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Soil fertility management for sustainable land use in the West African Sudano-Sahelian zone.

A Bationo[1], U. Mokwunye[2], P.L.G. Vlek[3], S. Koala[4] and B.I. Shapiro[5].
[1] A Bationo, T.S.B.F., P.O. Box 30592, Nairobi, Kenya
[2] United Nations University, University of Ghana, Legon, Ghana
[3] Zentrum fuer Entwicklungsforschung (ZEF University of Bonn), Center for Development Research, Friedrich-Wilhelm-Universitaet Bonn, Walter-Flex-Strasse 3, D-53113 Bonn, Germany
[4] ICRISAT, B.P. 12404, Niamey, Niger
[5] ICRISAT, B.P. 320, Bamako, Mali

Introduction

The Sudano-Sahelian zone of West Africa (SSZWA) is the home of the world poorest people, 90% of whom live in villages and gain their livelihood from subsistence agriculture. Per capita food production has declined significantly over the past three decades. According to FAO, total food production in Sahelian countries grew by an impressive 70% from 1961 to 1996, but it lagged behind the population which doubled, causing food production per capita to decline approximately by 30% over the same period (Bationo, 1996).

Low, erratic rainfall and high soil temperature, soil of poor native fertility, surface crusting and low water and nutrient holding capacity, and recurrent droughts are the main abiotic constraints to crop production in this environment.

The table on economic and human development characteristics of West African countries indicate that except for Senegal, Côte d'Ivoire, Mauritania and Ghana where the percentage of undernourished people is less than 19%, most countries have between 20 to 34% of undernourished people and countries like Niger have more than 35% of their population undernourished. Sahelian countries produce 80% of their total cereal production under very difficult conditions. The ability to obtain the remaining 20 percent of required food is limited by low income and underdeveloped marketing channels. Gross domestic product per capita, for example, ranged from US$177 in Chad to US$575 in Senegal and have stagnated in real terms over the past decade. From the United Nations Development Programme's Human Development index, which ranks countries in terms of life expectancy, education and income, Sahelian countries fall in the bottom 15 percent of the 174 countries ranked, the lowest being Niger.

In extensive agricultural systems, when crop yields decline to unacceptable levels, the land is left fallow to build up soil fertility, and new areas are then cultivated. Increasing population pressure has decreased the availability of land and resulted in reduced duration of fallow and increased the duration of cropping periods. Shifting cultivation is losing effectiveness and soil fertility is globally declining in many areas. The present farming systems are therefore unsustainable, low in productivity and destructive to the environment. Plant nutrient balances are negative (Stoorvogel and Smaling, 1990). The increasing need for cropland has prompted farmers to cultivate more and more marginal lands which are prone to erosion.

Agricultural output should expand by at least 4% annually by the year 2000 in order to ensure food security. Previous studies have clearly shown that the expansion of new farms cannot increase output by over 1% without accelerating environment degradation. Consequently, productivity of land currently under cultivation should increase by at least 3% per annum. Presently, over a quarter of West African sub-region's population of two hundred million inhabitants is threatened by food insecurity. Any program aimed at reverting the declining trend in agricultural productivity and preserving the environment for present and future generations in West Africa must begin with soil fertility restoration and maintenance (Bationo et al., 1996).

In this chapter, after a brief presentation of the crop production environment, we will present the state of the art of nitrogen, phosphorus and organic matter management for sustainable land use in the Sudano-Sahelian zone. Before presenting the new opportunities for future research for soil fertility restoration in this zone, we will discuss the effect of different cropping systems on soil fertility and also the main research achievements of the on-farm evaluation of soil fertility restoration technologies.

Crop production environments

a) Climate

The rainfall in West Africa shows a significant north-south gradient because of the inter-seasonal movement of the intertropical convergence zone, north and south of the equator. The rainfall is low, variable and undependable. The north-south rainfall gradient is very steep. The further one goes from the Sahara margins, the greater is the rainfall by approximately 1 mm km^{-1}. The isohyets run parallel (Toupet 1965).

Sivakumar (1986) proposed a soil climatic zonation scheme for West Africa that is calculated from rainfall and potential evapo-transpiration. In this scheme a growing period of 60–100 days was used for defining the Sahelian zone. The geographical extent of the Sudanian zone has an average growing period of 100–150 days. The extent of the Sudano-Sahelian zone of West Africa (SSZWA) is represented by the Semi-Arid zone in Figure 1. The average annual rainfall of the cultivated zones varies from 300 to 900 mm and the ratio of annual rainfall to annual potential evapo-transpiration from 0.20 to 0.65. High soil temperature, sometimes exceeding 40^{o}C, can prevent crop establishment. Sand blasting and burial of the seedlings caused by wind erosion adds to this problem.

Time dependent variations in rainfall are quite common in the region with coefficient of variation of annual rainfall ranges between 15-30%, and rainfall in some years can be 50% below or above the long-term average. In instance, Nicholson (1981) showed that in 1950 rainfall all over West Africa was above normal, at some location even 250% above normal. However, in 1970 rainfall was below normal throughout the region.

It is well documented that precipitation determines the potential distribution of terrestrial vegetation and extended drought have initiated or exacerbated desertification. In the past 25 years, the SSZWA has experienced the most substantial decline in rainfall (Hulme and Kelly 1997; Hulme 1992; Nicholson and Palao 1993) and the downward trend is persistent since 1951 with more areas experiencing more higher rainfall variability. As a result of the decrease in rainfall there will be a decrease in the vegetation cover of the land and a reduction in the vegetation cover logically leads to reduce precipitation (Charney 1975; Cunnington and Rowntree 1986; Xue et al. 1990). The other non-climatic forces of desertification includes unsustainable agricultural practices, overgrazing and deforestation.

With the reduction of the vegetation cover, the soil is left bare and therefore directly exposed to wind and water vegetation. The effect of these changes on wind and water erosion are aggravated by the sandy nature of the soils of SSZWA, which are frequently poorly aggregated, offering little resistance to the erosive forces. The Global Assessment of Soil Degradation (GLASOD) project estimates that 65% of the African agricultural land 31% of permanent pasture land, and 19% of forest and woodland has already been degraded. Three hundred and thirty two million hectares of African drylands are subjected to soil degradation. This represents one third of the entire area of dryland soil degradation in the world.

Land degradation is one of the most serious threats to food production and soil lost through erosion is about 10 times greater than the rate of natural soil formation while deforestation is 30 times greater than of planned reforestation. Buerkert et al. (1996a) measured absolute soil lost of 190 t ha^{-1} in one year on bare plots, as opposed to soil deposition of 270 t ha^{-1} on plot with 2 t ha^{-1} millet stover mulch. Sterk et al. (1996) reported a total loss of 45.9 t ha^{-1} of soil during four consecutive storms. Buerkert et al. (1996b) reported that in unprotected plot up to 7 kg of available P and 180 kg ha^{-1} of organic carbon are lost from the soil profile within one year. Wind erosion will decrease also the exchangeable base and increase soil acidification. Wind erosion constitutes one of the major causes of land degradation. This results from the low vegetation cover at the time when the most erosive winds are blowing in combination with sandy, easy erodable soils. Wind erosion induced damage includes direct damage to crops through sand blasting, burial of seedling under sand deposits, and loss of top soils (Fryar 1971, Ambust 1984, Fryar 1990. The loss of the top soil which can contain 10 times more nutrients than the sub-soil is particularly worrying, since it potentially affects crop productivity on the long-term by removing the soil that is inherently rich in organic matter.

b) Soils

Entisols and Alfisols occupy most of the landscape in the SSZWA. Entisols are mainly composed of quartz sand, with low water and nutrient holding capacity. Alfisols have a clay accumulation horizon and a high base saturation because of lower rainfall and leaching but they have poor structural stability, poor water and nutrient holding capacity and lower organic matter than the ultisols and oxisols in the sub-humid areas.

The data in Table 1 shows physical and chemical properties of soils in the SSZWA. Most of the soils are sandy. One striking feature of these soils is their inherent low fertility which, is expressed in low levels of organic carbon (generally less than 0.3%), low total and available phosphorus and nitrogen and low effective cation exchange capacity (ECEC). The ECEC is attributed to low clay content and the kaolinitic mineralogy of the soils. Bationo and Mokwunye (1991) found that the ECEC is more related to the organic matter than to the clay content, indicating that a decrease in organic matter will decrease the ECEC and then the nutrient holding capacities of those soils. De Ridder and Van Keulen (1990) reported that a difference of 0.1% in organic carbon content results in a difference of 4.3 Cmol kg^{-1} in ECEC.

Soil nutrient depletion is a major bottleneck to increased land productivity in the region and has largely contributed to poverty and food insecurity. Soil nutrient depletion occurs when nutrient inflows are less than outflows. Nutrient balances are negative for many cropping systems indicating that farmers are mining their soils. Table 2 shows the aggregated nutrient budgets for some West African countries. In Burkina Faso, current estimates indicate that in 1983, for a total of 6.7 million hectares of land cultivated, soil nutrient mining amounted to a total loss of 95000 tons of N, 28000 tons of P_2O_5 and 79000 tons of K_2O, equivalent to US$159 million of N, P and K fertilizers. In Mali, Van der Pol and Van der Geest (1993) reported that farmers extract, on average, 40% of their agricultural revenue from the soil mining. The significance of these figures is alarming when it is realized that productivity of these soils in their native state is already low because of low inherent levels of plant nutrients. The countries of the SSZWA consume less than 5 $kg.ha^{-1}$ of plant nutrients and in addition there is intense pressure on the governments to remove subsidies on fertilizers without alternative policies to sustain even the current low levels of use of plant nutrients.

The data in Table 3 indicates that continuous cultivation of the weakly buffered soils of northern Nigeria will result in a rapid decline of exchangeable cations and soil acidification in the Sudanian zone of Northern Nigeria. Soil calcium will decrease by 21% and pH by 4% after 50 years of continuous cultivation in farmers' fields.

Rains in West Africa frequently occurs in short and intense storms and pose special problems in term of soil conservation (Kowal and Kassam 1978). Charreau (1974) reported on rainfall intensities between 27 to 62 mm h^{-1}. In Northern Nigeria, Kowal (1970) reported rainfall intensities over 250 mm h^{-1} for a short period. Hoogmoed reported a pick intensity of 300 mm h^{-} in Niono, Mali and a pick of 386 mm h^{-1} for Niamey, Niger (Hoomoed 1986). Land degradation due to water erosion is more severe in the Sudanian zone than in the Sahelian zone. On the bare, weakly crusted surface of the sandy Sahelian soil, infiltration rate of up to 100 mm h^{-1} have been reported (ICRISAT 1985). For the Alfisols with indurate crust, infiltration rates of 10.8 mm h^{-1} in Central Burkina Faso have been reported. As a result of the high rainfall intensities and low infiltration rates, runoff and soil loss are common in the region. The data in Table 5 indicate runoff and soil loss will depend on soil types and erodibility, land form and management system (Lal 1980). Whereas Sefa in Senegal with a slope of 1.2% on a bare soil a total runoff of 39.5% was recorded resulting in soil loss of 21 t ha^{-1} Yr^{-1}, in Burkina Faso with a slope of 1.20% only 7.5% of runoff was recorded with soil loss of 6.4 t yr^{-1} on pearl millet field.

Management of Nitrogen, Phosphorus and Organic Matter

A) Nitrogen

a) Introduction

For many years, several scientists in the Sudano-Sahelian zones initiated research to 1) assess the performance of the different sources of N fertilizers 2) to assess the efficiency of different methods of N placement 3) to calculate ^{15}N balances in order to determine N uptake and losses and 4) to determine efficiency of N under different management systems and the effect of the different soil and agro climatic factors on the performance of N fertilizers (Mughogho et al. (1986), Bationo et al. (1989), Christianson and Vlek (1991), Ganry et al. (1973), Gigou et al. (1984)).

Soil nitrogen is derived from air and dust, biological nitrogen fixation, organic sources, and fertilizers. About 98% of the soil nitrogen is stabilized in the organic matter. Thus the total nitrogen in the soil and the amount of nitrogen released for plant nutrients uptake will depend on organic matter content.

b) Efficiency of N fertilizers as affected by N sources, methods of placement and time of application

Christianson and Vlek (1991) used data from long-term experiment from the Sudano-Sahelian Zone to develop response function to N by pearl millet and sorghum and found that the optimum rate is 50 kg N/ha for sorghum and 30 kg N/ha for pearl millet. At these N rates the returns were 20 kg grain per kg N for sorghum and 9 kg grain per kg N for pearl millet.

The use of ^{15}N in order to calculate N balances and to determine fertilizers N uptake and losses provide an important tool for nitrogen management. Results with ^{15}N research in early years are reported in Mughogho et al. from which the following conclusion can be made.

1) Apparent uptake of fertilizer N exceeds measured uptake using ^{15}N.
2) Uptake of ^{15}N labelled fertilizer and apparent recovery of unlabelled N decreases with increasing rates of application.
3) Loss of ^{15}N labelled fertilizer to the atmosphere and recovery of ^{15}N in the soil increases with increasing rates of fertilizer application.
4) Estimated losses of N are high regardless of N sources.

The urea and calcium ammonium nitrate (CAN) are the most common sources of nitrogen in the region. Trials were undertaken to evaluate these two sources of nitrogen with basal or split application, banded, broadcast or applied point placed as urea supergranule (USG) or CAN point placed. ^{15}N was applied in microplot in order to construct N balances and to determine N uptake and losses from the different sources of N, methods of application and timing of application.

From the data in table 5,6 and 7 the following conclusion can be made: 1) Fertilizer N recovery by plant was very low, averaging 25 – 30% over all years. 2) There is a higher loss of N with the point placement of urea (USG) (> 50%) and the mechanism of N loss is believed to have been ammonia volatilization. 3) For all years losses of N from CAN were less than from urea because one-half of the N in CAN is in the non-volatile nitrate form. 4) Although CAN has a lower N content than urea, it is attractive as an N source because of its low potential for N loss via volatilization, and its point placement will improve its spatial availability. The data in Figure 2 clearly indicates that CAN point placed outperformed urea point placed or broadcast and ^{15}N similar trials indicate that ^{15}N uptake by plants was almost three times higher from CAN than that of urea applied in the same manner (Table 7).

c) Efficiency of N fertilizers as affected by soil and crop management and rainfall

Mughogho et al. (1986) found significant relationships between crop yields and N recovery. N losses averaged 20% in the humid and sub-humid zones with maize and were significantly less than the average loss of 40% found over all treatments in the Sudano-Sahelian zone.

In the Sahelian zone, Bationo and Vlek (1998) reported nitrogen use efficiencies of 14% in plots without lime and phosphorus whereas this amount increased to 28% when P and lime were applied.

Rotation of cereals with legumes could be a way to increase N use efficiency. Bationo and Vlek 1998 reported a nitrogen use efficiency of 20% in the continuous cultivation of pearl millet but its value increased to 28% when pearl millet was rotated with cowpea.

Bationo et al. (1989) found a strong effect between planting density and response to N fertilizer. Christianson et al. (1990) developed a model on the effect of rainfall on N for pearl millet production in the Sahel and found that the response to N was affected by rainfall over a 45 days yield-sensitive period which coincides with the culms elongation and anthesis growth stages for millet (Figure 3).

(2) Phosphorus sources and management

a) Introduction

Among soil fertility factors, phosphorus deficiency is a major constraint to crop production in the Sudano-Sahelian zone. For many years, research has been undertaken to assess the extent of soil phosphorus deficiency, to estimate phosphorus requirement of major crops, and to evaluate the agronomic potential of various phosphate rock (PR) from local deposits (Goldsworthy, 1967; Pichot and Roche, 1972; Thibout et al. 1980; Bationo et al. 1987; Bationo et al. 1990; Hauck, 1966; Jones, 1973; Juo and Fox, 1977; Kang and Osiname, 1979; Boyer, 1954; Nalos et al. 1974; Juo and Kang, 1978; Mokwunye, 1979; Truong et al. 1978)

About 80% of the soils in sub-Saharan Africa are short of this critical nutrient element and without the use of phosphorus, other inputs and technologies are not effective. However, sub-Sahara Africa use 1.6 kg P/ha^{-1} of cultivated land as compared to 7.9 and 14.9 respectively for Latin America and Asia. It is now accepted that the replenishment of soil capital phosphorus is not only a crop production issue, but an environmental issue and P application is essential for the conservation of the natural resource base.

Availability and total P levels of soil are very low in the SSZWA as compared to the other soils in West Africa (Bache and Rogers, 1970; Mokwunye, 1974; Jones and Wild, 1975; Juo and Fox, 1977). For the sandy Sahelian soils total P values can be as low as 40 mg P kg^{-1} and the value of available P less than 2 mg P kg^{-1}. In a study of the fertility status of selected pearl millet producing soils of West Africa, Manu et al. 1991 found that the amount of total P in these soils ranged from 25 to 340% mg kg^{-1} with a mean of 109% mg kg^{-1}. The low content of both total and available P parameters may be related to several factors including 1) Parent materials, which are mainly composed of eolian sands, contain low mineral reserves and lack primary minerals necessary for nutrient recharge. 2) A high proportion of total P in these soils is often in occluded form and is not available to crop (Charreau, 1974). 3) Low level of organic matter and the removal of crop residue from fields. Organic matter has a favourable effect on P dynamics of the soil; in addition to P release by mineralization, the competition of organic ligands for Fe and Al oxides surface can result in a decrease of P fixation of applied and native P.

The P sorption characteristics of different soil types has been investigated and as compared to the soils of the more humid regions, the soils of the SSZWA have very low capacity to fix P (Sanchez and Uehara, 1980; Udo and Ogunwale, 1972; Fox and Kamprah, 1970; Juo and Fox, 1977; Syers et al. 1971). For pearl millet producing soils, Manu et al. 1991 fitted the sorption data to Langmuir equation (Langmuir 1918) and P sorption maximum was determined using the method of Fox and Kamprath, 1970. From these representative sites in the Sudano-Sahelian zone the values of maximum P sorbed ranged from 27 mg kg^{-1} to 253 mg kg-1 with a mean of 94 mg kg^{-1}.

Phosphorus deficiency is a major constraint to crop production and response to nitrogen is substantial only when both moisture and phosphorus are not limiting. Field trials were established to determine the relative importance of N, P and K fertilizers. The data in Table 8 indicates that from 1982 to 1986 the average control plot was 190 kg grain ha^{-1}. The sole addition of 30 kg P2O5/ha without N fertilizers increased the average yield to 714 kg ha^{-1}. The addition of only 60 kg N/ha did not increase the yield significantly over the control and the average grain yield obtained was 283 kg ha^{-1}. Those data clearly indicate that P is the most limiting factor in those sandy Sahelian soils and there is no significant response to N without correcting first for P deficiency. When P is applied the response to N can be substantial and with the application of 120 kg N ha-1 a pearly millet grain yield of 1173 kg ha-1 was obtained as compared to 714 kg ha-1 when only P fertilizers were applied. For all the years the addition of potassium did not increase significantly the yield of both grain and total dry matter of pearl millet.

b) The use of alternative locally available phosphate rock

Despite the fact that deficiency of P is acute on the soils of West Africa, very little P fertilizers is used by local farmers, partially because of the high cost of the imported fertilizers. The use of locally available phosphate rock indigenous in the region could be an alternative to use of high cost imported P fertilizers. The effectiveness of phosphate rock (PR) depends on its chemical and mineralogical composition (Khasawneh and Doll (1978), Lehr and McClellan (1972), Chien and Hammond (1978). The most important feature of the empirical formula of francolite is the ability of carbonate ions to substitute for phosphate in the apatite latice. Smith and Lehr (1966) concluded from their studies that the level of isomorphic substitution of carbonate for phosphate within the latice of the apatite crystal influences the solubility of the apatite in the rock and therefore controls the amount of phosphorus that is released when PR is applied to soil. The most reactive PR are those having a molar PO_4/CO_3 ratio less than 5. West African PR's are not very reactive. Chien (1977) found that the solubility of PR in neutral ammonium citrate (NAC) was directly related to the level of carbonate substitution. Diamond (1979) proposed a classification of phosphate rock for direct application based on citrate solubility as >5.4% high; 3.2–4.5% medium and <2.7% low. Based on this classification only Tilemsi PR has a medium reactivity.

Environmental conditions, crop types, and management practices control the P supply and hence the effectiveness of a given PR in a given crop management environment, (Mokwunye, 1995). The ability of the soil to provide H+, soil with low P and Ca, soil moisture, the acidification of the rhizosphere, plants with high root density and high Ca uptake play an important role in P availability from PR (Kasawneh and Doll, 1978; Chien, 1977; Mokwunye, 1995; Hammond et al. 1986; Kirk and Nye, 1986; Hedley et al. 1982; Sale and Mokwunye, 1993; Föhse et al. 1988; Barrow, 1990; Hammond et al. 1989).

Bationo et al. (1987) have shown that direct application of PR indigenous to the region may be an economical alternative to the use of more expensive imported water-soluble P fertilizers for certain crops and soils. Bationo et al. 1987 while evaluating Parc-W and Tahoua PR indigenous to Niger found that PR is only 48% as effective as single superphosphate (SSP), whereas the effectiveness of the more reactive Tahoua rock was as high as 76% of SSP. Further studies by Bationo et al. (1990) showed that Tahoua PR is suitable for direct application, but Parc-W has less potential for direct application. The data from a long-term benchmark experiment show that SSP outperformed the other sources and its superiority to sulphur-free Triple Superphosphate (TSP) indicates that with continuous cultivation, sulphur deficiency develops. For both pearl millet grain and total dry matter yields, the relative agronomic effectiveness was almost similar for TSP as compared to the partially acidulated Parc W phosphate rock (PAPR) with 50% acidulation (PAPR50) indicating that partial acidification of Parc-W PR can significantly increase its effectiveness (Bationo et al 1996).

In trials conducted in the different agro-ecological zones of Niger it was found that Tahoua PR outperformed Kodjari PR (from Burkina Faso) (Figure 4). The results are in agreement with the fact that the molar PO_4/CO_3 ratio is 23 for Kodjari PR and 4.9 for Tahoua PR, and Tahoua PR has also a higher solubility in NAC.

Bationo et al. (1997) found that Tilemsi PR can result in net returns and value/cost ratios similar to recommended cotton or cereal complex imported fertilizers.

There is ample evidence that indicates that market differences exist between species and genotype for P uptake (Föhse et al. 1988; Caradus, 1980; Nielsen and Schjorring, 1983; Spencer et al. 1980). Bationo et al. 2001 found that the PUE among nine pearl millet varieties varied from 25 kg grain/kg P for variety ICMVIS 85333 to 77 kg grain/kg P for Haini-Kirei cultivar.

The data on Table 9 clearly shows that hill placement of small qualities of P fertilizers will have a higher phosphorus use efficiency (PUE) as compared to the broadcasting of 13 kg P/ha as recommended by the extension services. Whereas in 1995 the PUE was 47 with the broadcasting of 13 kg/P ha, a value of 111 was obtained with the hill placement of 3 kg P/ha with the seed at sowing time. In on-farm researchers managed trials in the Sahelian zone, it was found that the efficiency of PR from Kodjari or Tahoua can be improved with the hill placement of 4 kg P/ha. Whereas the PUE of Kodjari PR applied alone was 14 it increased to 31 when additional P was hill placed at seedling time as 15-15-15 for pearl millet grain yield (Bationo, unpublished data).

