to the soil. Research done in the sahel on crop residue recycling has shown that crop residues and fertilizer have a complementary role and their simultaneous use will allow better crop yields. Application of crop residues is an effective means to reduce soil evaporation losses and improve soil organic matter status. This practice, if adopted, is equally important for sustained soil productivity in the Sahel.

5. INTEGRATION OF COMPONENT RESEARCH FOR SUSTAINED AGRICULTURE ON AN OPERATIONAL SCALE

From the results of research on various components of millet-based production systems described above, scientists at ISC have identified components of research that showed promising results (ICRISAT, 1987). these were : application of small quantities of P (13 kg ha^{-1}); use of improved varieties of millet (ICMV 5, ITMV 8001) and cowpea (TVX 3236) at higher densities than in the traditional system; ridging with first rain and planting on ridges for better establishment and survival of millet; and use of animal traction for ridging and weeding.

These individual components were systematically combined and tested for four years from 1986 to 1989 in an integrated Operational Scale Research (OPSCAR) at ISC. The millet/cowpea intercrop or pure millet was rotated with pure cowpea to assess the residual effects of a legume on the following millet crop.

In 1988, rainfall was 700 mm and was well distributed. In 1989, rainfall was 623 mm but a dryspell of 3 weeks occurred in July-August. In 1988, the traditional system produced 0.23 t ha^{-1} of millet grain and 0.91 t ha^{-1} of stover. In 1989 these figures were 0.13 and 0.47 t ha^{-1} respectively.

Yield advantages for millet grain and stover for different components of the production systems over the traditional system are presented in Fig. 8. From the point of sustainable agriculture, the effect of rotation was most striking in comparison to continuous cropping. In 1989, use of P, improved variety of millet and ridging with animal traction gave an 200% advantage over the traditional system. But the addition of a rotation treatment with a pure crop of cowpea in the system boosted the yield advantage to 400%.

The advantages of rotation does not appear to be solely from the nitrogen fixation by the legume and its contribution to the following cereal. There is evidence from other trials at ISC (see section 3.2) which suggests that legumes help enhance solubility of soil phosphorus, and stabilize the pH and organic matter content of the soil. These data demonstrate the value of rotating the cereal with a legume on the poor, sandy soils and suggest that simple rotations such as these might provide valuable strategies for sustaining agriculture in the SSZ.

REFERENCES

Aubreville, A. 1949. Climats, forets et desertification de l'Afrique tropicale; Soc. Edit. Geog. Marit. et Col. Paris, 351 pp.

Bationo, A., Christianson, C.B. and Baethgen, W.B. 1989a. Effect of plant density and nitrogen fertilizer rates onmillet yield in the sandy soils of Niger. Agronomy Journal (In Press)

Bationo, A., Manu, A., Mokwunye, and Christianson, C.B. 1989a. Soil fertility status and management for the millet producing soils of West Africa. Unpublished manuscript

Chevallier, A. 1933. Le territoire geobotanique de l'Afrique tropicale nord-occidentale et ses divisions; Bulletin Soc. Bot. (In Fr.) 80:4-26

Charreau, C. and Nicou, R. 1971. L'amelioration du profil cultural dans les sols sableux et sablo-argileux de la zone tropicale seche ouest africaine et ses incidences agronomiques. Agronomie Tropicale 26:209-255, 531-565, 903-978, 1138-1247

Chopart, J.L. 1983. Etude du systeme racinaire du mil (Pennisetum typhoides) dans un sol sableux du Senegal. Doc. mimeo IRAT/CNRA Bambey, Senegal

Christianson, C.B., Bationo, A., Henao, J. and Vlek, P.L.G., 1988. Fate and efficiency of nitrogen fertilizers in Niger. Plant and Soil (In Press)

Dancette, C. 1983. Water requirement of millet adaptation in the semi-arid tropics. Agronomie Tropicale 38:267-293

Diamond R.B. 1979. Views on marketing of phosphate rock for direct application. Pages 448-463 in Special Publication, IFDC S-1, International Fertilizer Development Center, Muscle Shoals, Alabama, USA

FAO/UNESCO, 1977. Soil map of the world, Vol V. Africa. UNESCO, Paris

Fransis, C.A. 1981. Development of plant genotypes for multiple cropping systems. In : Plant breeding II (Frey, K.J., ed). Iowa, USA: The Iowa State University Press. 497pp.

Fryrear, D.W. 1984. Soil ridges-clods and wind erosion. TRANSACTIONS of the ASAE 27(2): 445-448

Fryrear, D.W. 1985. Soil cover and wind erosion. TRANSACTIONS of the ASAE 28(3): 781-784

Fussell, L.K., Klaij, M.C., Renard, C. and Ntare, B.R. 1989. Millet based production systems for improving food production in the southern Sahelian zone. A paper presented at the Farming Systems Research Workshop on Appropriate Technologies for Achieving Sustainable Food Production Systems in Semi-arid Africa. Ougadougou, Burkina Faso, April 11-14, 1989. (In press)

Fussell, L.K., and Serafini, P.G. 1985. Crop associations in semi-arid tropics of West Africa. Research strategies present and future. Pages 218-235 in Appropriate Technology for Farmers in Semi-arid West Africa (Ohm, W., and Nagy, J.C., eds.). Ougadougou, Burkina Faso: Purdue University 359pp.

Fussell, L.K., and Serafini, P.G. 1987. Intercropping - its future as a cropping system in the drought-prone tropics of West Africa. Pages 557-565 in Food Grain Production in Semi-arid Africa (Menyonga, J.M., Bezuneh, T., and Uoudeowei, A., eds). Ougadougou, Burkina Faso : OUA/STRC-SAFGRAD.

Fussell, L.K., and Serafini, P.G., Bationo, A., and Klij, M.C. 1987. Management practices to increse yield and yield stability of millet in Africa. Pages 255-268 in Proceedings of the Interntional Pearl Millet Workshop, 7-11 April 1986, ICRISAT Center, India. Patancheru, A.P. 502 324, India : ICRISAT.

Hoogmoed, W.B. and Klaij, M.C. 1989. Soil management for crop production in the West African Sahel. I. Soil and climatic parameters. Soil Tillage Research 14 (In Press).

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Annual Report 1986. Patancheru, A.P. 502 324, India : ICRISAT.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1988. Annual Report 1987. Patancheru, A.P. 502 324, India : ICRISAT.

Klaij, M.C. and W. Hoogmoed. 1989. Crop responses to tillage practices in Sahelian soil. In Proceedings of the Workshop on "Soil, crop, and water management systems for rainfed agricultute in the Sudano-Sahelian zone", 11-16 January 1987, Niamey, Niger: International Crops Research Institute for the Semi-Arid Tropics (In Press).

Klaij, M.C. and Serafini, P.G. 1988. Management options for intensifying millet-based crop production systems on sandy soils in the Sahel. Conference paper. International Conference on Dryland Farming Texas Agriculture Experimental Station 15-19 August 1988, Amarillo/Bushland, Texas

Malton, P.J. 1980. Local varieties, planting strategies, and early season farming activities in two villages in central Upper volta. ICRISAT West Africa Economics Program Progress Report 2. Ouagadougou, Burkina Faso:ICRISAT. 53 pp (Limited distribution).

Mudahar, M.S. 1986. Fertilizer problems and policies in sub-Saharan Africa. Pages 1-32 in Management of nitrogen and phosphorus fertilizers in sub-saharan Africa (Mokwunye, A. and Vlek, P.L.G. ed.). Martinus Nijhoff Publishers, Dordrecht, The Netherlands

Nicholson, S. 1980. The nature of rainfall fluctuations in subtropical West Africa. Monthly Weather Review 108:473-487.

Normal, D.W. 1974. Rationalizing mixed cropping under indigenous conditions. The example of Northern Nigeria. Journal of Development Studies 11:3-21

Ntare, B.R. 1989. Intercropping morphologically different cowpeas with pearl millet in a short season environment in the Sahel. Field Crops Research 26 (In Press)

Ntare, B.R. and Fussel, L.K. 1988. Strategies for intensifying dryland cowpea production in the semi-arid West Africa. Paper presented at the International Conference on dryland Farming 15-19 August 1988, Amarillo, Bushland, Texas

Ntare, B.R., Serafini, P.G. and Fussel, L.K. 1989. Recent developments in millet/cowpea cropping systems for low rainfall areas in the Sudano-Sahelian zone of West Africa. In Proceedings of the workshop on "Soil, crop and water management systems for rainfed agriculture in the Sudano-Sahelian zone" 11-16 January 1987, Niamey, Niger : International Crops Research Institute for the Semi-Arid Tropics (In Press).