In long-term soil management trials, application of nitrogen, crop residue and ridging and rotation of pearl millet with cowpea were evaluated to determine their effect on PUE. The results show that soil productivity of the sandy soils can dramatically increase with the adoption of improved crop and soil management technologies, whereas the absolute control recorded 33 kg ha^{-1} of pearl millet grains, 1829 kg ha^{-1} was obtained when phosphorus nitrogen and crop residue was applied to the ridged and fallowed leguminous cowpea upon the previous season. Results indicate for the grain yield that PUE increases from 46 with only P application to 133 when P is applied in combination with nitrogen, crop residue and the crop is planted on ridge in a rotation system (Table 10).

D. Organic matter management

a) Introduction

Maintaining soil organic matter is a key to sustainable land use management. Organic matter acts as source and sink for plant nutrients. Other important benefits resulting from the maintenance of organic matter is low-input agro-systems include retention and storage of nutrients, increasing buffering capacity in low activity clay soils, and increasing water holding capacity. Nye and Greenland (1960) estimated that the annual increase in nitrogen under forest fallow was 30 kg N ha^{-1} in the soil and 60 kg N ha^{-1} in the vegetation. For the savanna ecosystems, the annual increase was 10 kg N ha^{-1} in the soil and 25 kg N ha^{-1} in leaves and vegetation. Bationo et al. 1995 reported that continuous cultivation in the Sahelian zone has led to drastic reduction in organic matter and a subsequent soil acidification. Bationo and Mokwunye (1991) reported that in the Sudano-Sahelian zone, 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 these soils. In a study to quantify the effects of changes in organic carbon on cation exchange capacity (CEC) De Ridder and Van Keulen (1990) found that a difference of 1 g kg-1 in organic carbon results in a difference of 4.3 mol kg^{-1}. In many cropping systems few if any agricultural residues are returned to the soil. This leads to decline soil organic matter, which frequently results in lower crop yields or soil productivity.

The concentration of organic carbon in the top soil is reported to average 12 mg kg^{-1} for the forest zone, 7 mg kg^{-1} for the Guinean zone, 4 mg kg-1 in the Sudanian zone and 2 mg kg^{-1} for the Sahelian zone (Windmeijer and Andriesse (1993). The soils of the Sudano-Sahelian zone are inherently low in organic carbon. This is due to the low root growth of crops and natural vegetation but also the rapid turnover rates of organic materials with high soil temperature and microfauna, particularly termites. In a survey of millet producing soils, Manu et al. (1991) found an average soil Corg content of 7.6 g kg^{-1} with a range from 0.8 to 29.4 g kg^{-1}. The data also showed that these Corg contents were highly correlated with total N (R = 0.97) which indicates that in the predominant agro-pastoral systems without the application of mineral N fertilizers, N nutrition of crops largely depend on the maintenance of soil Corg levels.

The importance of soil textural (clay and silt) properties for the Corg content of soil was stressed repeatedly as clay is an important component in the stabilization of organic molecules and mino-organisms (Amato and Ladd, 1992; Greenland and Nye, 1959; Feller et al. 1992). Thus Feller et al. (1992) reported that independently of climatic variations such as precipitation, temperature, and duration of the dry seasons Corg increased between 600 and 3000 mm annual rainfall with the clay and silt contents of low activity clay soils. Therefore small variations in topsoil texture at the field or watershed level could have large effects on Corg.

b) Effect of soil management practices on organic carbon contents

There is much evidence for rapid decline of Corg levels with continuous cultivation of crops in the SSZWA (Bationo et al. 1995). For the sandy soils, average annual losses in Corg often expressed by the K value (calculated as the percentage of organic carbon loss per year), may be as higher as 4.7%, whereas for the sandy loam soils, reported losses seem much lower, with an average of 2% (Pieri, 1989, Table 11). The data in Table 11 also clearly indicated that soil erosion can increase Corg losses from 2% to 6.3% and management practices such as crop rotation, following soil tillage, application of mineral fertilizers and mulching will have a significant effect on annual losses of Corg. The K-value in cotton cereal rotations were 2.8%, lower than the 2.8%, lower than the 2.8% in continuous cotton system. At Nioro-du-Rip in Senegal, soil tillage increased annual Corg losses from 3.8% to 5.2% and annual Corg losses declined from 5.2% without NPK to 3.9% with NPK application.

c) Effects of crop residues and manure on soil productivity

The Sahelian zone

In long-term crop residue and management trials, Bationo and Buerkert 2001 reported for the Sahelian zone a very significant effect between crop residue and mineral fertilizer (Figure 5). From this experiment started since 1984 Bationo et al. (1993) reported that the grain yield declined to 160 kg ha^{-1} in unmulched and unfertilized plots. However, grain yield could be increased to 770 kg ha^{-1} with a mulch of 2 t crop residue per hectare and 1030 kg ha^{-1} with 13 kg P plus 30 kg N ha^{-1}. The combination of crop residue and mineral fertilizers resulted in grain yield of 1940 kg ha^{-1}. The application of 4 t of crop residue per hectare maintained soil organic carbon at the same level that in an adjacent fallow field in the top soil but continuous cultivation without mulching results in drastic reduction of Corg (Figure 6). In the Sudanian zone, all available reports show a much smaller or even negative effect of crop residue use as soil amendment (Bationo et al. 1995; Sedogo, 1993). In the Sahelian zone the application of crop residue increased soil pH, and exchangeable bases and decrease the capacity of the soil to fix phosphorus.

On the nutrient poor West African soil, manure, the second farm-available soil amendment can substantially enhance crop yields. For Niger, McIntire et al. (1992) reported grain yield increase between 15 and 86 kg for millet and between 14 and 27 kg for groundnut per ton of applied manure. Similar manure effects have been reported from other Sahelian countries. However, given the large variation in the nutrient concentration of the manure types applied comparisons between results from different experiments should be made with precaution. Powell et al. (1998) a very significant effect of manure and urine application on pearl millet in the Sahelian zone.

In the SSZWA crop residues use as surface mulch can plan an important role in the maintenance of Corg levels and productivity of the prevailing acid soils through the recycling of mineral nutrients, increased in fertilizer use efficiency and a decrease in soil erosion effect. However, organic material available for surface mulching are scarce given the low overall production levels of biomass and their multiple competitive use as fodder, construction material and cooking fuel (Lamers and Feil, 1993). The crop residue quantities found on-farm at the beginning of the rainy season ranged from 0 to 500 kg ha^{-1}. McIntire and Fussel (1986) reported that on farmers' fields in the Sahel average grain yields were 236 kg ha^{-1} and mean crop residue yields barely reached 1300 kg ha^{-1}. Baidu–Forson (1995) reported on availability of 250 kg ha^{-1} of crop residue at the onset of the rains. Powell et al. (1987) showed that 50% of the disappearance rates of millet stover could be attributed to livestock grazing.

Animal manure has a similar role as residue mulching for the maintenance of soil productivity but depending on rangeland productivity, it will require between 10 to 40 ha of dry season grazing land and 3 to 10 ha of rangeland of wet season grazing to maintain yields one one hectare of cropland (Fernandez-Rivera et al. 1995). The potential of manure to maintain soil Corg and sustain crop production is thus limited by the number of animals available and the size and quality of the rangeland.

At the farm level, the maintenance of Corg levels in the soils of the region will largely depend on an increase in C fixation by plants. Given the strong limitation of plant growth by the low availability of mineral nutrients, a yield-effective application of mineral fertilizers is crucial. It would not only allow large increase in crop production and the amount of by-products but also to improve soil coverage by forage grass and weeds.

D) Relationships between cropping systems and fertility management

a) Introduction

The most common cropping system involves growing several crops in association as mixtures or intercrop. This practice provides the farmers with several options for returns from land and labor, often increases efficiency with scarce resources, and reduces dependence upon a single crop that is susceptible to environment and economic fluctuations. Steiner (1984) reported that traditional intercropping systems cover 75% of the cultivated land in the SSZWA. The principal reasons for farmers to intercrop are flexibility, profit and resource maximization, risk minimization, soil conservation and maintenance, weed control and nutritional advantages (Norman, 1974; Swinton et al. 1974; Fusel and Serafini, 1985).

Cowpea (Vigna unguiculata (L.) Walp) and groundnut (Arachis hypogea L.) are two of the predominant grain legumes in the SSZWA. Groundnut occupies 2.7 million hectares of arable land and cowpea 6 million hectares. The two legumes are important components of the mixed cropping systems of the resource-poor farmers. The most important cereals are sorghum and pearl millet and the two legumes are often intercropped with these cereals. While considerable information is available on fertilizer requirements for sole cropping of various crops, little is known on fertilizer requirement in intercropping.

In the mixed cropping systems, legume yields are very low due to low soil fertility, low planting densities and pest and decrease (Ntare,1989; Reddy et al. 1992). The yield of cowpea grain varies between 50 and 300 kg ha^{-1} in farmers fields in marked contrast to yield over 2000 kg ha^{-1} obtainable on research station and by large scale commercial enterprises in pure cropping. Rotation of cereals with legumes has been extensively studied in recent years. The use of rotational systems involving legumes for harvesting nitrogen fixation is gaining importance throughout the region because of economic and sustainability considerations. The beneficial effect of legumes on succeeding crops is normally exclusively attributed to the increased soil N fertility as a result of N-fixation. The amount of N2 fixed by leguminous crops can be quite high but some workers have demonstrated also that legumes can deplete soil nitrogen (Rupela and Saxena, 1987; Blumenthal et al. 1982; Tanaka et al. 1983). Most data reported on the quantity of N fixed by the legume crops in the SSZWA concerned the above ground part of the legume and very little is known on the nitrogen fixed by roots where much of the legume bio-mass is returned to the soil as green manure a positive N balance is to be expected. However, this may not be true for grain legumes and fodder. Where the bulk of above legume material is removed from the system. Nevertheless, many other positive effects of grain legumes such as the improvement of soil biological and physical properties and the ability of some legumes bounded phosphorus by roots exudates (Gardner et al. 1991; Arihara and Okwaki, 1989).

Other advantages of crop rotations include soil conservation (Stoop and Staveren, 1981) organic matter restoration (Spurgeon and Grimson, 1965) and pest and disease control (Sunnadurai, 1973).

In the mixed crop-livestock systems of the SSZWA, increasing legume component in the farming systems is important in order to increase the availability of fodder as source of livestock feed while increasing soil fertility.

b) Intercropping

Fussel and Serafini (1985) reported yield advantages from 10-100% in millet cowpea systems.

Yield stability has been proposed as a major advantage of intercropping (Wiley, 1979a, 1979b; Willey et al. 1985; Steiner, 1984) as farmers want to rely on management practices that increase yields, when this is possible, while improving the stability of the production in both good and poor rainfall years. Baker (1980) has compared relative stability of intercropping and cropping using stability analysis of Finlay and Wilkinson (1963) and found that in the groundnut/cereal systems in northern Nigeria, intercropping systems were found to be more stable. Ntare (1989) reported yield advantages of 20-70% depending on the different combinations of pearl millet and cowpea cultivars. Although traditional intercropping cover over 75% of the cultivated area in the SSZWA, there is a scarcity of information on the efficiency of fertilizers under these systems. The number of days before planting the second crop will depend on the importance of the next rains after the first cereal crops have been planted. With a basal application of P fertilizers the cereal growth is rapid and can suppress completely the second crop if its planting occurs after three weeks after the cereal crops have been sown. In contrast if the legume crops is planted early it will compete more with the cereal crop for light, water and nutrients and can significantly reduce the yield of the cereal crop.

c) Relay and sequential cropping

In the Sudanian zone with longer growing season and higher rainfall there is greater opportunity than in the Sahelian zone to manipulate the systems with appropriate genotypes and management systems. Field trials have been conducted to examine the performance of the cultivars under relay and sequential systems and revealed the potential of these alternative systems over traditional sole or mixed cropping (ICRISAT, 1984 and 1987).

In Mali, by introducing short season sorghum cultivars in relay cropping with other short duration cowpea and groundnut cultivars, substantial yields of legumes and sorghum were obtained as compared to traditional systems (IER, 1990; Sogodogo and Shetty, 1991).

In the Sahelian zone (Sivakumar, 1986) analysed the data of the onset and ending of the rains and the length of the growing period. He found that an early onset of the rains offers the probability of a longer growing period while delayed onset results in a considerable short term growing season. The above analysis suggests that even for the Sahelian zone, cropping management factors using relay cropping can increase soil productivity with an early onset of the rains.

d) Crop rotation

Despite the recognised 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 enabling policies and other socio-economic factors. Cheaper means of improving soil fertility and productivity are therefore necessary.

Cereals and legumes rotation effects on cereals yields have been reported by several scientists (Bationo et al. 1998; Klaij and Ntare, 1985; Stoop and Van Staven, 1981). Bationo and Ntare, 2000 data at Tara in the Sudanian zone clearly indicates that at all levels of nitrogen application the yield of pearl millet after cowpea outperformed the yield of millet in the continuous millet cultivation.

N has been used to quantify the amounts of nitrogen fixed by cowpea and groundnut under different soil fertility levels. The nitrogen derived from the air (NDFA) varies from 65 to 88% for cowpea whereas the values varied from 20 to 75% for groundnut. In the complete treatment where all nutrients were applied cowpea stover fixed up to 89 kg N ha^{-1} whereas for same treatment groundnut fixed only 40 kg N ha^{-1} in this Sahelian environment (Bationo and Vlek 1990). In order to determine ^{15}N recovery from different cropping systems, labelled nitrogen fertilizers were applied to microplots of pearl millet grown continuously, in rotation with cowpea, in rotation with groundnut, intercropped with cowpea, and intercropped with groundnut. The data indicates that nitrogen use efficiency increased from 20% in continuous pearl millet cultivation to 28% when pearl millet was rotated with cowpea (Bationo and Vlek, 1998). The same authors reported that in the Sudanian zone nitrogen derived from the soil increased from 39 kg N ha-1 in continuous pearl millet cultivation to 62 kg N/ha when pearl millet is rotated with groundnut. Those data clearly indicate that although all the above ground biomass of the legume will be used to feed livestock and not returned to the soil, rotation will increase not only the yields of succeeding cereal crop but also its nitrogen use efficiency.

Bayayoko et al. (2000) in studies of cereals legumes effects on cereal growth in the Sudano-Sahelian zone of West Africa reported that the rotation effect although significant in most of the cases varied with sites and years. At Sadore as an example, the millet rotated with cowpea yielded 1904 kg/ha whereas the continuous millet cultivation yielded 1557 kg ha-1. Bayoyoko et al. 2000 reported higher levels of mineral N and native arbuscular mychorrhizae infection in the rotation systems as compared to the continuous cereal cultivation.

The different cropping systems have a significant effect on the soil organic carbon. The soil organic carbon levels was 0.22% in the continuous systems whereas it is increased to 0.27% in the rotation systems. As a result of this soil pH was higher in the rotation systems as compared to the continuous monoculture (Bationo, unpublished data).

Farmers evaluation of soil fertility restoration technologies

a) Introduction

A review of the state of the art of the agronomic research in soil fertility management showed 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 these technologies developed on-station are not always built on indigenous practices, local socio-economic realities, farmers priorities and perceptions. Most often no account has been taken of enabling policy environment and indigenous knowledge. Therefore on-farm research should involve farmers, researchers, extension agents, non-governmental agencies at the design, implementation and evaluation stages. In this way, the technologies generated have a better chance of adoption by the land users. Promising technologies were identified to be tested on-farm under farmers managed trials knowing that a particular farm management practice is often less effective in the hand of the farmer, than it is on-station. There is need for experimental farm input packages to be tested under farmer's conditions to allow the scientists to observe the transfer of technologies to the farmers field and to determine associated management practices to be adopted by farmers in order to ensure good economic returns.

The objectives of on-farm research activities is: 1) to assess farmers' perception of the different technologies proposed 2) to identify the farmers' management practices affecting the good performance of the different technologies 3) to evaluate the profitability of the different technologies tested 4) to identify the constraints to technology adoption and means to alleviate them and 5) to assess the impact of technology adoption.

b) Effects of soil fertility restoration technologies on land productivity from farmers managed trials in the SSZWA

In the Sahelian zone of Gobery in Western Niger, 20 farmers evaluated phosphorus and nitrogen fertilizers including partially acidulated phosphate rock (PAPR) from parc-W. The data in Table 12 indicate a strongly response to P with yield increase of 181% over control with the application of N and P. No significant difference was found between PAPR and SSP, nor was difference between broadcasting and hill placement of nitrogen. However, crop response to fertilizer use was strongly affected by the cropping density chosen by individual farmers (Bationo et al. 1992). Averaged over all fertilized treatments and all years, when farmers planted at less than 3500 pockets per hectare, yield was very low and no response was found to fertilizer use. However, each 1500 pocket/ha increases about 200 kg grain/ha.

Bationo and Baidu-Forson (1998) reported the agro-economic evaluation of farmers managed trials on the evaluation of water soluble fertilizers, phosphate rock and rotation of cereals with legumes. The net grains, over three years, resulting from partial budgeting analysis show that farmers could make net financial gains with only the application of P fertilizer. The use of N in addition to P significantly improved net grains. Water soluble single superphosphate generated higher net gains than Tahoua phosphate rock. As a result of the higher cowpea price and is beneficial effect on the improvement of soil fertility, the rotation systems involving cowpea were more profitable than continuous pearl millet cultivation.

Bationo et al. 1997 reported the economic evaluation data of Tilemsi phosphate rock by farmers in three agro-ecological zones of Mali. The agro-ecological zones were Tafla with an average rainfall of 600 mm, Sougoumba with 800 mm rainfall and Tinfounga with 1200 mm rainfall. The cropping systems used were rotation of pearl millet with groundnut in Tafla, sorghum with cotton in Sougoumba and maize with cotton in Tinfounga. The data indicate that the different sources of fertilizers have a significant effect on crop yields and there was no difference between Tilemsi phosphate rock and the recommended imported water soluble fertilizers. However, the economic analysis of the data indicate that at some sites the imported recommended water soluble P fertilizers are more profitable than the use of Tilemsi phosphate rock.

Bationo et al. 1998 undertook an agro-economic evaluation of a set of soil fertility restoration technologies and concluded that hill placement of small quantities of P fertilizers at planting time had higher returns than broadcasting 13 kg P/ha.

From 1988 to 2000 farmers-managed trials in the Sahelian zone at Karabedji (~550 mm of rainfall per year) and in the Sudanian zone at Gaya (~800 mm of rainfall per year), over an average of about 2800 field plots showed the agronomic potential of fertilizers (Table 13). The hill placement of 4 kg P/ha almost doubled crop yield. Integrated use of hill placement of water soluble fertilizers in addition to Tahoua phosphate rock broadcast and soil amendment with crop residue application as mulch gave the highest crop yield (Figure 7). The returns over variable cost of fertilizers presented clearly demonstrate the economic importance of soil fertility restoration in the SSZWA.

New research opportunities in the SSZWA

a) New strategies for integrated nutrient management

In the past, integrated nutrient management concentrated mainly on the utilization of available organic and inorganic sources of plant nutrients in a judicious and efficient way. Integrated nutrient management is recently perceived much more broadly as the judicious manipulation of all soil nutrient inputs and outputs and internal flows.

Future research needs to adopt this new holistic approach to integrated nutrient management. For a given cropping system or watershed, this will require the establishment of the nutrient balances. Interventions to limit nutrient losses through erosion can be in some cases as important as research on increasing the efficiency of organic and inorganic plant nutrients for a sustainable land use. This new approach will enhance more carbon sequestration and increase more bio-mass production on the farms for domestic use and there will be more bio-man available for livestock feeds and for soil mulching.

b) Integration of socio-economic and policy research with the technical solution

In the past several technical solutions to the problem of land degradation in the SSZWA have been researched and tested, and may have shown the potential for addressing the problem in some places. Unfortunately a review of the state of the art indicated that very few of these technologies have been adopted by the resource poor farmers. Therefore future research should focus more on problems driven by socio-economic factors and enabling policy environment in order to enhance farmers' capacity to invest in soil fertility restoration. The adoption of the participatory approach will be essential. In this way, the technologies generated have a better chance of adoption by land users.

c) Combining rain water and nutrient management strategies to increase crop production and prevent land degradation

In the SSZWA high inter-annual variability and erratic rainfall distribution in space and time result in water-limiting conditions during the cropping season.

In areas with inadequate rainfall or in runoff-susceptible land, water conservation techniques and water harvesting techniques offer the potential to secure agricultural production and reduce the financial risks associated with the use of purchased fertilizers. Under the conditions of adequate water supply, the addition of organic and inorganic amendments is the single most effective means of increasing water use efficiency. Future research needs to focus on enhancing rainwater and nutrient use efficiencies and on capitalizing on their synergies for increasing crop production and preventing soil degradation.

d) Increasing the legume component for a better integration of crop-livestock production systems

The rotations of cereals with legumes have led to increased cereals yield at many locations in the SSZWA. Factors such as mineral nitrogen increase, enhancement of Vesicular-Azbuscular Mycorrhizal (VAM) for better P nutrition and a decrease in parasitic nematodes have been identified as mechanisms accelerating the enhanced yield of cereals in rotation with legumes. Most of the research quantify has focused on the quantification of the above-ground N fixed by different legumes cultivars, but very little is known on the below-ground N fixed.

There is need to increase the legume component in the mixed cropping systems for a better integration of crop-livestock. The increase of legume component in the present cropping system will not only improve the soil conditions for the succeeding cereal crop, but will provide good quality livestock feed, and the manure produced will be of better quality for soil amendment.

e) Exploiting genetic variation for nutrient use efficiency

Phosphorus is the most limiting plant nutrient for crop production in the SSZWA and there is ample evidence that indicates marked differences between crop genotypes for P uptake. A better understanding of the factors affecting P uptake such as the ability of plants to i) solubilize soil P through acidification of the rhizosphere and the release of chelating agents and phosphate enzymes ii) explore a large volume of soil and iii) absorb P from low P solution would help screening for the genotypes the best appropriate for nutrient use efficiency.

Another important future research opportunity is the selection of genotypes that can efficiently associate with Vesicular-Azbuscular Mycorrhizal (VAM) for better utilization of P applied as indigenous phosphate rock.

f) Use of decision support systems modelling, and GIS for the extrapolation of research findings

Farmers production systems vary with respect to rainfall, soil types and socio-economic circumstances and therefore they are complex. Dealing with such complexity only by empirical research will be expensive and inefficient. Use of models and GIS will facilitate the transfer of workable technologies to similar agro-ecological zones. The use of DSSAT, APSIM and GIS will facilitate extrapolation of findings to other agro-ecozones similar of the benchmark sites chosen for testing technologies and will be cost effective.

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Table 1: Mean and standard deviation of physical and chemical properties of selected West African soils, 0-15 cm

Parameters	**Mean**	**Standard deviation**
pH H_2O (2:1 water:soil)	6.17	0.66
pH KC1 (2:1 KC1:soil)	5.05	0.77
Clay (%)	3.9	2.67
Sand (%)	88	8
Organic matter (%)	1.4	1.09
Total nitrogen (mg kg^{-1})	446	455
Exchangeable bases (cmol kg^{-1})		
Ca	2.16	3.01
Mg	0.59	0.55
K	0.20	0.22
Na	0.04	0.01
Exchangeable acidity (cmol kg^{-1})	0.24	0.80
Effective cation exchange capacity (ECEC;	3.43	3.801
cmol kg^{-1})	88	17
Base saturation (%)	3	8

Source: Bationo et al., 1996

Table 2: Nutrient losses for some West African countries

Country	Area (1000 ha)	Nutrient losses (1000 tons)		
		N	P_2O_5	K_2O
Benin	2972	41.4	10.4	32.5
Burkina Faso	6691	95.4	27.8	78.8
Ghana	4505	137.1	32.3	90.5
Mali	8015	61.7	17.9	66.7
Niger	10985	176.1	55.3	146.6
Nigeria	32813	110.7	316.7	946.2

Source: Stoorvogel and Smaling, 1990

Table 3: Percentage of soil fertility over 50 years in farmers' fields under continuous cultivation in the savanna zones of Nigeria

Zone	Exchangeable cations			pH
	Ca	Mg	K	
Sudan	21	32.0	25.0	4.0
Northern Guinea	18.6	26.8	33.0	3.8
Southern Guinea	46.0	50.6	50.0	10.0

Source: Adapted from Balasubramanian et al. (1984).