Perrier, E.R. 1986. Adaptation of water management practices to rainfed agriculture on Alfisols in the Shel. Pages 445-464 in Food Grain Production in Semi-Arid Africa (Menyonga, J.M., Bezuneh, T. and Youdeower, A. ed.) Ouagadougou, Burkina Faso : OAUSTRC - SAFGRAD

Pichot, J., Sedogo, M.P., Poulain, J.F. and Arrivets, J. 1981. Evolution de la fertilite d'un sol ferrugineux tropical sous l'influence des fumures minerales et organiques. Agron. Trop. 36:122-133

Pieri, C. 1985. Food crop fertilization and soil fertility : the IRAT experience. Pages 74-109 in Appropriate technologies for farmers in semi-arid West Africa. (Ohm, H.W., and Nagy, J.G. , ed.) University of Purdue, West Lafayette, IN, USA

Schultz, J.J. 1986. Sulfuric acid-based partially acidulated phosphate rock, its production, cost and use. Tech. Bull. IFDC-T-32. International Fertilizer Development Center, Muscle Shoals, Alabama, USA

Sivakumar, M.V.K. 1988. Predicting rainy season potential from the onset of rains in the Sahelian and Sudanian climatic zones of West Africa. Agricultural and Forest Meteorology 42:295-305

Sivakumar, M.V.K. 1989a. Agroclimatic aspects of rainfed agriculture in the Sudano-Sahelian zone". In proceedings of the workshop on "Soil, crop and water management systems for rainfed agriculture in the Sudano-Sahelian zone" 11-16 January 1987, Niamey, Niger : International Crops Research Institute for the Semi-Arid Tropics (In Press).

Sivakumar, M.V.K. 1989b. Agroclimatical considerations for sustainable agriculture in the Sudano-Sahelian zone. Paper presented at the seminar on "Sustainability : Programs and priorities for the Sudano-Sahelian zone", 8 March 1989, ICRISAT Sahelian Center, Niamey, Niger

Sivakumar, M.V.K. 1989c. Drought spells and drought frequencies in West Africa. Research Bulletin No. 13, International Crops Research Institute for the Semi-Arid Tropics, Patancheru, P.O. 502 324, A.P., India. 340 pp (In Press)

Sivakumar, M.V.K. 1989d. Exploiting rainy season potential from the onset of rains in the Southern Sahelian zone of West Africa. Agricultural and Forest Meteorology 43 : (In Press)

Spencer, D.S.C. and Sivakumar, M.V.K. 1987. Pearl millet in African Agriculture. Pages 19-31. In Proceedings of the International Pearl Millet Workshop, 7-11 April 1986, ICRISAT, Patancheru, India

Traore, M.F. 1974. Etude de la fumure minerale intensive des cereales et du role specifique de la matiers organique dans la fertilite des sols du Mali. Agron. Trop. paris, 29:567-586

Vlek, P.L.G. (ed.) 1985. Micronutrients in tropical food crop production. Developments in plant and soil sciences. Vol 14. Martinus Nijhoff. Dr.w. Junk Publishers, Dordrecht, The Netherlands

West, L.T., Wilding, L.P., Landeck, J.K. and Calhoun, F.G. 1984. Soil survey of the ICRISAT Sahelian Center Niger, West Africa. Texas A&M University System/Tropsoils in cooperation with the International

Crops Research Institute for the Semi-Arid Tropics. Texas A&M University, College Station, TX., USA

Willey, R. 1979. Intercropping - Its importance and research needs. Part 1. Competition and yield advantages. Field Crops Abstracts 32:1-10

Zachar, D. 1982. Soil erosion development in soil science. Elesevier scientific publishing company. Amsterdam-Oxford-New York.