Table 4: Runoff and soil loss data for selected locations in west Africa

Country	Location	Mean annual rainfall (mm)	Slope %	Treatments	Annual runoff %	Soil loss (tons ha^{-1} $year^{-1}$)
Benin	Boukombe	875	3.7	Millet conventional	11.7	1
Niger	Allokoto	452	3	Village	16.3	8
Nigeria	Samaru	1062	0.3	Sorghum, cotton	25.2	3
	Ibadan	1197	15	Bare soil	41.9	229
				Bare soil	13.5	40
				Maize-maize	2.6	0
				Maize-cowpea	1.7	4
Senegal	Sefa	1300	1.2	Cowpea-maize	39.5	21
		1241	1.2	Bare soil	22.8	69
		1113	1.2	Groundnut	34.1	83
Burkina Faso	Ougadougou	850	0.5	Sorghum	40.6	10.2
				Bare soil	2.32	0.6
				Crop	2.5	0.1
Côte d' Ivoire	Bouake	1200	0.3	Forest	15.3	18.3
	Abidjan	2100	7.0	Bare soil	38.0	108.2
Mali	Niono		1.3	Bare soil	25.0	NA
Niger	Sadore	560		Millet	1.5	NA
				Millet	0.2	NA
Sierra Leone	Mebai	2000		Bare soil	11	NA
Sierra Leone	Mabai	2000		Unfertilized maize	8	NA

Source: Bationo et al. (1996)
Na=not available

Table 5: Recovery of ^{15}N in the millet plant and soil at harvest, Sadore, Niger 1982

Treatment	Grain yield[a] (kg ha)	N recovery (%)			
		Grain	Plant[b]	Soil	Loss
Check	590	-	-	-	-
CAN split band	970	20.8	36.8	38.2	25.0
Urea split band	1.070	19.0	31.0	37.3	31.7
Urea split broadcast	1.070	17.0	31.3	41.0	27.7
Urea basal broadcast	1.010	16.9	26.7	41.6	31.7
USG basal	960	16.2	27.5	39.3	33.2
USG split	1.070	14.3	26.5	33.2	40.3
LSD (0.01)	167	4.6	6.0	6.0	9.8

a. Average yield for all N rates for each source
b. Sum of grain and stover ^{15}N
CAN: Calcium ammonium nitrate
USG: Urea super granule
Sources: Christianson et al. 1990

Table 6: Yield and recovery of ^{15}N in the millet plant and soil at harvest (1983-85), Sadore, Niger

Year	Treatment	Grain yield[a] (kg ha^{-1})	Stover yield (kg ha^{-1})	^{15}N recovery (%)			
				Grain	Plant[b]	Soil	Loss
1983	Check	660	-	-	-	-	-
	CAN split band	940	-	13.0	28.8	34.2	37.0
	Urea split band	1.040	-	9.8	22.8	39.2	38.0
	USG split	990	-	8.0	22.0	25.3	52.7
	LSD (0.01)	110	-	1.6	3.2	3.4	2.2
1984	Check	460	1.570	-	-	-	-
	CAN split band	480	1.850	9.9	36.8	37.1	26.1
	Urea split band	470	1.930	5.5	20.0	40.1	39.9
	USG split	490	1.780	8.1	21.6	24.8	53.6
	LSD (0.01)	30	220	1.6	3.8	4.2	4.4
1985	Check	900	2.315	-	-	-	-
	CAN split band	1.320	2.910	-	-	-	-
	Urea split band	1.225	3.020	-	-	-	-
	USG split	1.350	3.000	-	-	-	-
	LSD (0.05)	175	386	-	-	-	-

^{15}N was not used in 1985
[a]. Average yield for all N rates for each source
[b]. Sum of grain and stover ^{15}N
CAN: Calcium ammonium nitrate
USG: Urea super granule

Sources: Christianson et al. 1990

Table 7. Recovery ^{15}N fertilizer by millet applied at Sadore, Niger, 1985

N source	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

Sources: Christianson and Vlek, 1991
CAN: Calcium ammonium nitrate

Table 8: Effect of N, P, and K on pearl millet grain and total dry matter (kg/ha) at Sadoré and Gobery (Niger)

Treatments	1982		1983		1984		1985	1986	
	Sadoré		Sadoré	Gobery	Sadoré		Sadoré	Sadoré	
	Grain	TDM	Grain	Grain	Grain	TDM	Grain	Grain	TDM
N0P0K0	217	1595	146	264	173	1280	180	180	1300
N0P30K30	849	2865	608	964	713	2299	440	710	2300
N30P30K30	1119	3597	906	1211	892	3071	720	930	3000
N60P30K30	1155	3278	758	1224	838	3159	900	880	3200
N90P30K30	1244	3731	980	1323	859	3423	1320	900	3400
N120P30K30	1147	4184	1069	1364	1059	3293	1400	1000	3300
N60P0K30	274	2372	262	366	279	1434	290	230	1500
N60P15K30	816	2639	614	1100	918	3089	710	920	3100
N60P45K30	1135	3719	1073	1568	991	3481	1200	980	3500
N60P30K0	1010	3213	908	1281	923	3377	920	910	3400
S.E.	107	349	120	232	140	320	162	250	400
C.V(%).	24	22	26	30	24	22	28	32	25

N.B. Nutrient applied are N, P_205 and K_20 kg/ha
TDM= Total dry matter

Table 9: Effect of phosphorus placement on pearl millet total dry matter (TDM), grain yield, and phosphorus use efficiency (PUE), Niger, 1995-1996 cropping seasons

	1995				**1996**			
	TDM		**Grain**		**TDM**		**Grain**	
Treatments (Kg/ha^{-1})	**Yield ($kg\ ha^{-1}$)**	**PUE**	**Yield ($kg\ ha^{-1}$)**	**PUE**	**Yield ($kg\ ha^{-1}$)**	**PUE**	**Yield ($kg\ ha^{-1}$)**	**PUE**
0	1951		532		2413		641	
13 (broadcast)	4012	159	1138	47	4884	190	1240	46
3 (HP)	3157	402	864	111	3216	268	846	68
5 (HP)	3341	278	937	81	3847	287	996	71
7 (HP)	3498	221	1018	69	4041	233	1074	62
13 (broadcast) + 3 (HP)	4830	180	1382	53	5314	181	1279	40
13 (broadcast) + 5 (HP)	4713	153	1425	50	5180	154	1295	36
13 (broadcast) + 7 (HP)	4381	122	1287	38	4685	114	1131	35
SE	314		92		425		89	

HP Hill placed, TDM : Total dry matter; PUE = kg yield/kg P
Source: Muelhing-Versen et al 1997

Table 10: Effect of mineral fertilizers, crop residue (CR) and crop rotation on pearl millet yield wasts (kg/ha) and phosphorus use efficiency (PUE) Sadore, Niger, 1998 rainy season.

Treatment	**Without CR, without N**				**Without CR, with N**				**With CR, without N**				**With CR, with N**			
	TDM		**Grain**		**TDM**		**Grain**		**TDM**		**Grain**		**TDM**		**Grain**	
	Yield	**PUE**	**Yield**	**PUE**	**Yield**	**PUE**	**Yield**	**PUE**	**Yield**	**PUE**	**Yield**	**PUE**	**Yield**	**PUE**	**Yield**	**PUE**
Control	889		33		2037		58		995		61		1471		98	
13 kg P/ha	2704	140	633	46	4339	177	1030	75	4404	185	726	51	240	4594	1212	86
13 kg P/ha + ridge	2675	137	448	32	4057	155	946	68	3685	210	785	56	4530	235	1146	81
13 kg P/ha + rotation	5306	340	1255	94	6294	327	1441	106	5392	338	1475	109	6124	358	1675	121
13 kg P/ha + ridge + rotation	5223	333	1391	104	5818	291	1581	117	6249	404	1702	126	7551	468	1829	133
SE	407		407		407		407		407		407		407		407	

CR Crop Residue; N Nitrogen; TDM Total Dry Matter; PUE (kg grain/kgP);
TDM= Total dry matter

Table 11: Annual loss rates of soil organic carbon measured at selected research stations in the SSWA

Place and Source	Dominant cultural succession	Observations	Clay + Silt (%) (0-0.2 m)	Annual loss rates of soil organic carbon (k)	
				Number of years of measurement	k (%)
Burkina Faso		With tillage			
Saria, INERA-IRAT	Sorghum monoculture	Without fertiliser	12	10	1.5
	Sorghum monoculture	Low fertilizser	12	10	1.9
	Sorghum monoculture	High fertiliser	12	10	2.6
	Sorghum monoculture	Crop residues	12	10	2.2
CFJA, INERA-IRCT	Cotton-cereals	Eroded watershed	19	15	6.3
Senegal		With tillage			
Bambey, ISRA-IRAT	Millet-groundnut	Without fertiliser	3	5	7.0
	Millet-groundnut	With fertiliser	3	5	4.3
	Millet-groundnut	Fertiliser + straw	3	5	6.0
Bambey, ISRA-IRAT	Millet monoculture	with PK fertiliser + tillage	4	3	4.6
Nioro-du-Rip, IRAT-ISRA	Cereal-leguminous	F0T0	11	17	3.8
	Cereal-leguminous	F0T2	11	17	5.2
	Cereal-leguminous	F2T0	11	17	3.2
	Cereal-leguminous	F2T2	11	17	3.9
	Cereal-leguminous	F1T1	11	17	4.7
Chad		With tillage, high fertility soil			
Bebedjia, IRCT-IRA	Cotton monoculture		11	20	2.8
	Cotton - cereals			20	2.4
	+ 2 years fallow			20	1.2
	+ 4 years fallow			20	0.5

F0 = no fertiliser, F1 = 200 kg ha^{-1} of NPK fertiliser, F2 = 400 kg ha^{-1} of NPK fertiliser + Taiba phosphate rock, T0 = manual tillage, T1 = light tillage, T2 = heavy tillage.

Source: Pieri, 1989

Table 12: Millet grain yields by treatment (mean of 3 years), Goberi, Niger

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

Source, Bationo et al., 1992

Table 13. Mean millet yield (kg ha^{-1}) as affected by fertilizer, phosphate rock and crop residue in Sudano-Sahelian zone, Niger, 1998-2000

*Treatment	Karabedji	Gaya
Farmer practice (FP)	210	505
P hill placement (HP)	470	990
HP + Phosphate rock (PR)	580	1150
HP+PR+Crop residue	835	1320

*Hill placed (HP): P applied at 4 kg ha^{-1} as 15-15-15.
Phosphate rock (PR): P broadcast and incorporated at 13 kg ha^{-1} as Tahoua PR
Crop residue (CR): millet stover applied as mulch at 2 t ha^{-1}
Average rainfall: 600 mm and 800 in Karabedji and Gaya

Figure 1: Agro-ecological zones of West Africa

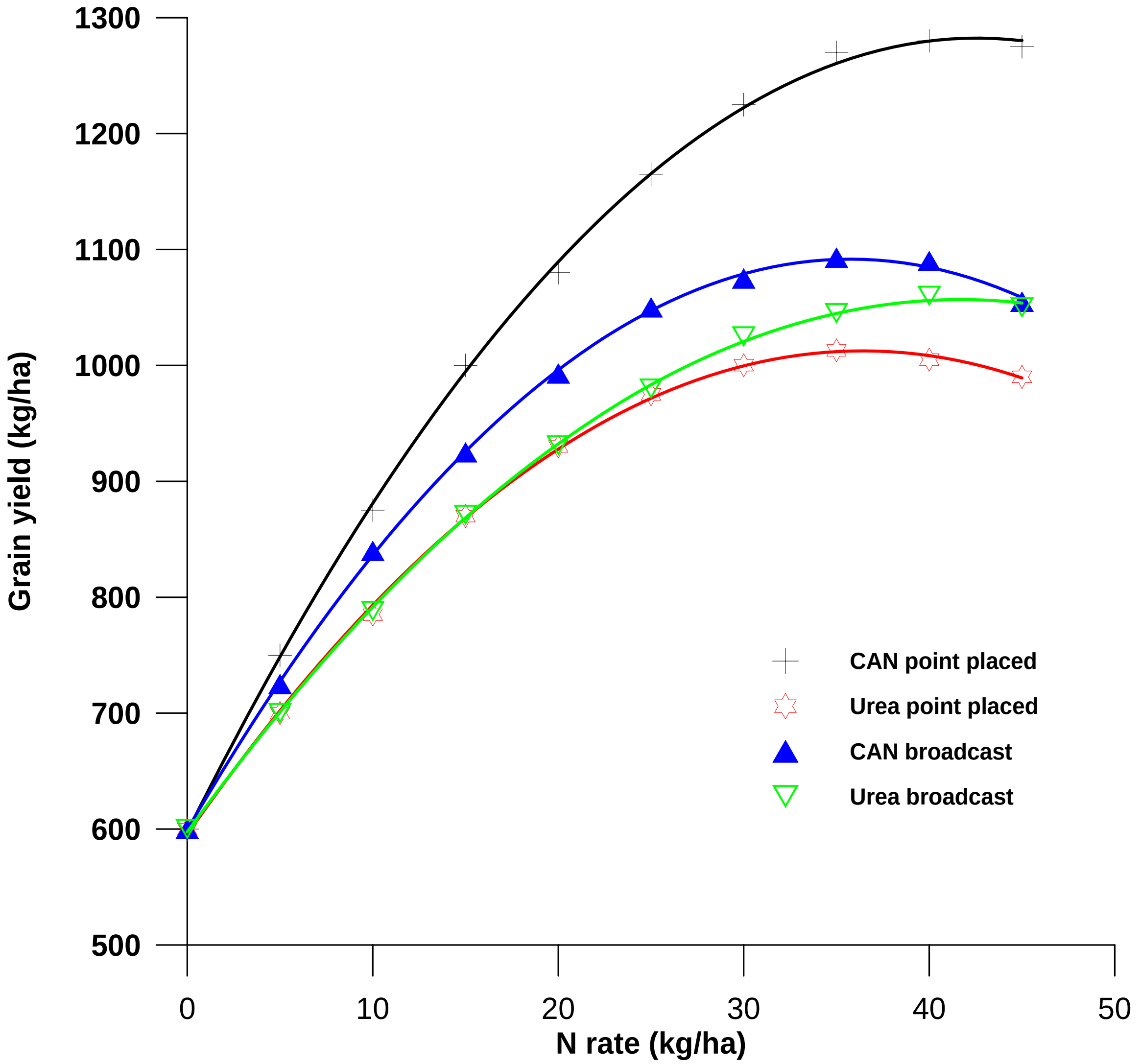

Figure 2: Effects of urea and calcium ammonium nitrate application on grain yield, Goberi, Niger, 1985
Source: Christianson and Vlek, 1991

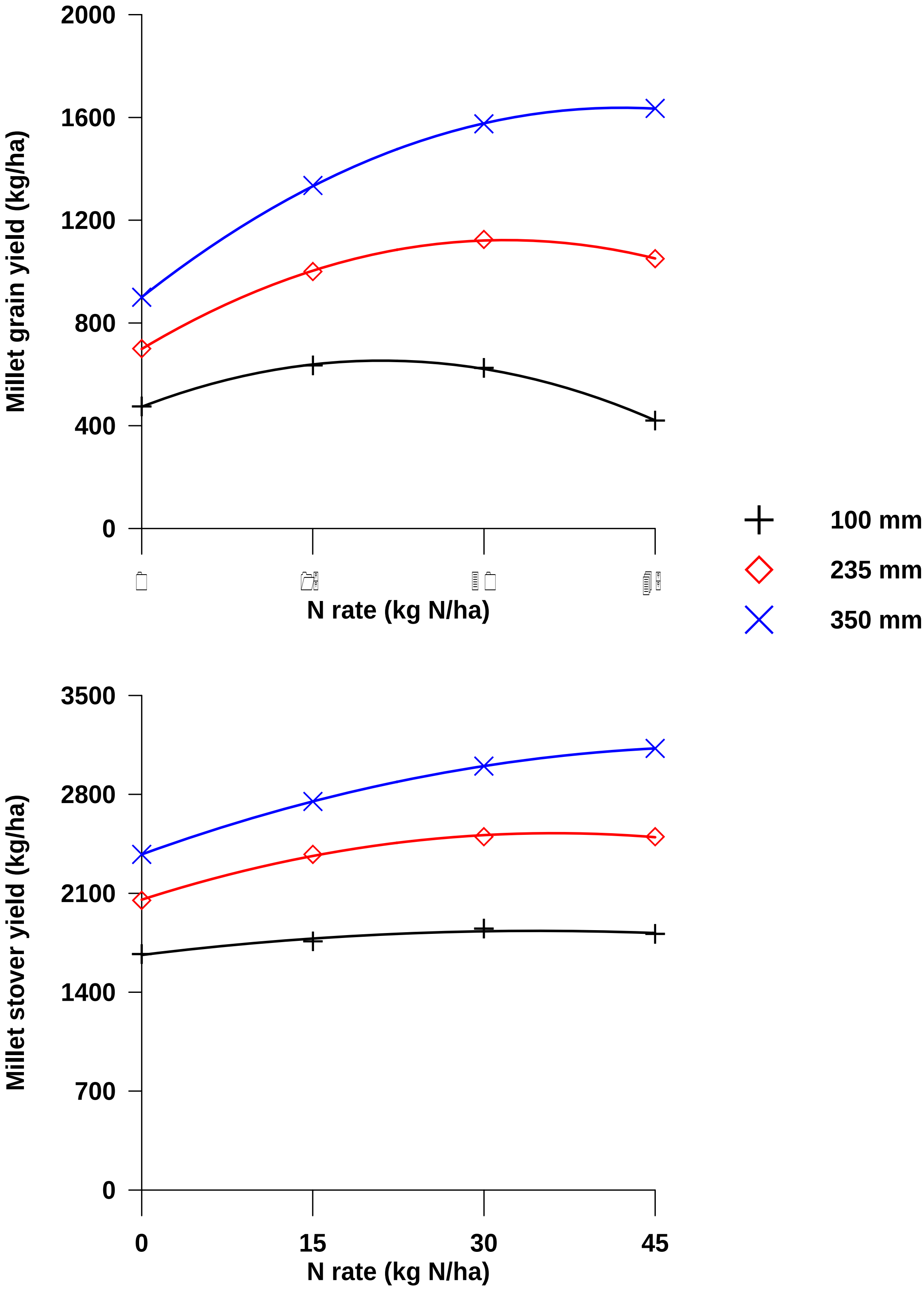

Figure 3: Grain and stover yields affected by N rate and midseason rainfall. Sadore, Niger, 1982 to 1985
Source: Christianson et al., 1990

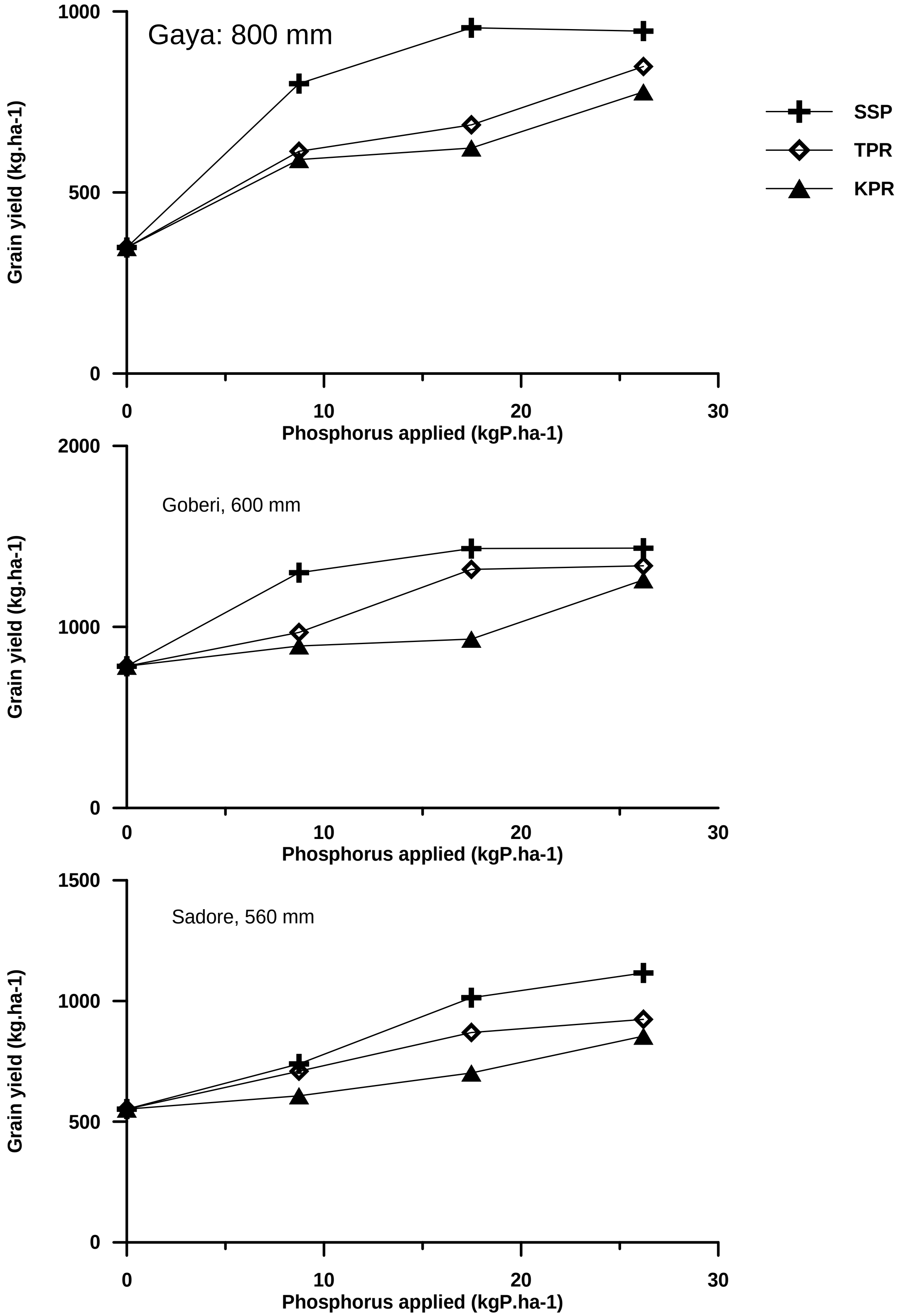

Figure 4: Relationship between P sources and rates on pearl millet grain yield in three agro-ecological zones of Niger, 1996 rainy season.