Table-1 : Major soil units and their approximate extent in the Sudano-Sahelian zone

Soil type	Approximate extent (m ha)	Percent of total area
Luvisols	42.3	31.7
Arenosols	32.2	24.2
Regosols	19.7	14.8
Vertisols	9.5	7.1
Lithosols	8.2	6.2
Fluvisols	6.5	4.8
Gleysols	3.2	2.4
Nitosols	2.9	2.1
Planosols	2.8	2.1
Cambisols	2.6	1.9
Other soils	3.6	2.7

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

Date of onset of rains	Length of growing season (days) exceeding			
	80	100	120	140
24 May	100	99	71	15
2 June	100	91	40	3
12 June	98	71	15	0
22 June	91	40	3	0
2 July	71	15	0	0

Table-3 : Means and ranges of selected physical and chemical properties of soils in the Sudano-Sahelian zone

Parameter		Range	Mean
pH:H_2O (2:1 water:soil)		5.2 - 8.2	6.3
In KCl		4.0 - 7.5	5.1
Clay (%)		0.7 - 11.7	3.6
Sand		71.3 - 99.0	87.3
Organic matter (%)		0.08 - 2.94	0.75
Total nitrogen (mg kg^{-1})		31 - 1800	266
Exchangeable bases (cmol kg^{-1})			
	Ca	0.15 - 16.5	2.45
	Mg	0.02 - 2.16	0.55
	K	0.03 - 1.82	0.24
	Na	0.02 - 0.09	0.04
Exchangeable Al (cmol kg^{-1})		0.00 - 14.51	1.60
Effective cation exchange capacity		0,54 - 19.2	3.10

Table-4 : Effect of pre-sowing cultivation and fertilization on plan popultion (in percentage of number of hills survived at harvest) and grain yield, ISC, Sadore, Niger, rainy seasons 1985 and 1986

Treatment	% stand at harvest			Grain yield (Mg ha^{-1})		
	FO	F1	Mean	FO	F1	Mean
Plowing	68	87	78	0.254	0.681	0.467
Ridging	44	80	62	0.180	0.649	0.414
Sandfighting	31	63	47	0.089	0.352	0.220
Zero-til	42	63	53	0.139	0.402	0.271
SE		$\pm$3.3	$\pm$2.5		$\pm$0.040	$\pm$0.034
Mean	46	73		0.165	0.521	
SE		$\pm$1.5			$\pm$0.015	

a. FO = no fertilizers added; F1 = 17 kg ha^{-1} of P fertilizer and 40 kg N ha^{-1}. Split split plot replicated 4 times, subsub plot size 30 m^2.

Average across 2 years and 3 cultivars

Table-5 : Effect of cowpea plant type on grain and fooder yields of intercropped cowpea and pearl millet. ISC, Sadore, Niger, rainy seasons 1985-86, 1988

1 Plant type cultivar	1985			1986			1988		
	Cowpea grain	Cowpea fodder	Millet grain	Cowpea grain	Cowpea fodder	Millet grain	Cowpea grain	Cowpea fodder	Millet grain
Extra early determinate (60-65 days) :									
IT82E 60	0.10	0.32	2.04	0.09	0.11	1.30	0.10	0.21	1.01
IT82D 716	0.12	0.40	2.17	0.10	0.18	1.14	0.19	0.41	0.99
Early, spreading inderminate (70 days) :									
TVX 3236	0.40	0.83	1.79	0.20	0.23	1.10	0.22	0.54	0.72
SUVITA 2	0.62	1.34	1.55	0.43	0.50	1.13	0.26	0.61	0.77
Medium maturity, indeterminate (80 days):									
TN88-63	0.42	1.06	1.60	0.18	0.46	1.23	0.30	0.58	0.54
58-57	0.60	1.30	1.56	0.38	1.77	1.17	0.41	0.91	0.77
Late maturity, indeterminate (120 days):									
Sadore local	-	1.97	0.63	0.03	1.31	0.68	0.17	1.16	0.68
Sole millet (cv. CIVT)	-	-	2.24	-	-	1.30	-	-	1.20
SE	±0.08	±0.08	±0.12	±0.06	±0.06	±0.21	±0.03	±0.05	±0.0[illegible]

Source : Fussell et al, (1989)

Table-6 : Results of second year of the long term soil fertility management trials on fertilizers, lime, crop residue, secondary micronutrients and manure on pearl millet grain yield, Sadore, Niger, Rainy season, 1988

Treatments	Grain yield ($t\ ha^{-1}$)
Control	0.355
Single Superphosphate	0.855
Triple Superphosphate	0.838
SSP + N + K + MgO + ZnO	1.077
SSP + N + K	1.071
SSP + N + K + lime every three years	1.130
SSP + N + MgO + ZnO	1.097
Crop residue each year (2 tons ha^{-1})	0.778
SSP + N + crop residue each year (2 tons ha^{-1}	1.134
Manure every three years (10 tons ha^{-1})	1.035
SSP + N + K + MgO + ZnO + lime every three years	0.974
SSP + N + K + MgO + ZnO + lime each year + Manure every three uears + lime every three years	1.283
SE ($\pm$)	0.109
CV (%)	29

Table-7 : Effect of application of pearl millet crop residues over a 4-year period (1983-86) on grain yield (kg ha^{-1}) of pearl millet, and soil chemical properties measured at the end of the 1986 rainy season, ISC, Sadore, Niger

Treatment	Grain yield kg ha^{-1}	Bray P (mg P kg^{-1} soil)	pH (KCl suspension)	Organic matter (%)	Total N (mg kg^{-1} soil)	Ca+Mg (cmol kg^{-1}	Al+H saturation
Control	56	2.6	4.1	0.24	126	0.43	48
Crop residue	743	3.0	4.4	0.29	155	0.68	20
Fertilizers	816	7.1	4.1	0.25	151	0.44	43
Crop residue and fertilizers	1532	8.1	4.4	0.33	171	0.72	16
SE (±)	66	0.46	0.04	0.01	8	0.34	3
CV (%)	12	18	2	10	10	11	19

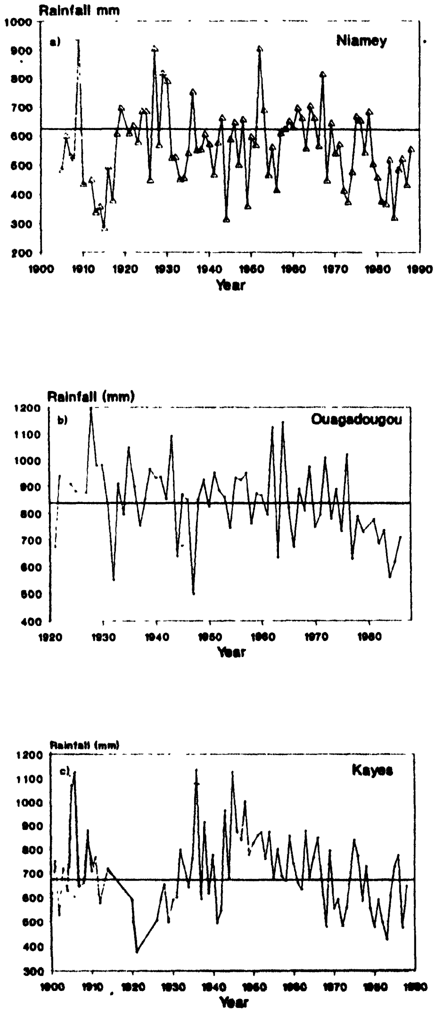


Figure 1. Annual rainfall variation at a) Niamey, Niger b) Ouagadougou, Burkina Faso and c) Kayes, Mali located in the Sudano-Sahelian zone