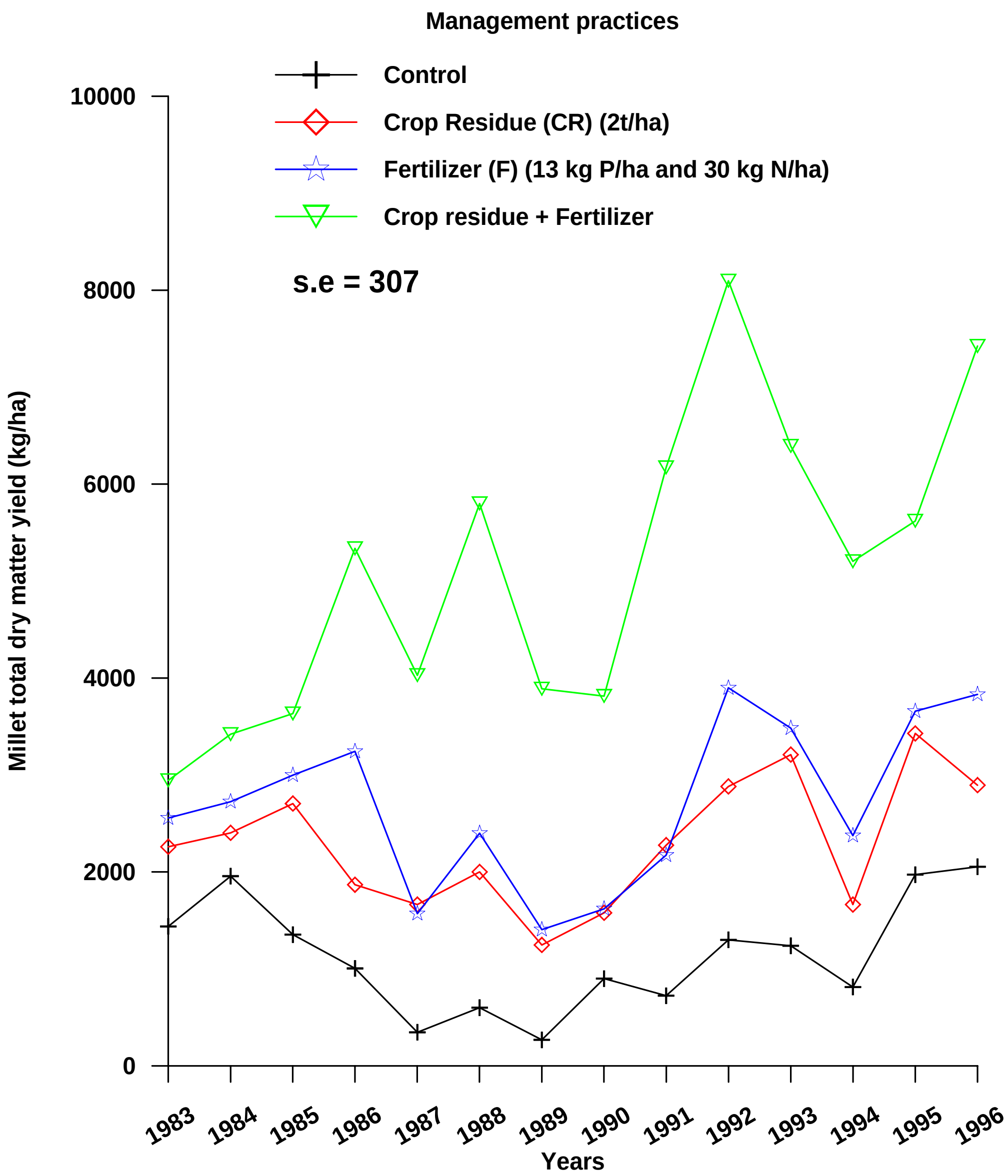

Figure 5: Effect of different management practices on pearl millet total dry matter yield over years, Sadore, Niger.

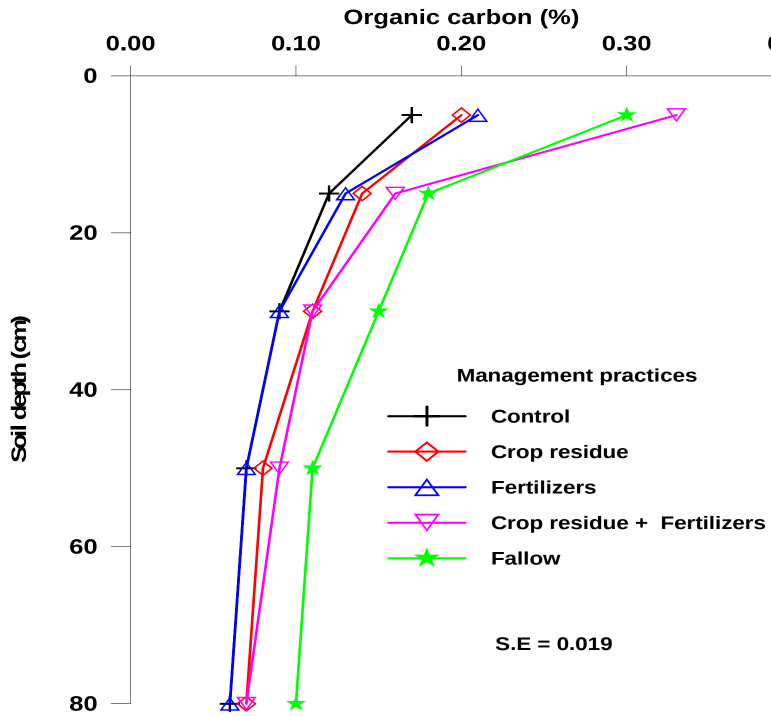

Figure 6: Effect of different management practices on soil organic carbon content after 14 years of cultivation, Sadore, rainy season 1997.

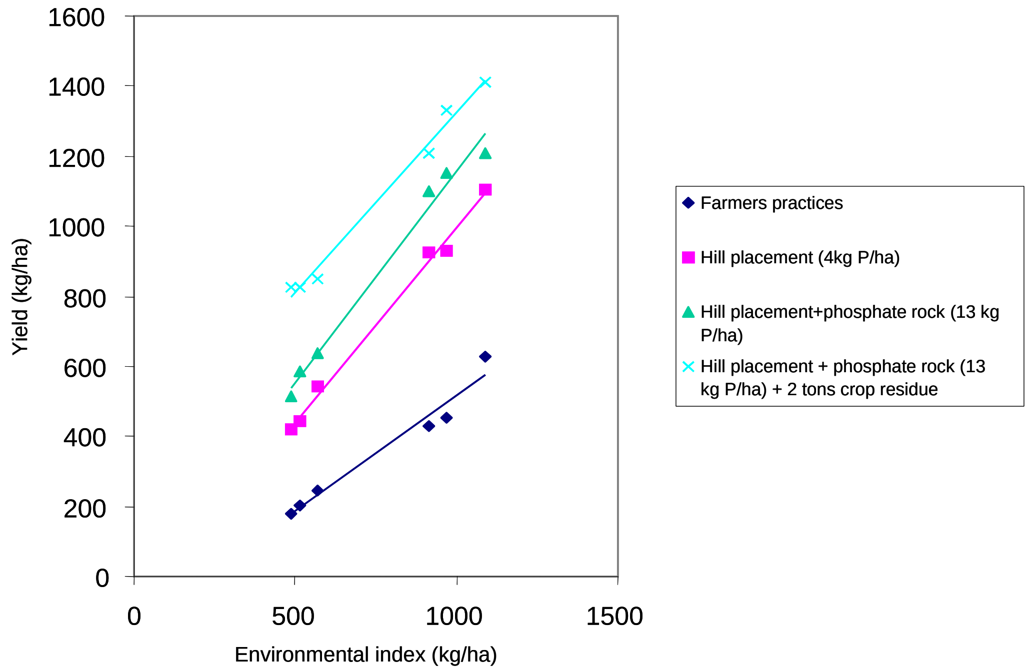

Figure 7: Relationship between environmental index and treatment yield of pearl millet in different agro-ecologiacl zones of Niger

World Cowpea Conference IITA (in press)

Soil Fertility Management and Cowpea Production in the Semi-Arid Tropics of West Africa

Bationo[1], A., B.R. Ntare[2], S. Tarawali[3] and R. Tabo[2]
[1]IFDC/ICRISAT BP 12404 Niamey, Niger; [2]. ICRISAT Bamako, BP 320 Bamako, Mali[3]. ILRI/IITA, PMB 5320 Ibadan, Nigeria

Abstract
Cowpea (*Vigna Unguiculata* L. Walp) is an important grain legume in West Africa as it is a major source of dietary protein for the people. It is usually grown as an intercrop with the major cereals, namely millet and sorghum. Despite its importance, its yields are very low due to several constraints including poor soil, insect pests and drought.

The soils in the Semi-Arid West Africa are inherently low in nitrogen and phosphorus. Soil, water and nutrients management practices are inadequate to sustain food production and to meet the food requirement of the fast growing population.

Research results show that proper management of organic amendments such as crop residues and manure, which are essential complement to mineral phosphorus fertilizers, can increase yields of cowpea and associated cereals more than three fold. Direct application of indigenous phosphate rocks can be an economical alternative to the use of imported, more expensive soluble phosphorus fertilizers for cowpea production in semi-arid tropics of West Africa. The agronomic effectiveness of indigenous phosphate rock is about 50% as compared to the imported single super-phosphate. Furthermore when the unreactive phosphate rocks are partially acidulated at 50%, their agronomic effectiveness can increase to more than 70%..

Studies on cereal-cowpea rotation revealed that yields of cereals succeeding cowpea can, in some cases, double as compared to continuous monoculture. In an efficient soil fertility management, cowpea can fix up to 88 kg N/ha and this results in an increase of nitrogen-use efficiency on the succeeding cereal crop from 20% in the continuous cereal monoculture to 28% when cereals are in rotation with cowpea. Furthermore, the use of soil nitrogen increased from 39 kg N/ha in the continuous cereal monoculture system to 62 kg N/ha in the rotation systems.

The increase of cowpea productivity and component in the cropping systems in this region will improve nutrition of people, increase the feed quantity and quality for livestock, and contribute to soil fertility maintenance. This should contribute to reduction in poverty and environmental degradation.

I. Introduction

Per capita food production in the West African Semi-Arid Tropics (WASAT) has declined significantly over the past three decades and countries like Niger have more than 35% of their population undernourished. According to FAO, total food production in Sahelian countries grew by an impressive 70% from 1961 to 1996, but it lagged behind the population, which doubled causing food production per capita to decline approximately by 30% the same period. Low rainfall, infertile soils, and under-developed marketing channels markets are the main constraints preventing farmers to invest in productivity enhancing inputs. This situation has stemmed from increasing population pressure, and soil degradation in a particular drought-prone region where the soils are naturally infertile. The increasing need for cropland prompted the farmers to cultivate more and more marginal lands which are prone to erosion. Agricultural output should expand by at least 4% annually by the year 2000 in order to ensure food security. Previous studies have clearly shown that the expansion of new farms cannot increase output by over 1% without accelerating environmental degradation.

Consequently, the productivity of land currently under cultivation should increase by at least 3% per annum. As at now, over a quarter of West Africa Sub-region's population of two hundred million inhabitants is threatened by food insecurity. Any program aimed at reverting the declining trend in agricultural productivity and preserving the environment for present and future generations in West Africa must begin with soil fertility restoration and maintenance.

Cowpea (*Vigna unguiculata* (L.) Walp) and groundnut (*Arachis Hypogea* L.) are two of the predominant grain legumes in the semi-arid tropics of West Africa. Groundnut occupies 2.7 million hectares of arable land and cowpea 6 million hectares. The two legumes are important components of the mixed cropping systems of resource poor farmers. The most important cereals are sorghum and pearl millet and legumes are often intercropped with these cereals (Steiner 1984).

The common cropping system involves growing several crops in association as mixtures or intercrop. This practices provide the farmers with several options for returns from land and labor, often increase efficiency with which scarce resources are used, and reduce dependence upon crop that is susceptible to environmental and economic fluctuations. While considerable information is available on fertilizer requirements for sole cropping of various crops, little is known on fertilizer requirement for inter-cropping. Steiner (1984) reported that traditional intercropping systems cover 75% of the cultivated area in the WASAT. The principal reason for farmers to intercrop are flexibility, profit resource maximization, risk minimization, soil conservation and maintenance, weed control and nutritional advantages (Norman 1974; Swinton et al. 1974; Shetty et al. 1995; Fussel and Serafini 1985).

Rotation of cereals with legumes has been extensively studied in recent years. Use of rotational systems involving legumes for harvesting nitrogen fixation is gaining importance throughout the region because of economic and sustainability considerations. The beneficial effect of legumes on succeeding crops is normally exclusively attributed to the increased soil N fertility as a result of N_2-fixation. The amount of N_2 fixed by leguminous crops can be quite high but some workers has demonstrated also that legumes can deplete soil nitrogen (Rupela and Saxena 1987; Blumenthal et al. 1982; Tanaka et al. 1983; Yoshida 1982; Ozaki 1969).

Most of the data reported on the quantity of N fixed by the legume crops in the WASAT concerned the above ground part of the legume and very little is known on the nitrogen fixed by the roots. Where much of the legume biomass is returned to the soil as green manure, a positive N balance is to be expected. However this may not be true for grain legumes and fodder crops, where the bulk of above legume material is removed from the systems. Nevertheless, many other positive effects of grain legumes such as the improvement of soil biological and physical properties (Hoshikawa 1990) and the ability of some legumes to solubilize occluded P and highly insoluble calcium bounded phosphorus by roots exudates (Gardner et al. 1991, Arihara and Ohwaki 1989). Other advantages of crop rotations include soil conservation (Stoop and Staveren 1981) organic matter restoration (Spurgeon and Grimson 1965) and pest and disease control (Curl 1963; Sunnadurai 1973).

Cowpea is often the only crop that survives severe drought in the WASAT. Cowpea grain contain about 22% protein, constitutes a major source of protein for resource poor people. It is estimated that cowpea supplies about 40% of the daily requirements to most of Nigeria population (Muleba et al. 1997).

In the mixed cropping systems, legumes yields are very low due to low soil fertility, low planting densities and pest and diseases (Ntare 1989; Reddy et al. 1992). The yield of cowpea grain varies between 50 kg ha^{-1} and 300 kg ha^{-1} in farmers fields in marked contrast to yield over 2000 kg ha^{-1} obtainable on research stations and by large scale commercial enterprise in pure cropping. In the mixed farming systems of the WASAT, increasing legume component in the farming systems is important in order to increase the availability of fodder as source of livestock feed while increasing soil fertility.

In this paper, after a brief presentation of the cowpea production environment, we will discuss the effect of plant nutrient on cowpea production before reviewing the effect of cowpea cultivation on soil fertility maintenance and presenting the new opportunities for future research on soil fertility and cowpea production.

II. Crop production environments

a) Climate

Sivakumar (1986) proposed a soil climatic zonation scheme for West Africa that is calculated from rainfall and potential evapotranspiration. In this scheme, a growing period of 60 – 100 days was used for defining the Sahelian zone. The geographical extent of the Sudanian zone has an average growing period of 100 – 150 days (**Figure 1**).

The rainfall in West Africa shows a significant north-south gradient because of the inter-seasonal movement of the intertropical convergence zone, north and south of the equator. The rainfall is low, variable and undependable. The rainfall gradient is very steep. The further one goes from the Sahara margin, the greater is the rainfall, approximately 1 mm km^{-1}. The isohyets run nearly parallel (Toupet 1965). Time dependent variations in rainfall are quite common in the region with coefficient of variation of annual rainfall ranges between 15-30%. The data in **Figure 2** clearly show the instability of the traditional mean figures for crop production as rainfall in some years can be 50% below or above the long-term average. Nicholson (1981) showed that in 1950, rainfall all over West Africa was above normal, at some location even 250% above normal. However, in 1970 rainfall was below normal throughout the region. As a result of rainfall variability, average yields of sorghum and pearl millet are unstable over years (**Figure 3**). The data in **Figure 4** give the annual rainfall values for a period of 40 years in the Douentza region of northwest Mali. From 1950 to 1990 median rainfall figures dropped from 650 mm/year to 350 mm/year.

It is well documented that precipitation determines the potential distribution of terrestrial vegetation and extended drought have initiated or exacerbated desertification. In the past 25 years, the WASAT has experienced the most substantial decline in rainfall (Hulme and Kelly 1997; Hulme 1992; Nicholson and Palao 1993) and the downward trend is persistent since 1951 with more areas experiencing more rainfall variability. As a result of the decrease in rainfall there will be a decrease in the vegetation cover of the land. Because evapotranspiration constitutes the only local input to the hydraulic cycle in the WASAT where there is no significant surface water, a reduction in the vegetation cover logically leads to reduce precipitation (Charney 1975). The reduction of vegetative cover will increase the albedo, which in turn, will lower surface temperature, decrease convection, cloud formation and precipitation. A further decrease in the rainfall will further decrease the vegetative cover (Cunnington and Rowntree 1986; Xue et al. 1990). However, Jackson and Idso 1974 disputed the importance of albedo. The non-climatic anthropogenic forces of desertification includes unsustainable agricultural practices, overgrazing and deforestation.

As already indicated, one important consequence in the reduction in rainfall is the reduction of vegetation cover. Consequently, the area of soil left bare and therefore directly exposed to wind and water erosion has considerably increased. The effect of these changes on wind and water erosion are aggravated by the sandy nature of the WASAT soils, which are frequently poorly aggregated, offering little resistance to the erosive forces. Buerkert et al. (1996a) measured absolute soil loss of 190 t ha^{-1} in one year on bare plots, as opposed to soil deposition of 270 t ha^{-1} on plot with 2 t ha^{-1} millet stover mulch (**Figure 5**). Sterk et al. (1996) reported a total loss of 45.9 t ha^{-1} of soil during four consecutive storms. Buerkert et al. (1996b) reported that in unprotected plots up to 7 kg of available p and 180 kg ha^{-1} of organic carbon are lost from the soil profile within one year. Wind erosion will also decrease the exchangeable bases and increase soil acidification **(Table 1)**.

b) Soils

Entisols and Alfisols occupy most of the landscape for rainfed cropping in the WASAT. Entisols are mainly composed of quartz sand, with low water and nutrient holding capacity. The Alfisols have a clay accumulation horizon a high base saturation because of lower rainfall and leaching but they have poor structural stability, poor water and nutrient holding capacity and lower organic matter than the Utisols and Oxisols of the humid areas of the rainforest.

The data in **Table 2** show physical and chemical properties of soils from the WASAT. The soils have low organic carbon and total nitrogen content because of the low biomass production and a high rate of decomposition. One striking feature of these soils is their inherent low fertility which expressed in low level of organic carbon (generally less than 0.3%) total and available phosphorus and nitrogen and effective cation exchange capacity (ECEC). About 98% of the soil nitrogen is stabilized in organic matter. Thus the total nitrogen in the soil and the amount of nitrogen released for plant nutrients uptake will depend on the organic matter level of the soil. Soil total organic carbon is highly correlated with the clay content of soil and as a result of the sandy nature of the soils in the WASAT, total nitrogen remain very low in most of the soils in the region. The importance of soil textural (clay and silt) properties for the organic carbon content was stressed repeatedly as clays are important component in the direct stabilization of organic molecules and micro-organisms (Amato and Ladd 1992; Greenland and Nye 1959; Feller et al., 1992). Thus Feller et al. (1992) reported that independently of climatic variations such as precipitation, temperature and duration of the dry season organic carbon content increased between 600 and 3000 mm annual rainfall soil organic carbon will increase with the clay and silt content of low activity clay soils. This is much evidence for a rapid decline of organic carbon levels with continuous cultivation in the sandy WASAT (Bationo et al. 1995). For the sandy soils, average annual losses in organic carbon expressed by K-value (calculated as the percentage of organic carbon per year), may be as high as 4.7%, whereas for sandy loam soils reported losses much lower, with average of 2% (Pieri 1989).

The low ECEC is attributed to low clay content and the kaolinitic mineralogy of the soils. Bationo and Mokwunye (1991) found that the ECEC is more related to the organic matter than the clay content, indicating that a decrease in organic matter will decrease the ECEC and then the nutrient holding capacities of those soils. De Ridder and Van Keulen (1990) reported that a difference of 1 g kg^{-1} in organic carbon results in a difference of 4.3 mmol kg^{-1} in ECEC.

Both total and available P levels are very low and P deficiency is the most limiting soil fertility factor for cowpea production. Apart from low P stocks, the low-activity nature of these soils results in a relatively low capacity to fix added P (Bationo et al. 1995). Phosphorus sorption maxima of the WASAT soil ranged from 27 to 405 mg P kg^{-1} with a mean of 109 mg P kg^{-1}. The data in **Figure 6** indicate that low quantities of P are needed to be added in the soil to maintain 0.2 ppm P in the soil solution. For example, the sandy loam soil of Gaya with relatively high level of sesquioxydes 35 mg P/kg soil are needed to be added to the soil to maintain 0.2 ppm P in the soil whereas for the sandy Sahelian soil at Sadore only 10 mg P/kg soil is needed. Compared with the Utisols and Oxisols found in the humid tropical regions these soils can be considered to have relatively low P-fixing capacities, hence small additions of P fertilizers will increase available P in the soil and will give significant crop response.

At present, most cultivated land in the region losses more N, P and K that it gain and in that zone, continuous cultivation has lead to nutrient mining and loss of topsoil by wind and/or water erosion (**Table 3**).

Although organic amendments such as crop residue, manure or compost are essential in the sustainability of the cropping systems, they cannot prevent nutrient mining. The addition of organic amendments corresponds in most cases to a recycling process which cannot compensate for nutrient exported through crop products. As a result, the use of external input such as inorganic plant nutrient or local sources of P such as phosphate rock is an essential requirement if soil productivity is to be maintained. Thus increase in water use efficiency (WUE) and alleviation of nutrient mining and increase is paramount.

III. Effect of soil fertility improvement on cowpea production

Many research results in the region have shown the importance of the improvement of soil fertility for crop production (Mokwunye and Vlek 1986; Pieri 1989; Van Reuler and Jansen 1984; Vander Heide 1989; Bationo and Mokwunye 1991; Sedogo 1993; Delvaux et al. 1993). In the Sahelian zone, the various research work concluded that soil fertility is more limiting to crop and fodder production than rainfall (Penning de Vries and Djiteye1991; Breman and de Wit 1983). The data in **Table 4** clearly indicate that the use of mineral fertilizers will significantly increase water use efficiency. The data in **Table 5** clearly indicate a significant effect of N on cowpea and groundnut fodder production in different agro-ecological zones of the WASAT. These significant responses for legumes N to indicate that the predominantly sandy soils of the WASAT may be deficient in molybdenum required for efficient symbiotic fixation (Hafner et al. 1992). On the sandy acid soil at Bengou in the Sudanian zone at Gaya, significant molybdenum response was obtained at different level of soil fertility management for cowpea (Figure 7). Mühlig-Versen (personal communication) on a study on the effect of molybdenum and P effect on groundnut and cowpea found that for cowpea found that for cowpea, application of P doubled the above ground biomass compared to the control. Application of molybdenum to the soil was less effective (+29%). The combination of both increased biomass up to 152% over the control. Groundnut responded only marginally to P or molybdenum, but the combination of both increased the biomass by 53% (Synergetic effect) **(Figure 8)**.

Legumes such as cowpea have a high P requirement. P is reported to stimulate root and plant growth, initiate nodule formation as well as influence the efficiency of the rhizobium-legume symbiosis (Robinson et al. 1981). It is also involved in reactions with energy transfer, more specifically ATP in nitrogenase activity (Israel 1987). The data in **Figure 9** clearly indicate a strong response to P by cowpea cultivars at Ikeme in the humid zone and Kamboinse in the Sudanian zone of West Africa, but there are large differences between cultivars for their response to P. The local Kamboinse variety is a fodder type and the application of P resulted in higher fodder production but lower grain production. As reported by several scientists such as Dwivedi et al. (1975); Khan and Zende (1977); Stukenholtz et al. (1966); Takkar et al. (1976) and Youngdhal et al. (1977) the application of P resulted in significant decrease of Zinc concentration in the cowpea grain **(Figure 10)** and this can affect the nutritional quality of cowpea (Buerkert et al. 1998).

Despite the importance of P in these soils, the use of commercial P fertilizers in the WASAT is limited due to the high cost of imported fertilizers. Several countries in the region however, are known to have phosphate deposits. Direct application of indigenous phosphate rocks (PR) can be an alternative to the use of more expensive water-soluble P fertilizers. This practice would also promote savings in scarce foreign exchange. The effectiveness of PR depends on its chemical and mineralogical composition, soil factors, and the crops to be grown (Khasawneth and Doll 1978; Lehr and McClellan 1972; Chien and Hammond 1978). The data in **Table 6** give the relative agronomic effectiveness of Tahoua PR and Kodjari PR in different agro-ecological zone of the WASAT. The data indicate that Tahoua PR agronomic effectiveness outperformed Kodjari PR. These results are in agreement with the chemical composition of the two rocks where the molar PO_4/CO_4 ratio is 25 for Kodjari PR and 4.88 for Tahoua PR. As soils in Gaya and Gobery are more acidic and receive more rainfall than the Sadore site, the agronomic effectiveness is higher at those sites. The agronomic effectiveness of the leguminous cowpea is not better than that of the cereal pearl millet crop. This is in contradiction to other reports where legumes have highest strategy to solubilize PR than cereals by rhizosphere acidulation (Aguilar and Van Diest 1981; Kirk and Nye 1986; Hedley et al. 1982) and exudation of organic acids (Ohwaki and Hirata 1992).

The data in **Figures 11** and **12** give the response of cowpea grain and stover to different sources of P fertilizers. The application of P fertilizers can triple cowpea stover production but the higher stover production resulted in lower grain yield. The relative agronomic effectiveness data in **Table 7** indicate that Parc-W PR indigenous to Niger agronomic effectiveness varied from 42% to 54% as compared to the water soluble SSP but the acidulation of PR at 50% (PAPR50) with sulfuric acid can increase the relative agronomic effectiveness to 96% for cowpea stover production. For fodder production TSP relative agronomic effectiveness varied from 77 to 91% indicating that sulfur application is needed for a better growth of cowpea.

Over the past years, research at ICRISAT-Niger has focussed on the placement of small quantities of P fertilizers at planting stage in order to develop optimum farmer-affordable P application recommendation. For cowpea stover production phosphorus use efficiency increased from 44 kg/kg P with the addition of Kodjari PR to 99 when Kodjari PR is broadcast with hill placement of 4 kg P/ha as 15-15-15 (**Table 8**)

Long-term experiments are practical means to address the difficult issues associated with quantitative assessment of sustainability in agriculture. In summarizing the results of long-term soil fertility management in Africa, Pieri (1986) concluded that soil fertility in intensive arable farming in the WASAT can only be maintained through efficient cycling of organic materials in combination with mineral fertilizers and with rotation with leguminous N_2-fixing species. The data in **Figure 13** clearly indicate that the application of small quantities of fertilizers and the application of crop residue resulted in an increase of cowpea fodder yield to 5300 kg/ha. In researcher on-farm management trials, it was found that pocket application of small quantities of manure (3 t/ha) plus 4 kg/ha of P at seedling time will increase cowpea yield from …….. in the control plot to …… **(Figure 14)**.

IV. Effect of cowpea production on soil fertility improvement

Despite the recognized need to apply chemical fertilizers for high yields, the use of mineral fertilizers in West Africa is limited by lack of capital, inefficient distribution systems, poor enabling policies and other socio-economic factors. Cheaper means of improving soil fertility and productivity is therefore necessary. Cereal/legume rotation effects on cereal yields have been reported for the WASAT (Bakayoko et al. 1996; Bakayoko et al. 2000; Bationo et al. 1998; Klaij and Ntare 1995; Nicou 1977; Stoop and Staveren 1981; Bationo and Ntare 2000).

Isotopic dilution method with ^{15}N was used to determine the nitrogen fixed by cowpea using pearl millet as non-fixing crop. The data in **Table 9** indicate that nitrogen derived from the atmosphere by cowpea varied from 65 to 88% and the total nitrogen fixed by cowpea depends of the level of soil fertility improvement. The quantity of nitrogen fixed by cowpea varied from 27 kg/ha in the control plot to 87 kg/ha in the treatment where the soils were amended with mineral and agronomic plant nutrients.

In order to determine ^{15}N recovery from different cropping systems, labeled nitrogen fertilizers were applied to microplot where pearl millet was grown continuously (M – M) in rotation with cowpea (C – M), in rotation with groundnut (G – M), intercropped with cowpea (C/M – C/M) and intercropped with groundnut (G/M – G/M). The data in **Table 10** indicate that at Sadore in 1990, nitrogen use efficiency increased from 20% in continuous pearl millet cultivation to 28% when pearl millet was rotated with cowpea. For both Bengou and Sadore, nitrogen derived from the soil was better used in rotation systems than with continuous millet cultivation.

Bationo and Ntare (2000) carried long-term experiments to investigate the effect of continuous monoculture as compared to crop rotation. At all the three sites in the WASAT, rotation of pearl millet with groundnut and cowpea resulted in higher significant pearl millet yields than in monoculture cropping of pearl millet over the 4-year period **(Figures 15** and **16)**. Legumes also gave significant responses to rotations **(Figures 17)** and this suggest that factors other than N alone contributed in the yield increases in the cereal-legume rotations. Bagayoko et al. (2000) in studies of cereal legumes effects on cereal growth in the WASAT reported that the rotation effect although significant in most of the cases varied with sites and years. At Sadore as an example, whereas grain yield of pearl millet in 1998 was 1557 kg/ha in the continuous millet production, the millet rotated with cowpea yielded 1905 kg/ha and in Gaya for the same year, sorghum grain yield increased by 50% due to rotation with groundnut in the Sudanian zone **(Table 11)**. The data in **Tables 12** and **13** show higher level of mineral N and native arbuscular mychorrhizae in the rotation system as compared to the continuous cultivation of cereals. In sorghum-groundnut system in the Sudanian zone, nematode densities were consistently lower in rotation system compared to continuous sorghum cultivation **(Figure 18)**.

Bationo et al. (2000) studied nitrogen dynamics in different cropping systems. In order to determine N availability, the soil were incubated and mineral nitrogen determined at 7, 21, and 35 days(Keeny 1982). Crop rotation significantly affected mineral nitrogen **(Figure 19)**. The fallow millet rotation supplied more nitrogen than the cowpea-millet rotation, but the latter was more productive for millet production. These results suggest that other factors in addition to biological nitrogen fixation may be involved in the positive effect of legume cereal rotation (Crookston et al. 1988). Crop rotation is known to substantially increase soil microbial activity and this may lead to an increase in nutrient availability.

In the long-term field trials carried out on the sandy Sahelian soil of the Sahel to study the effect of N and P in different cropping systems, the data show that P application has a very significant effect on yield of cowpea and pearl millet and rotation performed better than continuous cultivation of both crop **(Figure 20)**. The data in **Table 14** indicated that the land equivalent ratio varied from 24% to 200% showing that even with the use of external input, intercropping is better than pure cropping. In this long-term cropping system experiment, it was found higher level of organic carbon in the rotation systems as compared to the continuous cropping systems due in part of the fall of cowpea leaves **(Figure 21)**.

In another long-term soil management trials, application of phosphorus nitrogen, crop residue, and ridging and rotation of pearl millet with cowpea were evaluated to determine the P use efficiency. The results show that soil productivity of the sandy Sahelian soils can very significantly increased with the adoption of improved crop and soil management technologies. Whereas the absolute control recorded 33 kg ha^{-1} of grain yield, 1829 kg was obtained when phosphorus, nitrogen and crop residue were applied to plots that were ridged and followed leguminous cowpea. The plots without rotation yielded 1146 kg ha^{-1} without rotations. Results indicated that for grain yield, P use efficiency will increase from 46 with only P application, to 133 kg/kg P when P is combined with nitrogen and crop residue application and the crop is planted on ridges **(Table 15)**.

V. Conclusion and new research opportunities

In the mixed traditional cropping systems cowpea is grown between cereals at very low density as the farmers primary goal is to produce cereal for their family subsistence, and consider the additional cowpea as an additional benefit. This means that farmers need to be assured of sufficient cereal harvest to feed their families before integrating more cowpea in the cropping systems. The yield of cowpea grain in the mixed systems is very low, varying between 50 kg and 300 kg ha^{-1} in marked contrast to over 2000 kg ha^{-1} realized at research station and by large scale commercial enterprise in sole cropping. In addition to the low planting densities, pests and disease control, the inherent low fertility of the soil in the WASAT (particularly P) is one of the major constraint to cowpea production in the region and soil fertility replenishment should be an integral part of any program aimed at reverting trend in cowpea production and the conservation of the environment.

Phosphorus is the most limiting plant nutrient for cowpea production in the WASAT and there is ample evidence that indicates marked differences between cowpea genotypes for P uptake. Understanding the factors affecting P uptake such as the ability of plants to (i) solubilize soil P through acidification of the rhizosphere and the release of chelating agents and phosphate enzymes (ii) explore a large soil volume and (iii) absorb P from low P solution would help increase cowpea production and yield in the semi-arid tropics.

The available and total P values are very low in the region. With these extreme low values of total P, selecting cultivars adapted to low P condition would not be feasible as one cannot mine what is not there. Direct application of indigenous PR can be an economic alternative to the use of more expensive imported water-soluble P fertilizers. The effectiveness of mycorrhizal in utilizing soil P has been well documented (Silberbush and Barber 1983; Lee and Wani 1991; Daft 1991). An important future research opportunity is the selection of cowpea genotypes that can efficiency associate with vesicular-Arbuscular Mycorrhizal (VAM) for better utilization of P applied PR.

Cereal/cowpea rotations have led to increased cereal yields at many locations in the WASAT. Factors such as mineral nitrogen, (VAM) for P nutrition improvement and plant parasitic nematodes have been identified as mechanisms accelarating the enhanced yield of cereals in rotation with cowpea. Most of the research quantified the above-ground N fixed by different cowpea cultivars, but very little is known on the below-ground N fixed by cowpea. In the WASAT, most of the above-ground cowpea biomass are used for animal feed and not used as green manure. Future research need to focus more on the on-farm quantification of the below-ground N fixed by cowpea in order to identify the best cultivar for soil N. The identification and alleviation of technical and socio-economic constraints in order to increase cowpea component in the present cropping systems needs attention in future. As cash crop, farmer will increase their credit access to external inputs such as fertilizers. The enhancement of cowpea component in the present cropping system will not only improve the soil conditions for the succeeding cereal crop, but will provide good quality livestock feed, and the manure produced will be of better quality for soil the fertility amendment.

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Table 1: Nutrient balance after two years of erosion and deposition, Sadore, Niger

Relative losses of a bare compared to a protected (plastic mulch) soil at two depths				
Soil properties	---[kg ha^{-1} g^{-1}]---			
	0 to 0.1 m depth	0.1 to 0.2 m depth	Sum#	
N total	-14.0	3.0	-11.0	±9.8
P Bray	-4.2	-2.8	-7.1	±1.4
P H_2O	-0.08	-0.06	-0.14	±0.07
K	-3.2	-2.2	-5.4	±2.2
Ca	-18.7	-12.7	-31.4	±9.4
Mg	-1.7	-1.3	-3.0	±2.3
C organic	-115	-65	-180	±83
Al total	10.9	11.4	22.3	±7.5

\# Sums followed by their standard errors (n=3)

Source: adapted from Buerkert et al. 1996

Table 2: Means and ranges of selected physical and chemical properties of West African semi-arid soils

Parameter	Range	Mean
pH-H_2O (2:1 water:soil)	3.95 - 7.6	6.17
pH-KCl (2:1 water:soil)	3.41 - 7.0	5.05
Clay (%)	0.7 - 13	3.9
Sand (%)	71 - 99	88
Organic matter (%)	0.14 - 5.07	1.4
Total nitrogen (mg kg^{-1})	31 - 226	446
Exchangeable bases (cmol kg^{-1})		
Ca	0.15 - 16.45	2.16
Mg	0.02 - 2.16	0.59
K	0.03 - 1.13	0.20
Na	0.01 - 0.09	0.04
Exchangeable Al (cmol kg^{-1})	0.02 - 5.6	0.24
Effective Cation Exchange Capacity (cmol kg^{-1})	0.54 - 19.2	3.43
Base saturation (%)	36 - 99	88
Al saturation (%)	0 - 46	3
Total phosphorus	25 - 941	136
Available phosphorus	1 - 83	8
Maximum P sorbed	27 - 406	109

Source: Bationo et al.

Table 3: Nutrient losses for some West African countries

Country	Area (1000 ha)	Losses for the region (10^5tones)		
		N	P_2O_5	K_2O
Benin	2972	41388	10366	32499
Burkina Faso	6691	95391	27754	78764
Ghana	4505	137140	32313	90474
Mali	8015	61707	17888	66725
Niger	985	176120	55331	146617
Nigeria	2813	1107605	316687	946157

Table 4: Water use (WU), grain yield (Y) and water use efficiency (WUE) for millet at Sadore and Dosso (Niger)

Treatments	Sadore			Dosso		
	WU (mm)	Y (kg/ha)	WUE (kg/ha/mm)	WU (mm)	Y (kg/ha)	WUE (kg/ha/mm)
Fertiliser	382	1570	4.14	400	1700	4.25
Without fertiliser	373	460	1.24	381	780	2.04

Table 5. Effect of nitrogen on pearl millet, cowpea and groundnut yield at three sites in 1988

N Rates kg N/ha^{-1}	Millet grain			Cowpea fodder			Groundnut fodder		
	Sadore	**Bengou**	**Tara**	**Sadore**	**Bengou**	**Tara**	**Sadore**	**Bengou**	**Tara**
0	915	1172	55O	4069	2213	2974	1470	1128	1088
15	1098	1358	671	4474	2510	2963	1944	1243	1681
30	1194	1424	727	4288	2548	3025	2105	1278	1820
45	1233	1539	804	4264	3008	3500	2486	1359	2093
S.E.(D.F.27)	60.0	58.3	52.3	218.3	153.7	161.3	132.7	55.0	104.3
CV (%)	23	18	32	15	17	15	19	13	18

Table 6: Relative agronomic effectiveness for pearl millet and cowpea as compared to SSP (%) Of Tahoua phosphate rock (TPR) and Kodjari phosphate rock (KPR) in three agro-ecological zones of Niger

	Sadore		**Goberi**		**Gaya**	
	TPR	**KPR**	**TPR**	**KPR**	**TPR**	**KPR**
Grain yield (kg/ha)	63	32	76	41	80	57
Total biomass (kg/ha)	65	35	60	40	68	63
Cowpea fodder (kg/ha)	43	28	73	51	42	42
Cowpea total dry matter (kg/ha)	56	40	72	51	52	55

Source: **Mahaman et al., 1997**

Table 7: Relative agronomic effectiveness of different sources of P

P sources	1993		1994	
	Grain	Fodder	Grain	Fodder
PRA	70	54	49	42
PAPR25	45	58	61	75
PAPR50	72	92	88	96
TSP	68	91	65	77
SSP	74	87	86	91
PRB	50	53	55	49

Table 8: Effect of different sources* of phosphorus and their placement on cowpea yield and PUE, Karabedji, 1998 rainy season**

P Sources and method of application	**Grain**		**Fodder**	
	Yield (kg ha^{-1})	**PUE**	**Yield (kg ha^{-1})**	**PUE**
Control	505		1213	
SSP broadcast	1073	44	2120	70
SSP broadcast + SSP HP	1544	61	3139	113
SSP HP	1050	136	2021	452
15-15-15 broadcast	1165	51	2381	90
15-15-15 broadcast + 15-15-15 HP	2383	110	3637	142
15-15-15 HP	1197	173	2562	337
PRT broadcast	986	37	2220	77
PRT broadcast + SSP HP	1165	68	3127	113
PRT broadcast + 15-15-15 HP	1724	72	3163	115
PRK broadcast	920	32	1791	44
PRK broadcast + SSP HP	1268	45	2588	81
PRK broadcast + 15-15-15 HP	1440	55	2792	93
S.E	164		313	

PUE Kg grain/KgP; HP Hill Placed; TDM Total Dry Matter
**For broadcast, 13 KgP/ha was applied ** For HP, at 4 KgP/ha
*SSP Single superphosphate; 15-15-15 compound fertilizer containing 15% N, 15% P_2O_5, 15% K_2O; TPR Tahoua Phosphate Rock; KPR Kodjari Phosphate Rock

Table 9. Nitrogen derived from the air (NdFA%) and ^{15}N recovery by cowpea stover, Sadoré, Niger, 1991 rainy season

Treatment	Yield (t ha^{-1})	N (%)	N yield (kg ha^{-1})	NdFF (%)	NdFa (%)	N fixed (kg ha^{-1})
Control	1.75	2.18	38.1	2.43	65.1	25.6
Molybdenum	3.08	2.28	71.4	1.37	80.4	58.1
Carbofuran	2.58	2.19	57.4	2.04	70.8	41.4
Manure	2.42	2.44	59.7	0.79	88.6	53.3
Phosphorus	3.58	2.01	65.2	1.56	77.6	50.6
Complete	3.75	2.66	99.8	0.80	88.6	89.1
SE	±0.47	±0.09	±10.39	±0.18	±2.56	±9.06
CV (%)	28	6	27	20	6	29

1. FUE: Fertilizer use efficiency

Table 10. ^{15}N recovery by pearl millet in different cropping systems

Treatment	Year	Site	Yield (t ha^{-1})	N Yield (kg ha^{-1})	N-uptake from soil (kg ha^{-1})	N uptake from fertilizer (kg ha^{-1})	Nitrogen use efficiency (%)
M-M	1990	Bengou	4.17	56	39.03	17	38
G-M			4.94	74	62.19	12	49
LSD (0.05)			1.31	21	16.56	11	25
CV (%)			13	14	15	26	26
M-M	1989	Sadore	3.81	48	38.32	8	27
M-G			4.50	56	45.51	10	35
LSD (0.05)			1.43	22	20.07	22	
CV (%)			15	19	21	10	
M-M	1989	Sadore	3.25	38.34	30	6	19
G-M			3.96	45.56	37	8	28
LSD (0.05)			0.63	11.04	12	1	4
CV (%)			8	16	7	7	24

Table 11. Millet and sorghum dry matter at thinning and grain and total dry matter yield at harvest as influenced by millet/cowpea cropping systems at Gaya, Goberi and Sadoré (Niger) and sorghum groundnut cropping systems at Kouaré (Burkina Faso)

Sites and Cropping system	Thinning					Harvest		
	TDM		Grain yield			TDM[b]		
	1996	1998	1996	1997	1998	1996	1997	1998
				Kg ha^{-1}				
Sadoré								
Continuous millet	4	6	937	321	1557	4227	2219	6992
Millet after cowpea	5	7	1255	340	1904	5785	2832	8613
P>F[a]	*<0.001*	*0.059*	*<0.001*	*0.344*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Goberi								
Continuous millet	13	8	-	779	956	2328	3444	4220
Millet after cowpea	16	9	-	827	1151	2579	3743	4800
P>F	*<0.001*	*0.063*	-	*0.145*	*<0.001*	*<0.001*	*0.019*	*<0.001*
Gaya								
Continuous millet	13	13	794	378	645	2601	2469	2598
Millet after cowpea	15	11	889	466	636	2823	2684	2510
P>F	*0.001*	*0.014*	*0.085*	*<0.001*	*0.801*	*0.025*	*0.069*	*0.353*
Kouaré								
Continuous sorghum	30	26	397	786	238	3056	4505	2689
Sorghum after cowpea	36	25	553	884	357	4191	5316	3633
P>F	*<0.001*	*0.352*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*

a. Probability of a treatment effect (significance level)
b. Total dry matter

Table 12. Effects of cereal-legume cropping systems on soil mineral N In May, June and September 1997 and 1998 at Gaya, Goberi and Kouare. Sampling depth was 0-0.3 m

Time	Goberi		Gaya		Kouaré	
	Millet/cowpea				Sorghum/groundnut	
Cropping systems	Nmin	NO3-N	Nmin	NO3-N	Nmin	NO3-N
			Mg N kg-1 soil			
May						
Continuous	3.1	1.3	8.9	4.7	12.1	8.3
Rotation	3.5	1.2	11.0	6.0	23.1	18.6
P>F[a]	*0.448*	*0.587*	*0.045*	*0.025*	*0.050*	*0.008*
June-July	5.2	3.4	9.6	5.6	14.4	11.2
Continuous	5.2	3.2	12.1	7.9	20.0	15.9
Rotation	*0.675*	*0.706*	*0.055*	*<0.001*	*0.025*	*0.016*
P>F						
September						
Continous	1.2	0.2	6.5	3.3	10.6	6.6
Rotation	1.6	0.2	4.9	1.8	17.9	13.8
P>F	*0.626*	*0.803*	*0.706*	*0.035*	*0.021*	*0.002*

Table 13. Root infection by mycoryiase (AM) in millet (0-0.3 m) affected by cropping system at Sadoré, Goberi and Gaya, Niger

Cropping system	1996		1997				
	Goberi	Gaya	Sadore		Goberi		Gaya
	120 DAS[b]		35 DAS	75 DAS	45DAS	75 DAS	50 DAS
			AM infection (% of roots)				
Continuous millet	35	31	23	44	27	48	11
Millet after cowpea	39	33	32	50	48	64	31
P>P[a]	*0.280*	*0.325*	*<0.001*	*0.109*	*0.001*	*<0.001*	*<0.001*

a. Probability of a treatment effect significance level
b. Days after sowing (DAS)

Table 14. Land equivalent ratios in different cropping systems over a period of four years

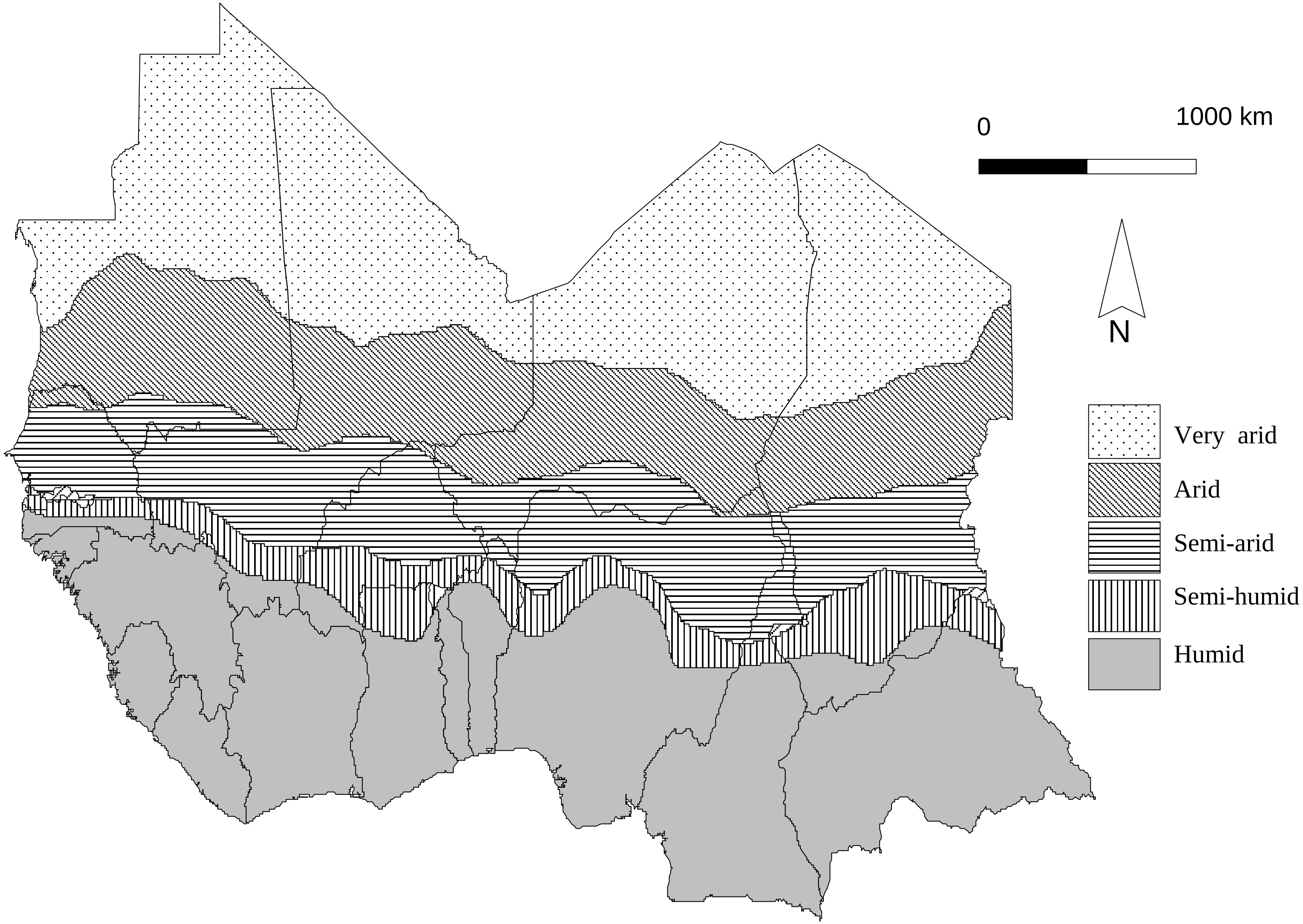
P. Rate	N Rate	Continuous intercropping			Rotation following millet			Rotation following cowpea		
		Cowpea	Millet	Total	Cowpea	Millet	Total	Cowpea	Millet	Total
	0	1.12	0.92	2.04	0.65	0.87	1.52	0.71	0.76	1.47
0	30	0.85	1.12	1.97	0.72	0.85	1.57	0.93	0.84	1.77
	0	0.77	0.72	1.49	0.65	0.69	1.34	0.58	0.73	1.31
15	30	0.73	0.86	1.59	0.64	0.78	1.42	0.61	0.86	1.47
	0	0.76	0.57	1.33	0.57	0.67	1.24	0.57	0.83	1.40
30	30	0.77	1.00	1.77	0.76	1.06	1.82	0.48	0.88	1.36

Table 15: Effect of mineral fertilizers, crop residue (CR) and crop rotation on pearl millet yield wasts and PUE wasts, Sadore, Niger, 1998 rainy season.