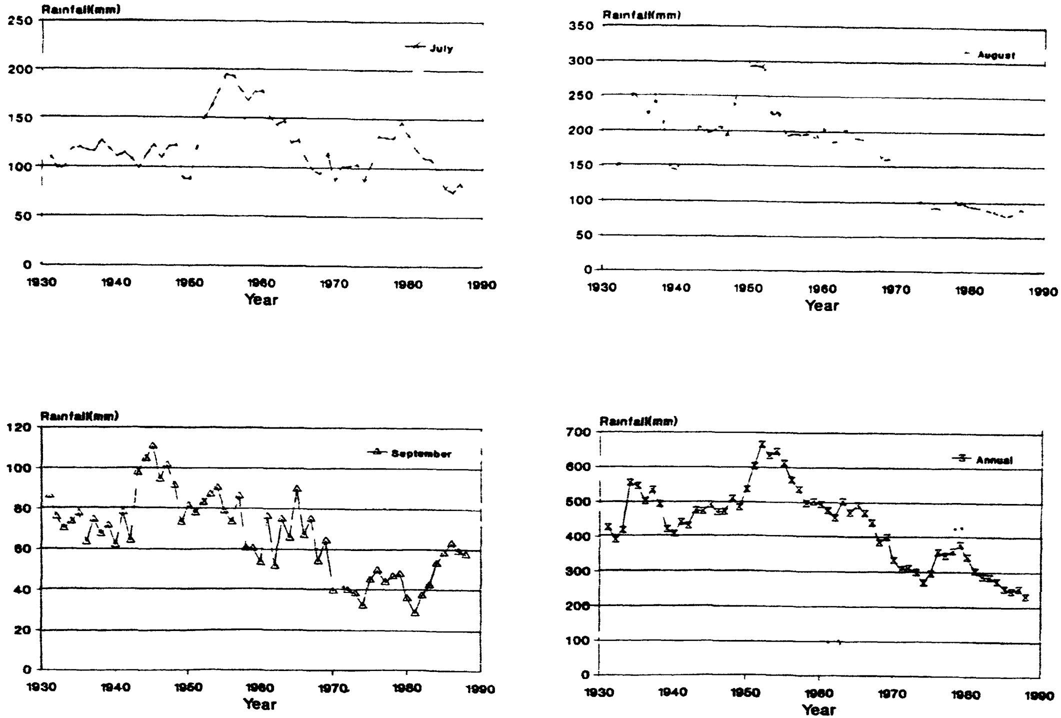


Figure 2. 5-year moving averages of monthly and annual rainfall at Filingué, Niger.

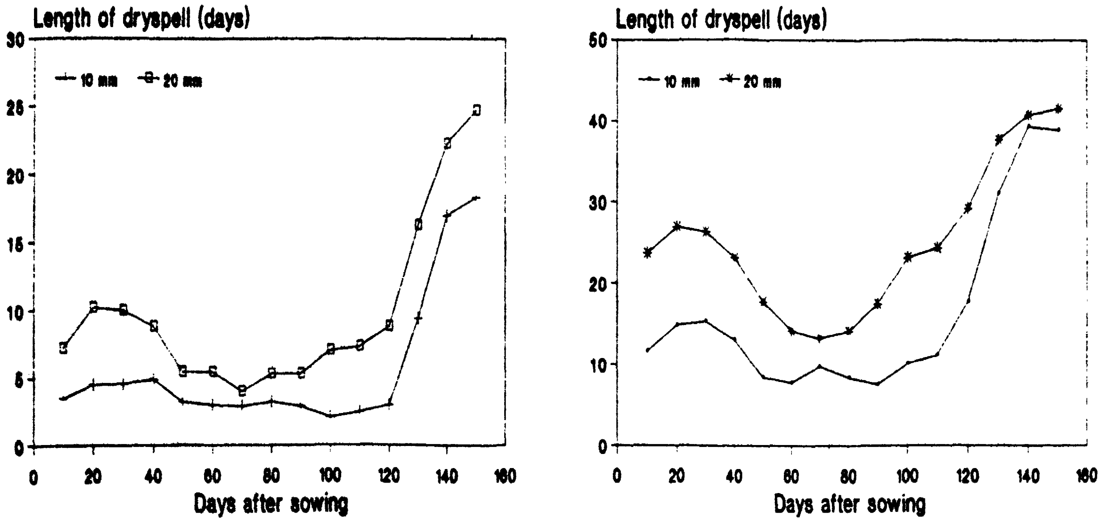
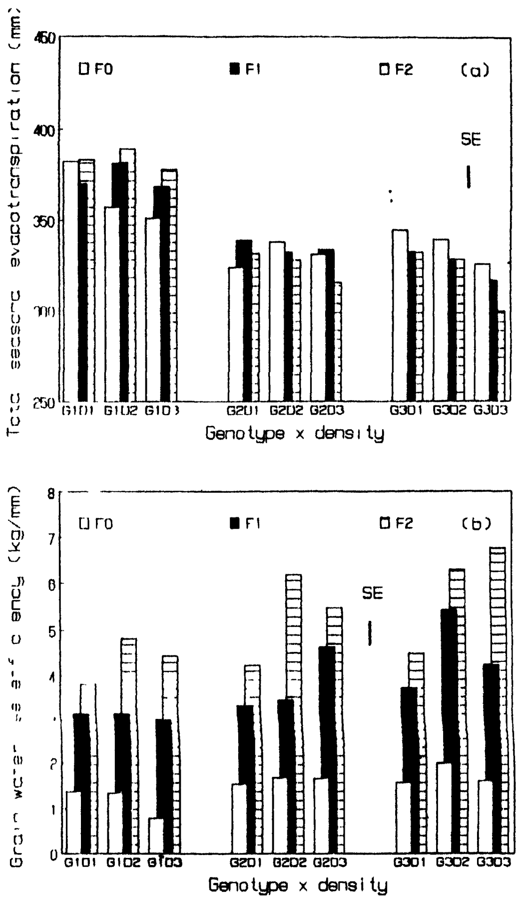