Treatment	Without CR, without N				Without CR, with N				With CR, without N				With CR, with N			
	TDM		Grain		TDM		Grain		TDM		Grain		TDM		Grain	
	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE
Control	889		33		2037		58		995		61		1471		98	
13 kg P/ha	2704	140	633	46	4339	177	1030	75	4404	185	726	51	240	4594	1212	86
13 kg P/ha + ridge	2675	137	448	32	4057	155	946	68	3685	210	785	56	4530	235	1146	81
13 kg P/ha + rotation	5306	340	1255	94	6294	327	1441	106	5392	338	1475	109	6124	358	1675	121
13 kg P/ha + ridge + rotation	5223	333	1391	104	5818	291	1581	117	6249	404	1702	126	7551	468	1829	133
SE	407		407		407		407		407		407		407		407	

CR Crop Residue; N Nitrogen; TDM Total Dry Matter; PUE (kg grain/kgP); Yield (g/ha)

Figure 1: Agro-climatic zones of West Africa Semi-Arid Tropics (WASAT)



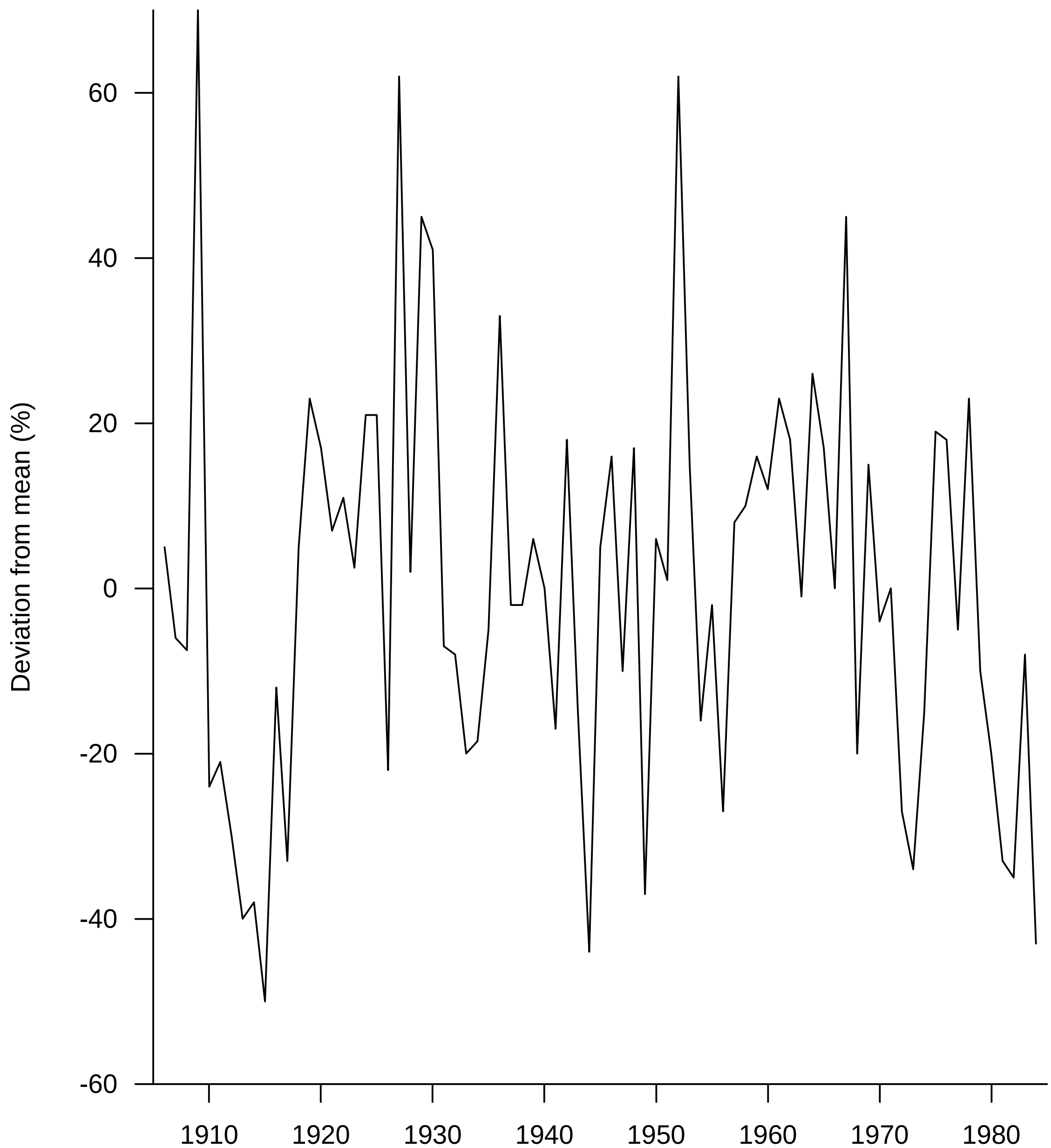


Figure 2: Percentage deviation of annual rainfall at Niamey, Niger.

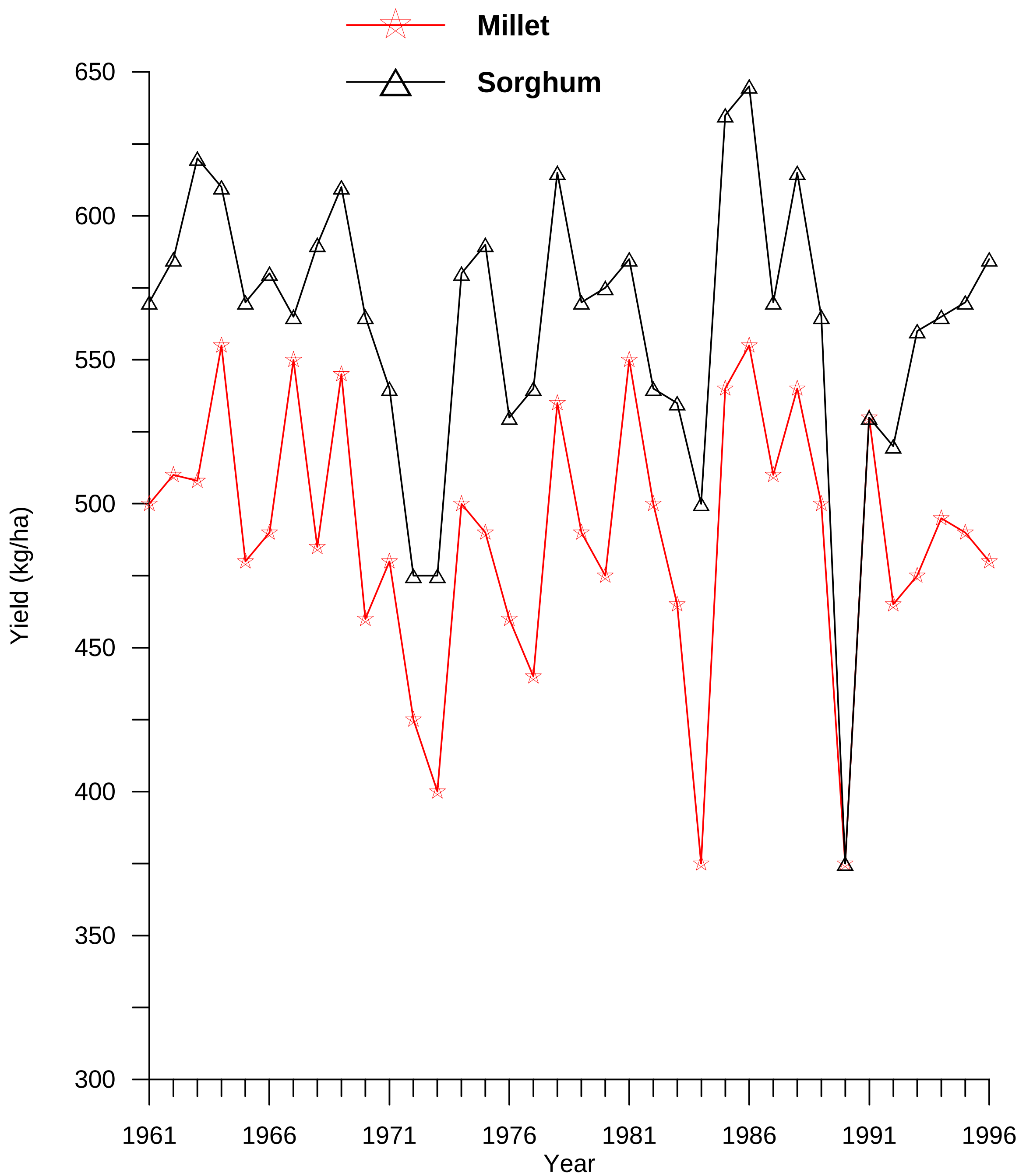


Figure 3:Sorghum and Millet yields in the Sahel

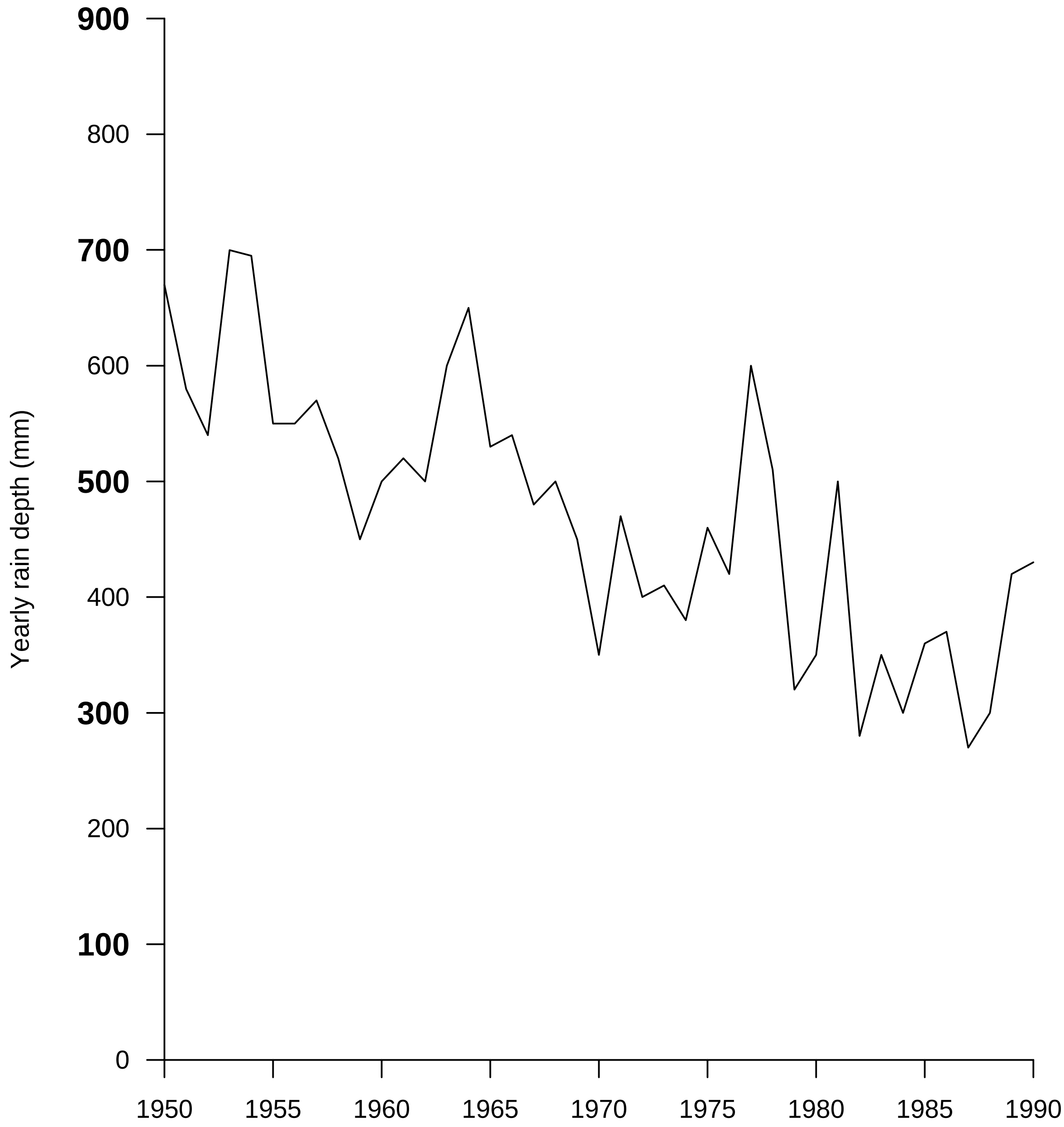


Figure 4: Rain variation (mm) in Douentza, Mali over a 40 year period

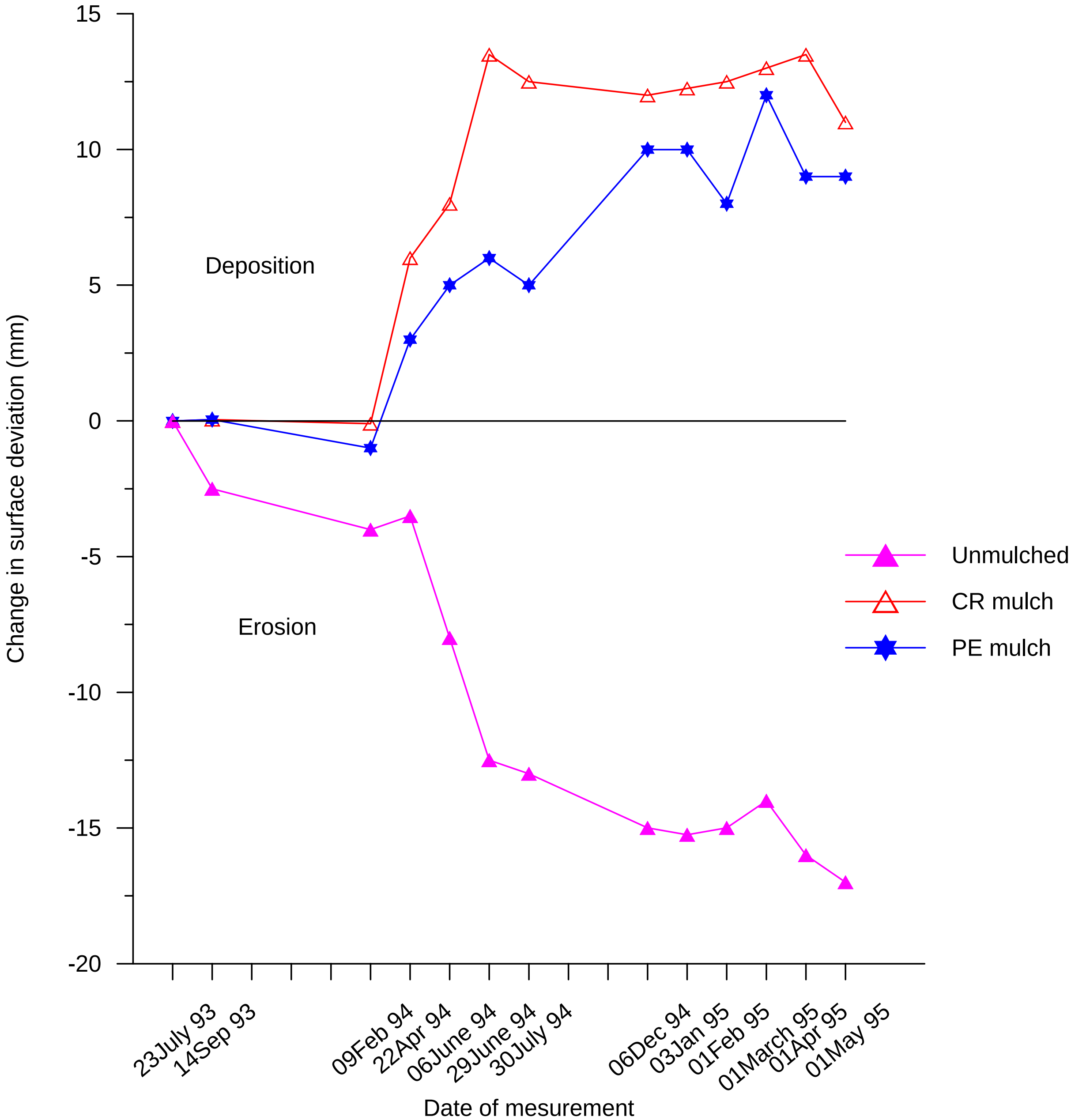


Figure 5: Soil erosion and deposition as measured with U-shaped stanless steel bars. (Buerkert and Hiernaux, 1998)

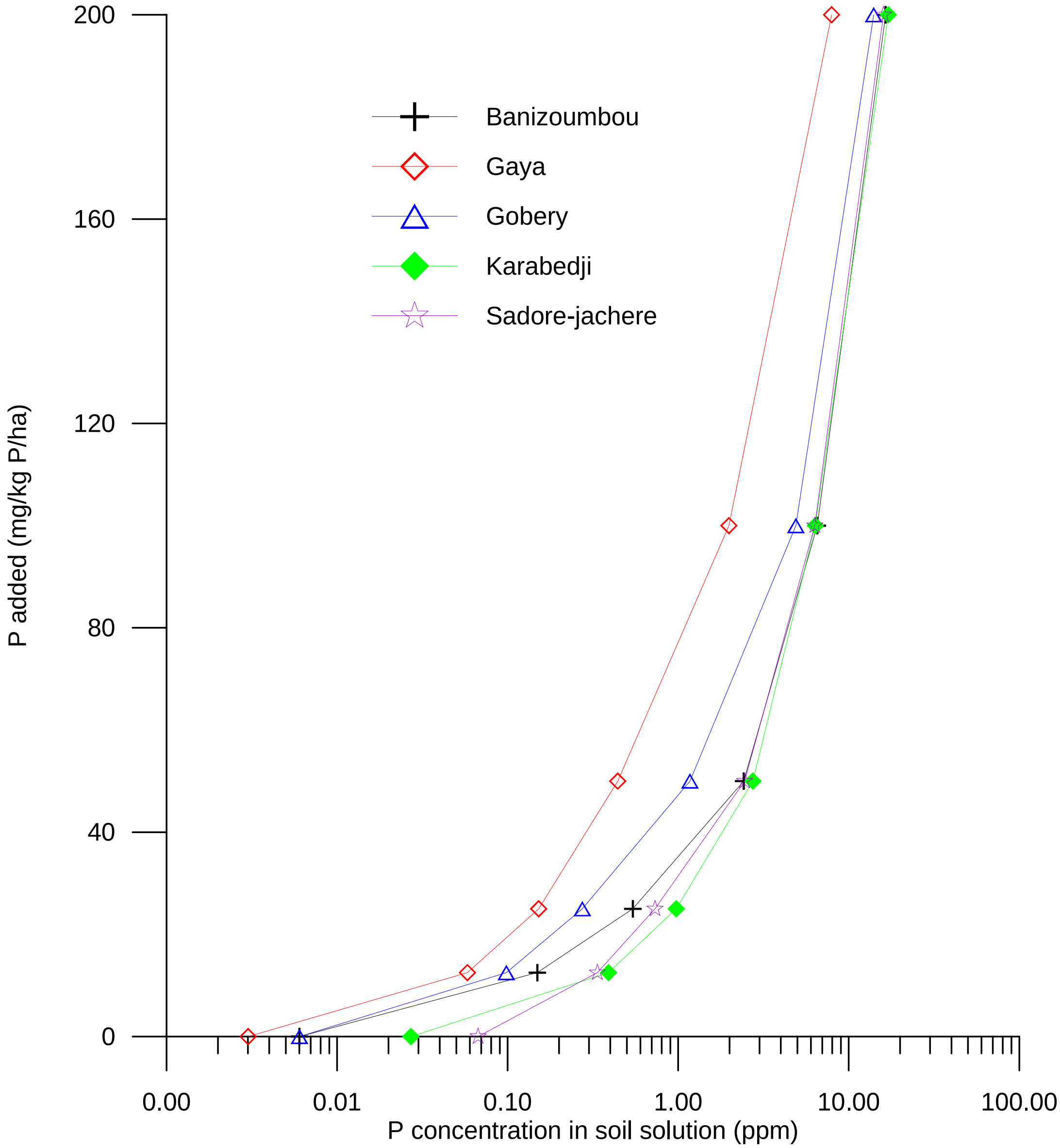


Figure 6: Relationship between phosphorus added and phosphorus in soil solution at equilibrium for selected soils of the West African Semi-Arid Tropics

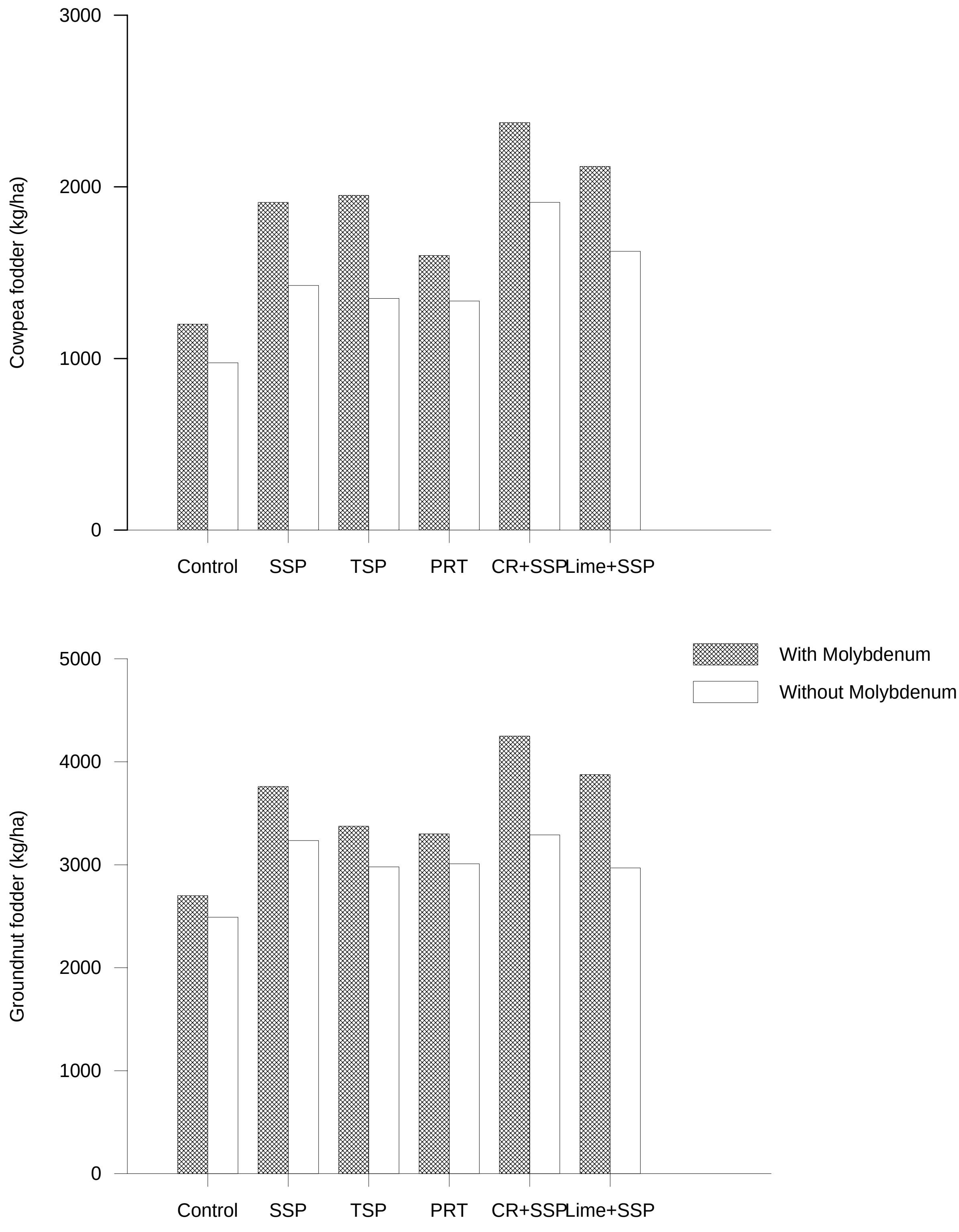


Figure 7: Effects of different phosphorus sources, crop residue, lime and molybdenum on cowpea and groundnut fodder yield. Tara Niger 1993

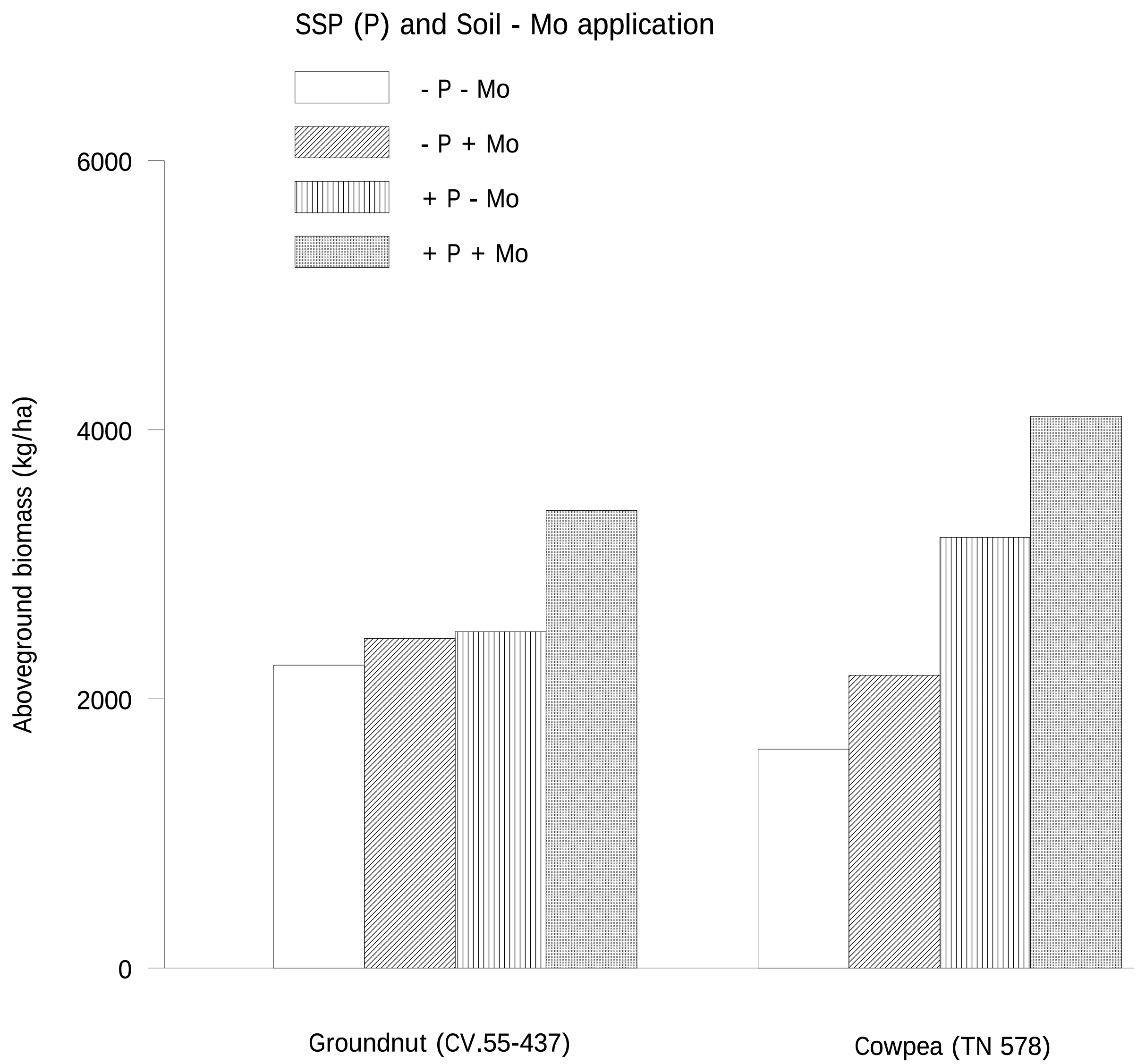
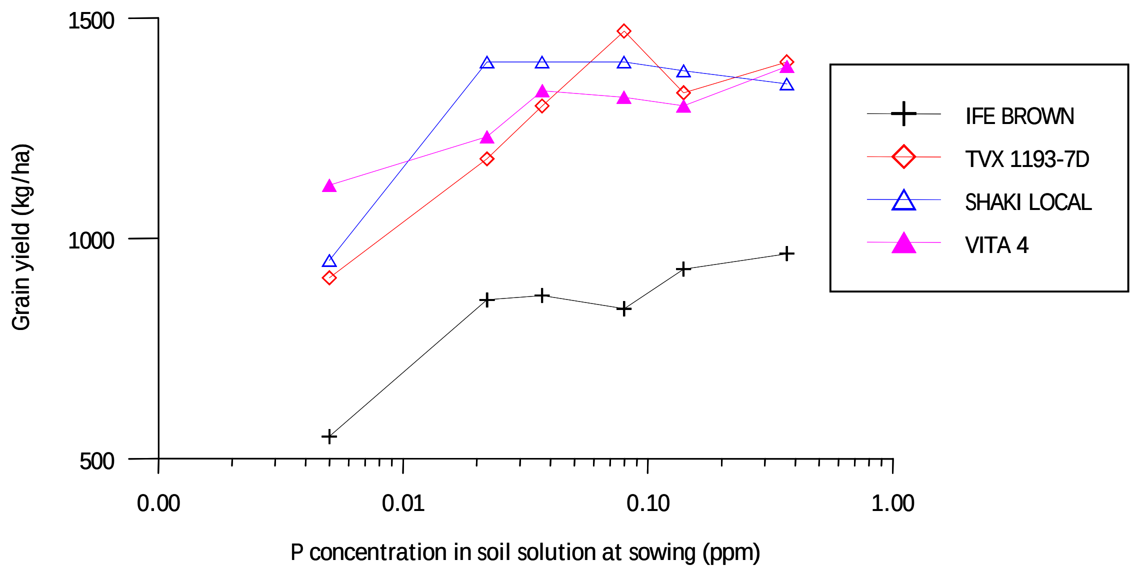


Figure 8: Effects of SSP (13 kg P/ha) and soil applied Mo (500 g Mo/ha) on groundnut and cowpea biomass (kg dry wt/ha) at final harvest. Bengou, 1995



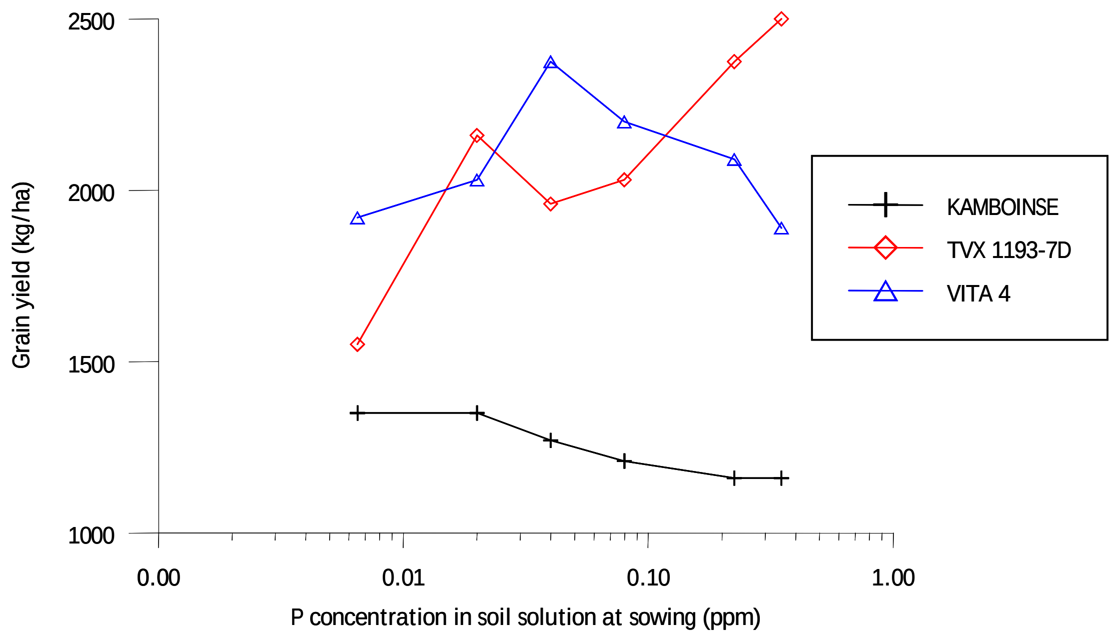


Figure 9: Relationship between grain yield and P concentration in soil solution at sowing in sandy loam paleustatif oxique at Ikenne and Kamboinse

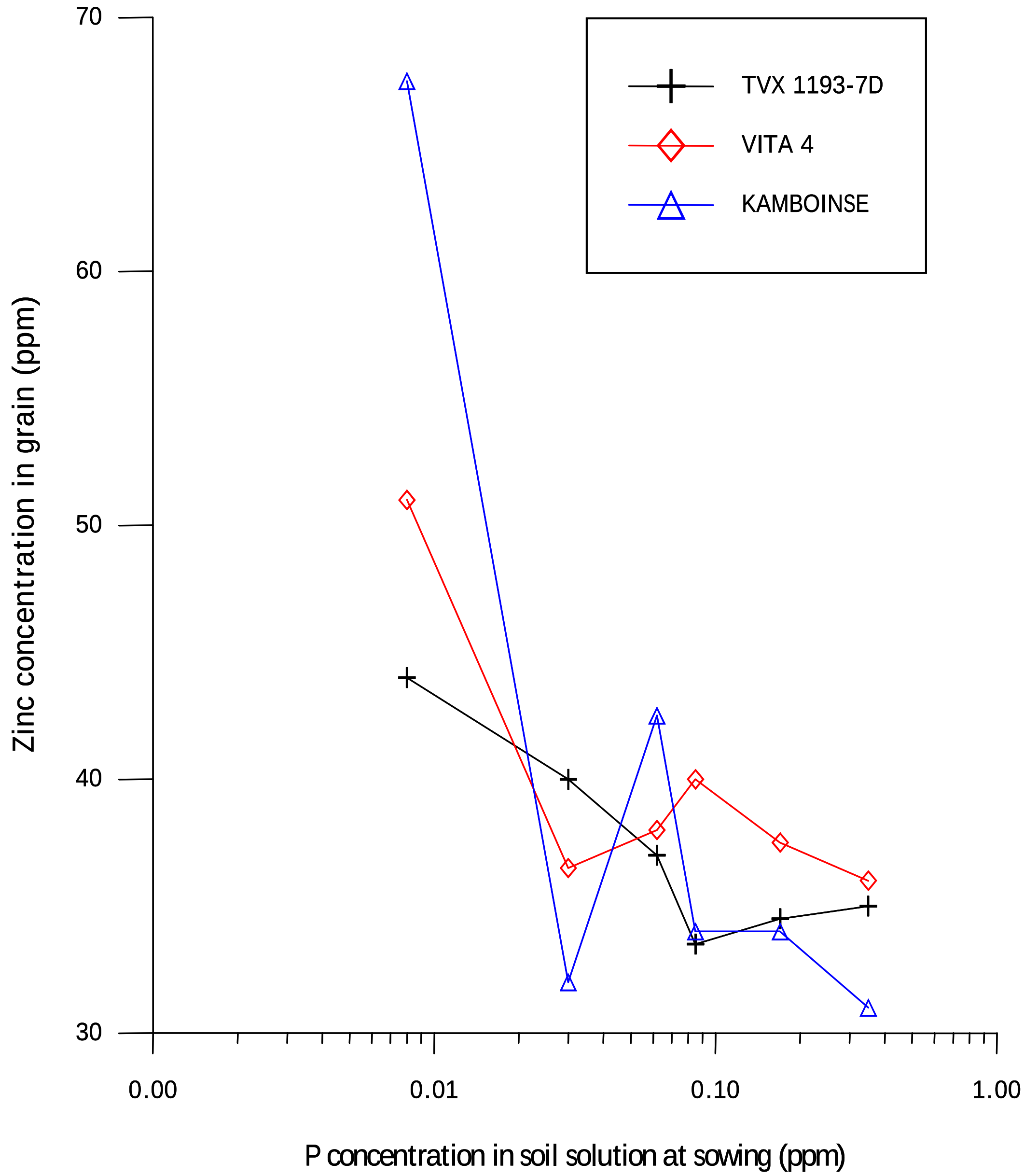


Figure 10: Relationship between zinc concentration in grain and P concentration in soil solution at Kamboinse

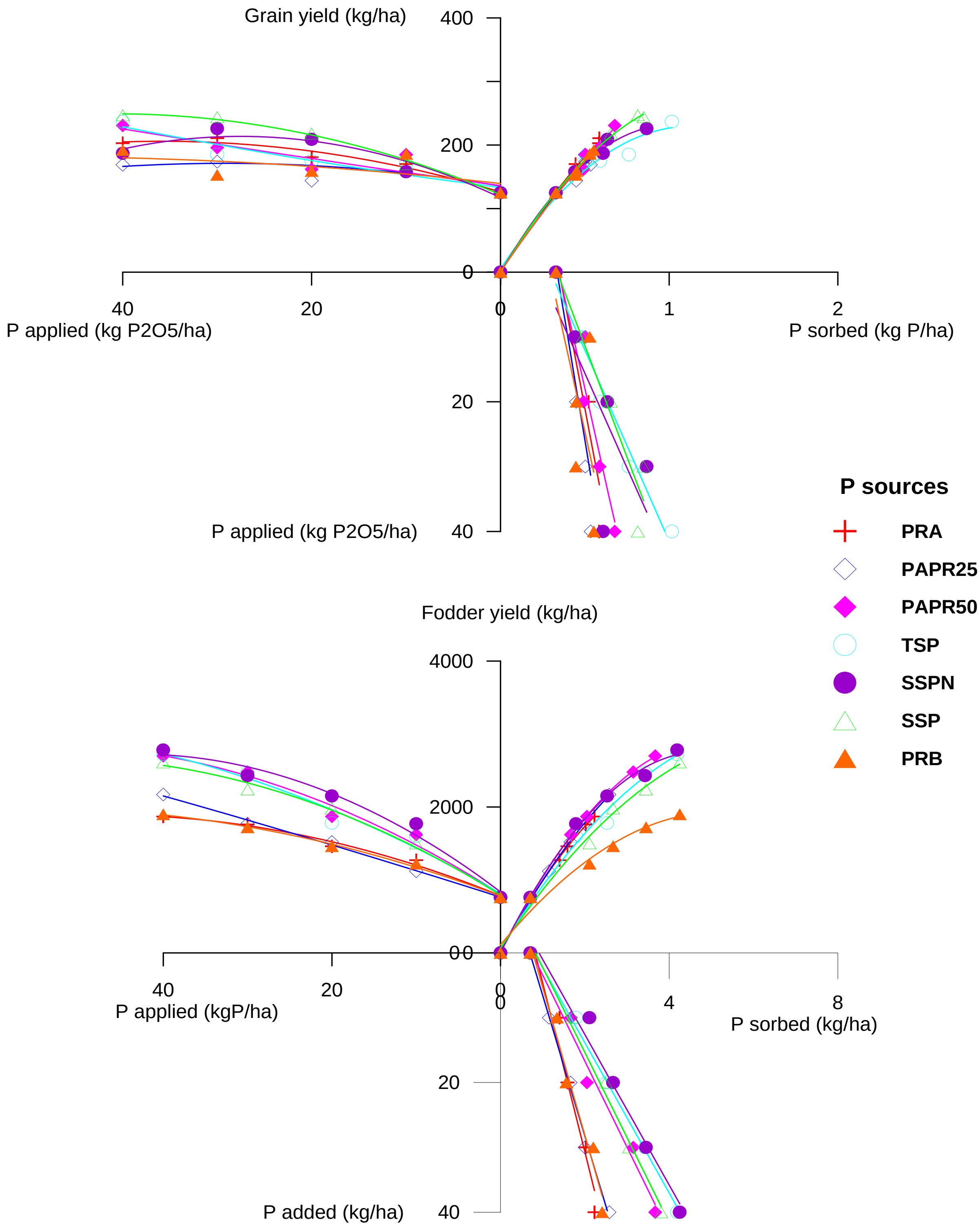


Figure 11: Relationship between cowpea grain and fodder yield with P applied, and between P applied nd P sorbed, Sadore, Niger, 1983.