Figure 3. Length of dry spell at a) 50% and b) 90% probabilities for 10 and 20 mm rainfall thresholds at Ouagadougou, Burkina Faso.



Fertilizer level (kg/ha):	Density (hills/ha):	Genotype:
Fo = 0 N: 0 P_2O_5	D1 = 5000	G1 = Sadoré Lo
F1 = 23 N: 20 P_2O_5	D2 = 10000	G2 = CIVT
F2 = 46 N: 40 P_2O_5	D3 = 20000	G3 = ICH 412

Figure 4. The effect of fertilizer, density and genotype on (a) tot seasonal evapotranspiration and (b) grain water use efficiencies i pearl millet. ISC, Niger, rainy season 1985. (Source: Fussell et a 1989)

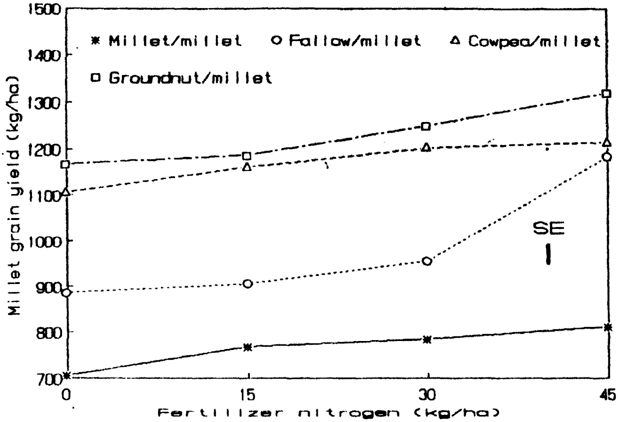
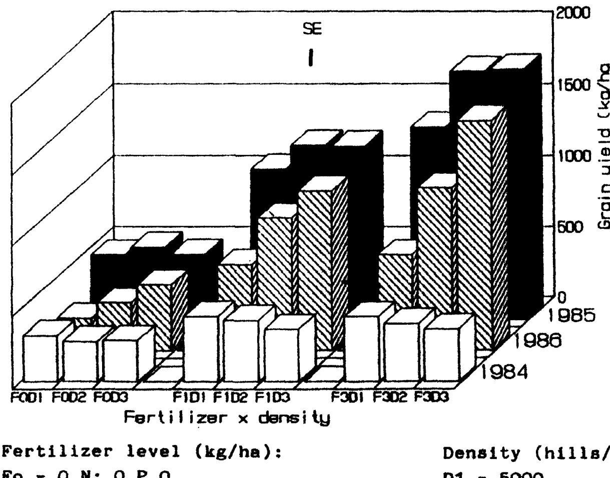


Figure 5 . Effect of crop rotation and nitrogen fertilizer on grain yield of pearl millet after one cycle of the rotation. Tara, Niger, 1989.



Fertilizer level (kg/ha):

Fo = 0 N: 0 P_2O_5

F1 = 23 N: 20 P_2O_5

F2 = 46 N: 40 P_2O_5

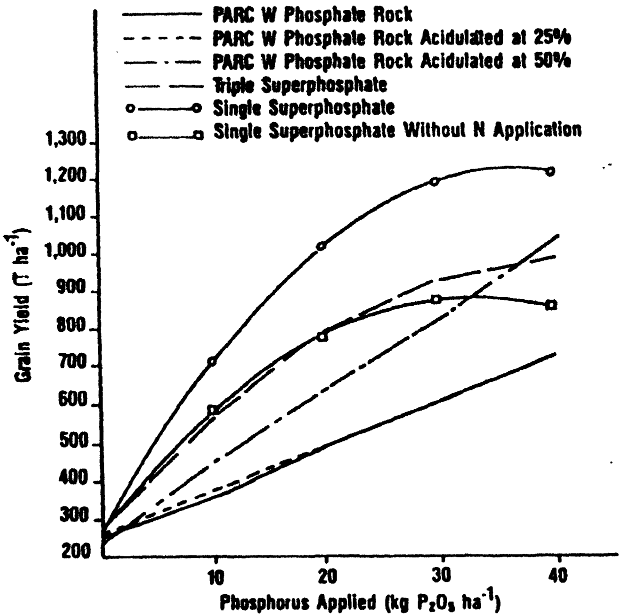
Density (hills/ha):

D1 = 5000

D2 = 10000

D3 = 20000

Figure 6. Variation in grain yield of pearl millet in different years due to fertilizer and density. ISC, Niger, rainy season 1984-86. (Source: Fussell et al., 1989)



$\hat{Y} = .259 + .01179\,P \quad R = .72 \quad RSE = .168$

$\hat{Y} = .266 + .01157\,P \quad R = .66 \quad RSE = .195$

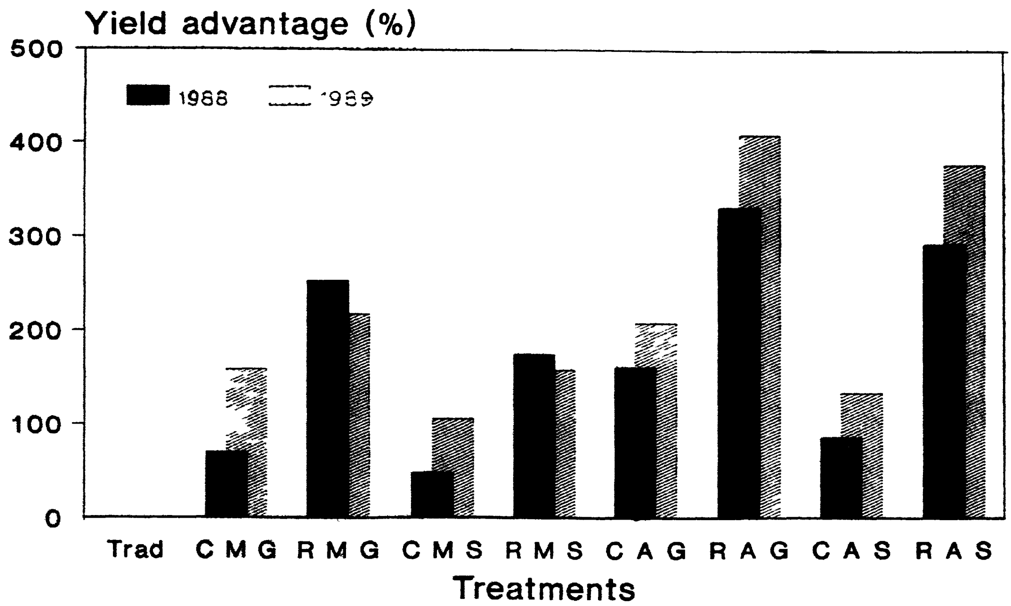
$\hat{Y} = .239 + .01976\,P \quad R = .86 \quad RSE = .172$

$\hat{Y} = .273 + .03324\,P - .00038\,P^2 \quad R = .83 \quad RSE = .197$

$\hat{Y} = .262 + .05163\,P - .00069\,P^2 \quad R = .82 \quad RSE = .278$

$\hat{Y} = .256 + .03741\,P - .00055\,P^2 \quad R = .85 \quad RSE = .165$

Figure 7. Effect of Phosphorus Sources and rates of Application on Pearl Millet Grain Yield, Sadore, Niger, Rainy Season 1988.



T= Traditional, C= Continous
R= Rotation, M= Manual, S= Straw
A= Animal traction, G= Grain

Figure 8. Effect in improved technologies (expressed as yield advantage over traditional system in %) on pearl millet grain and stover yields at ISC for 1988-1989.