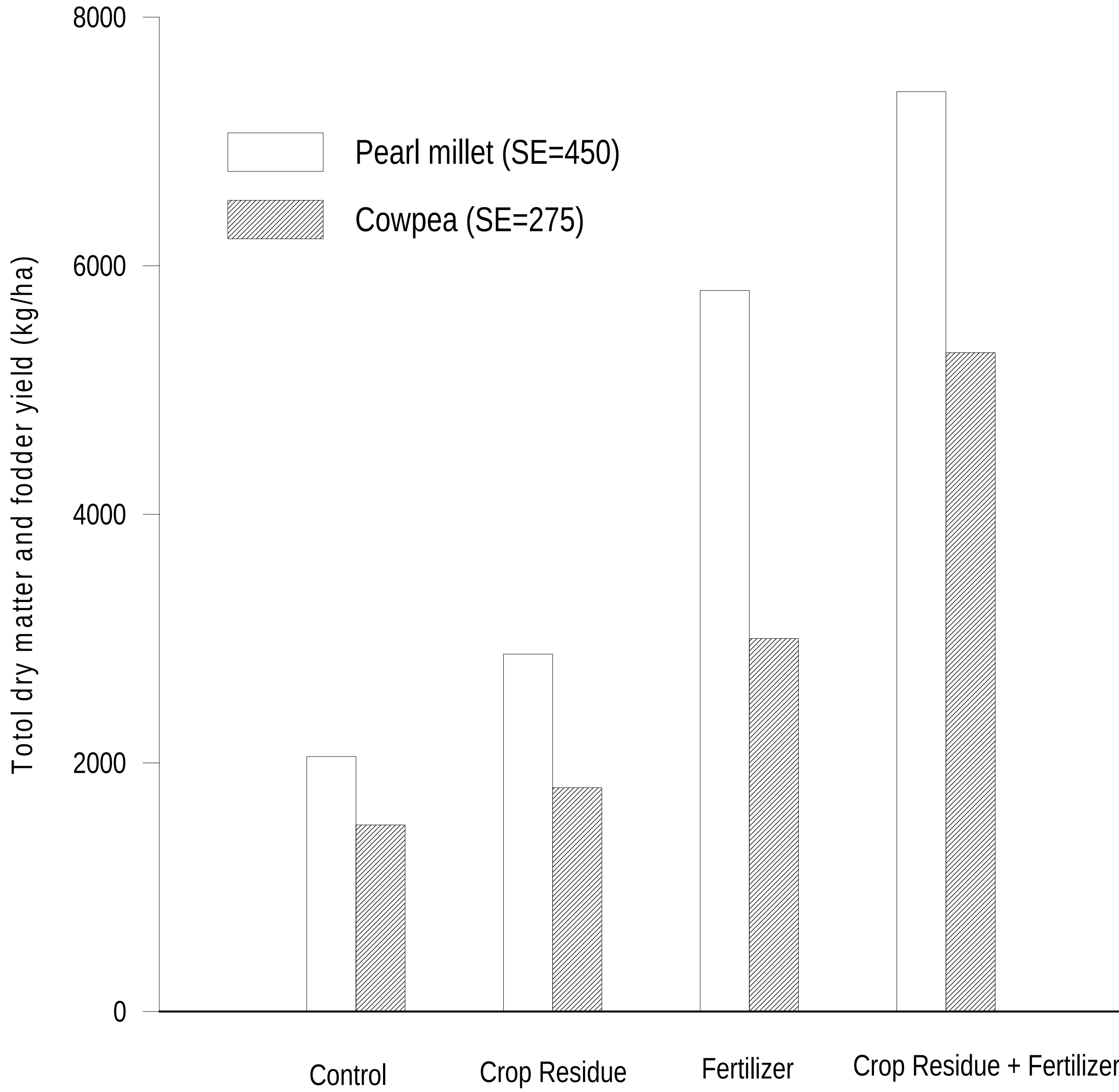


Figure 13: Long term crop residue management at Sadore, Niger 1996

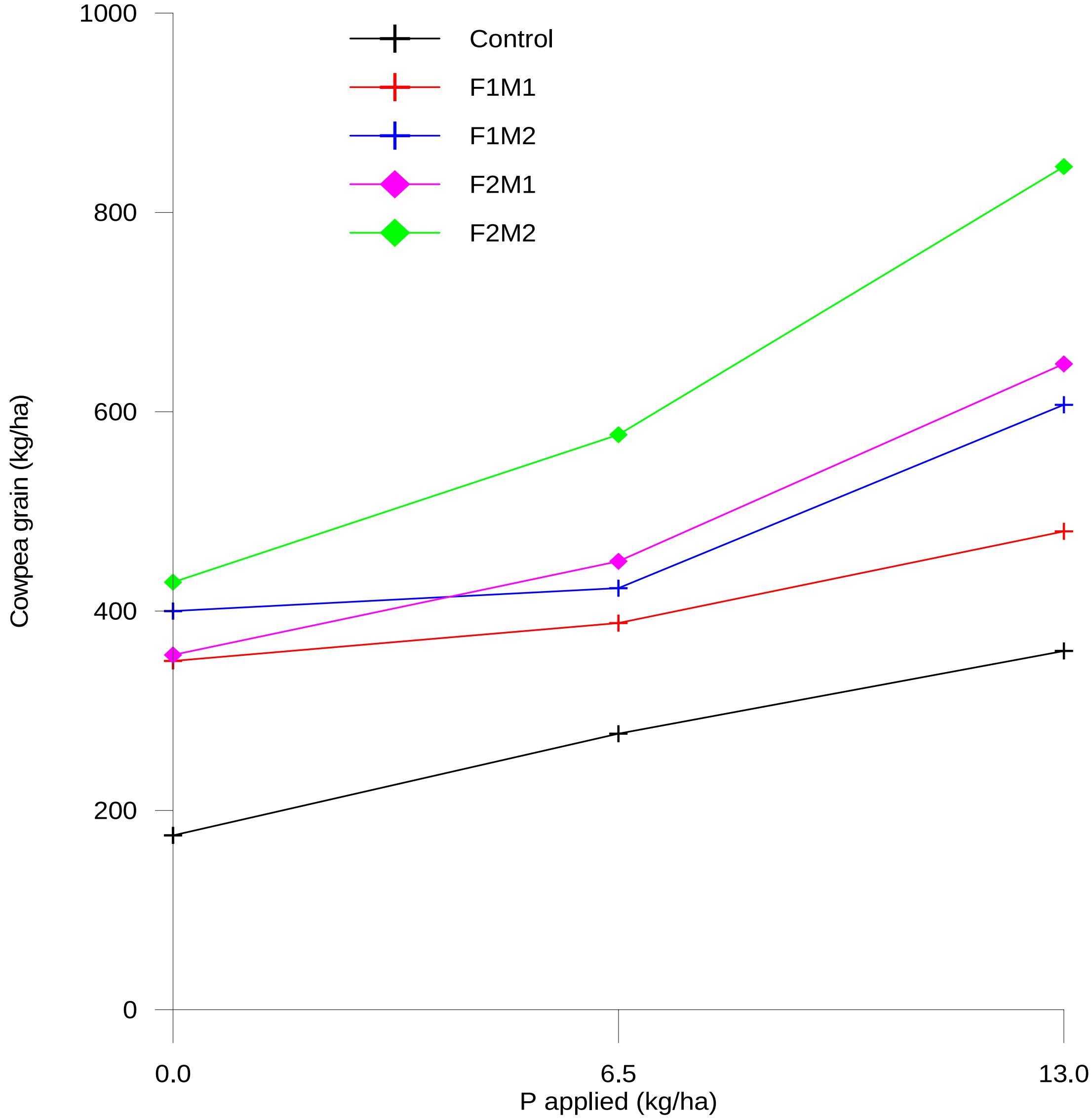


Figure 14: Effects of fertilizer and manure placement on cowpea grain yield, Karabedji 1999

F: manure 1=3 tons; 2=6 tons
M: method of placement: 1=broadcast; 2=hill placed

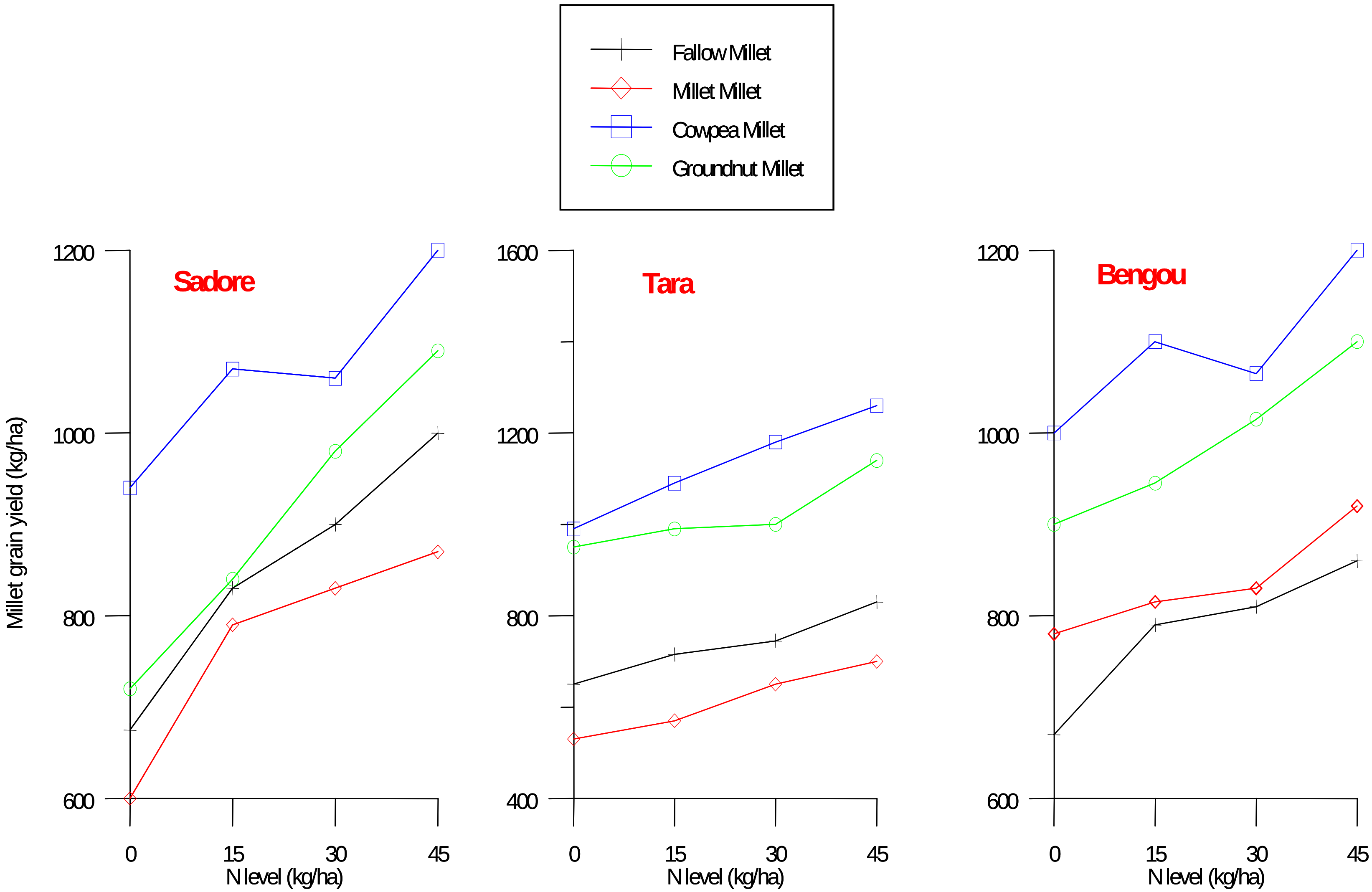


Figure 15: Effects of Nitrogen and rotation on pearl millet grain yield (kg/ha, average of four years) at Sadore, Tara, and Bengou.

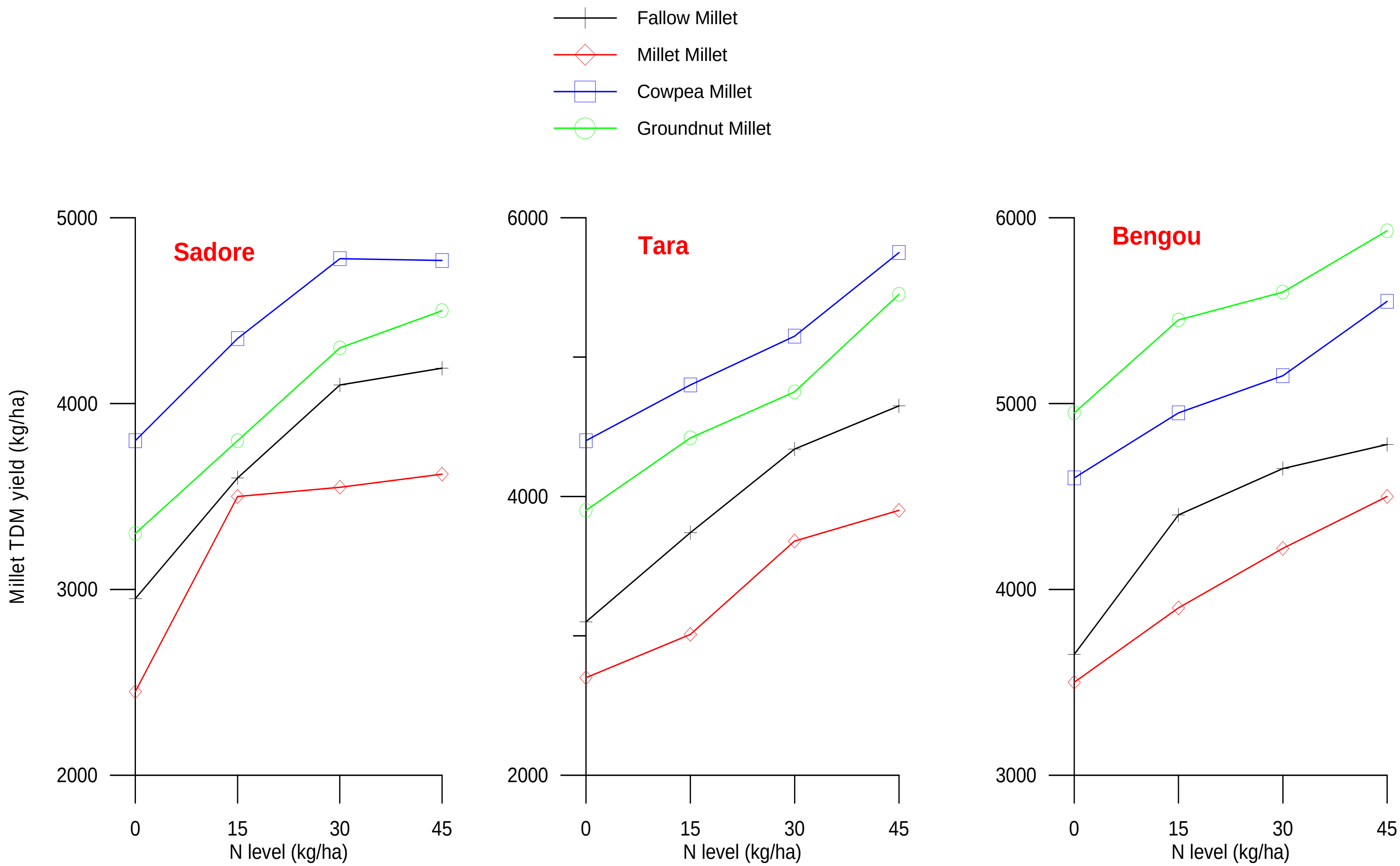


Figure 16: Effects of nitrogen and rotation on pearl millet total dry matter yield (kg/ha, average of four years) at Sadore, Tara, and Bengou

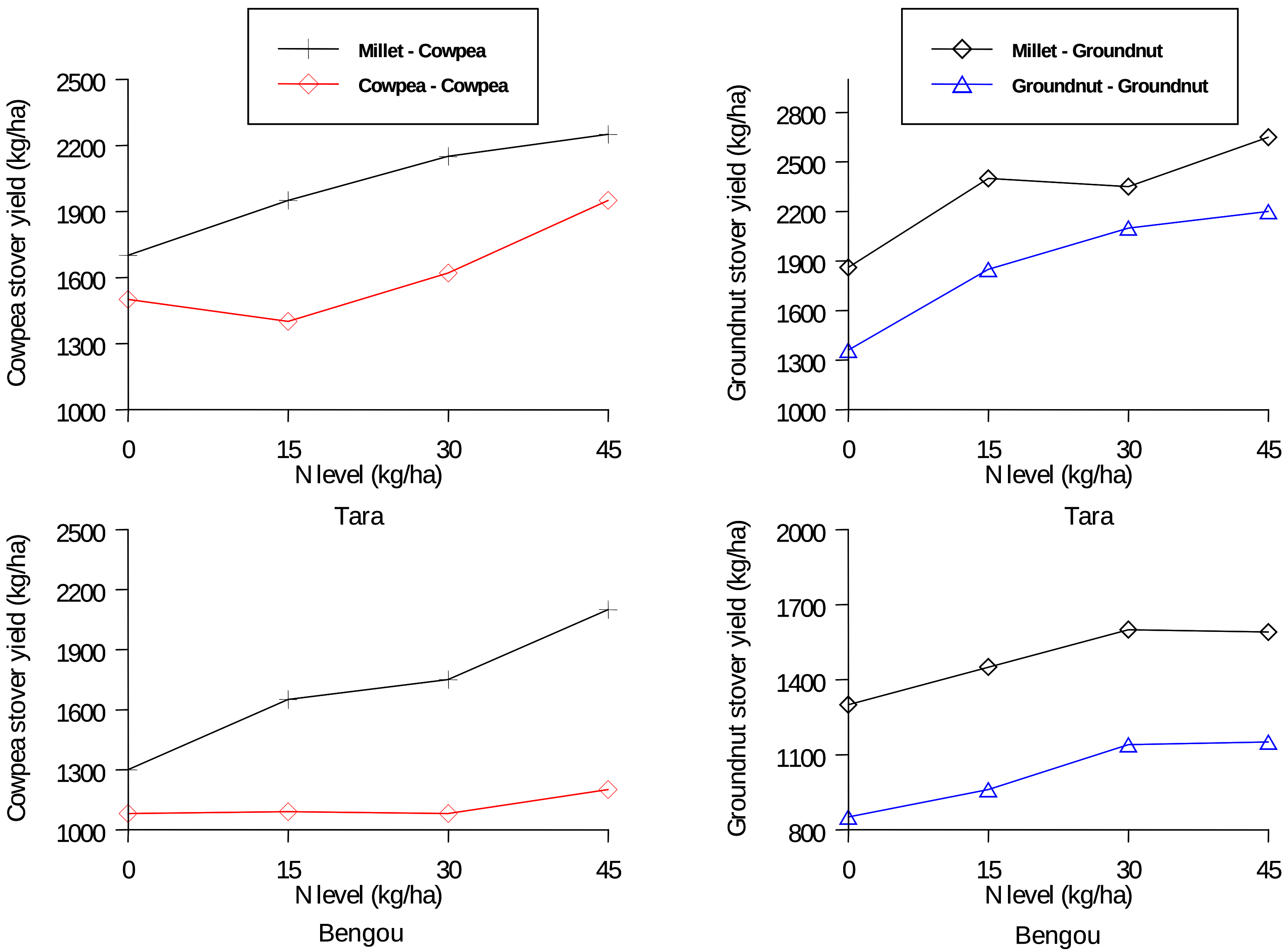


Figure 17: Effects of nitrogen and rotation on legume stover yield (kg/ha, average of four years) at Tara and Bengou

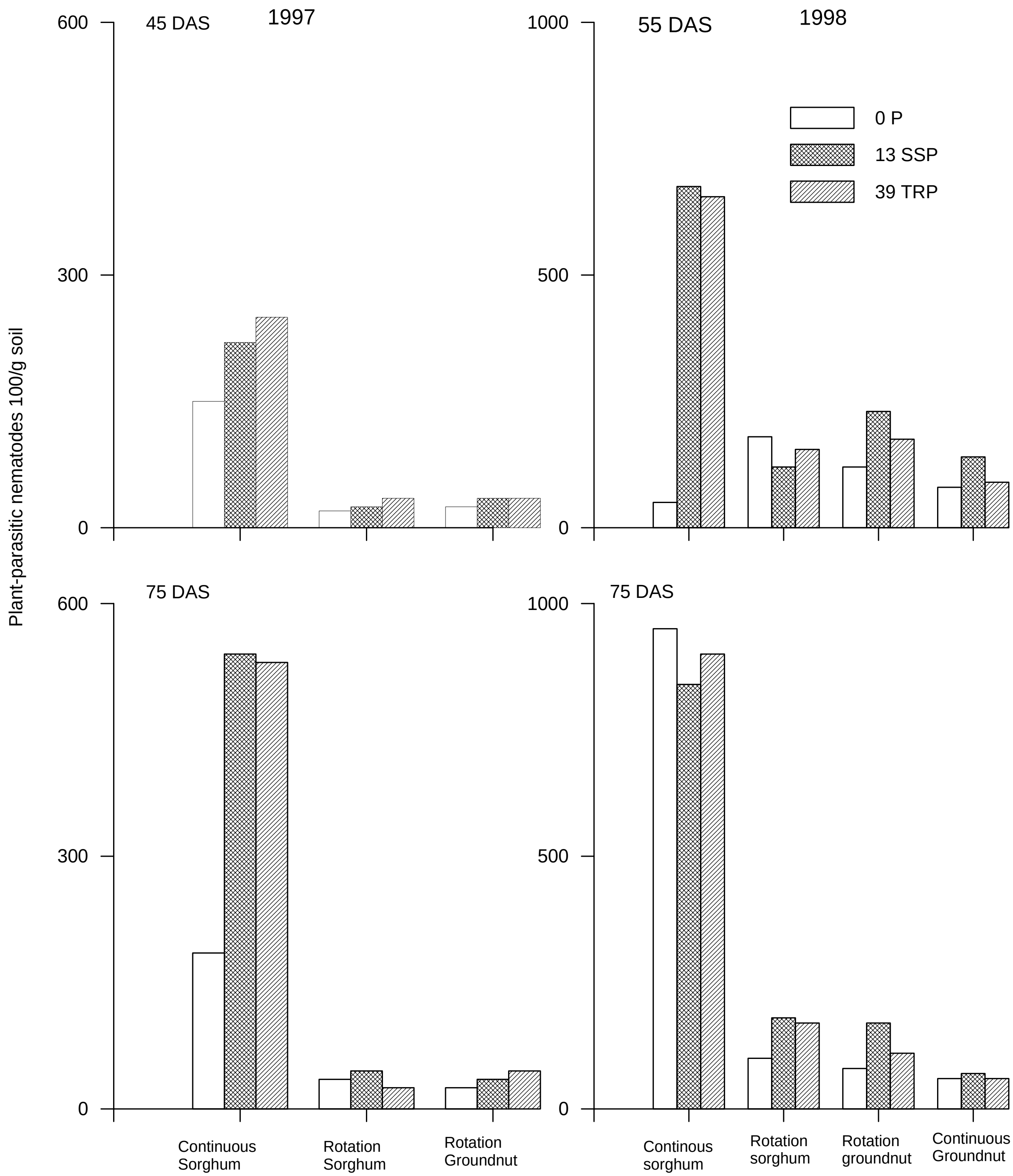


Figure 18: Plant-parasitic nematode numbers as affected by sorghum/groundnut rotations and phosphorus (P) application in 1997 and 1998 at Kouaré. Phosphorus was applied as single superphosphate at 13 kg P/ha (13 SSP) and Tahoua rock phosphate at 39 kg P/ha (39 TRP).
Source: Bagayoko et al. 2000.

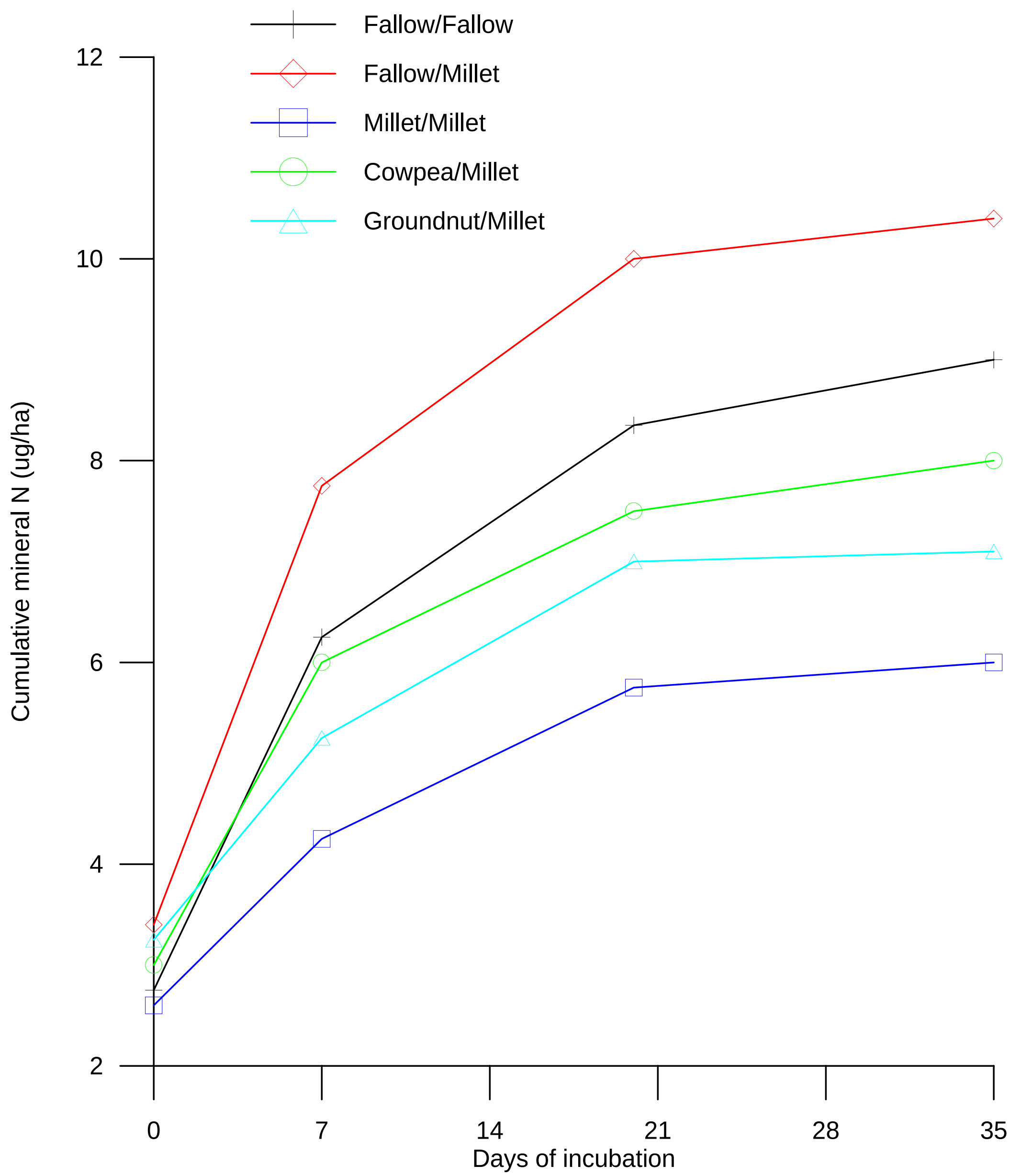


Figure 19: Relationship between cumulative mineral nitrogen and time of incubation of soils from different crop rotations pooled over three sites.

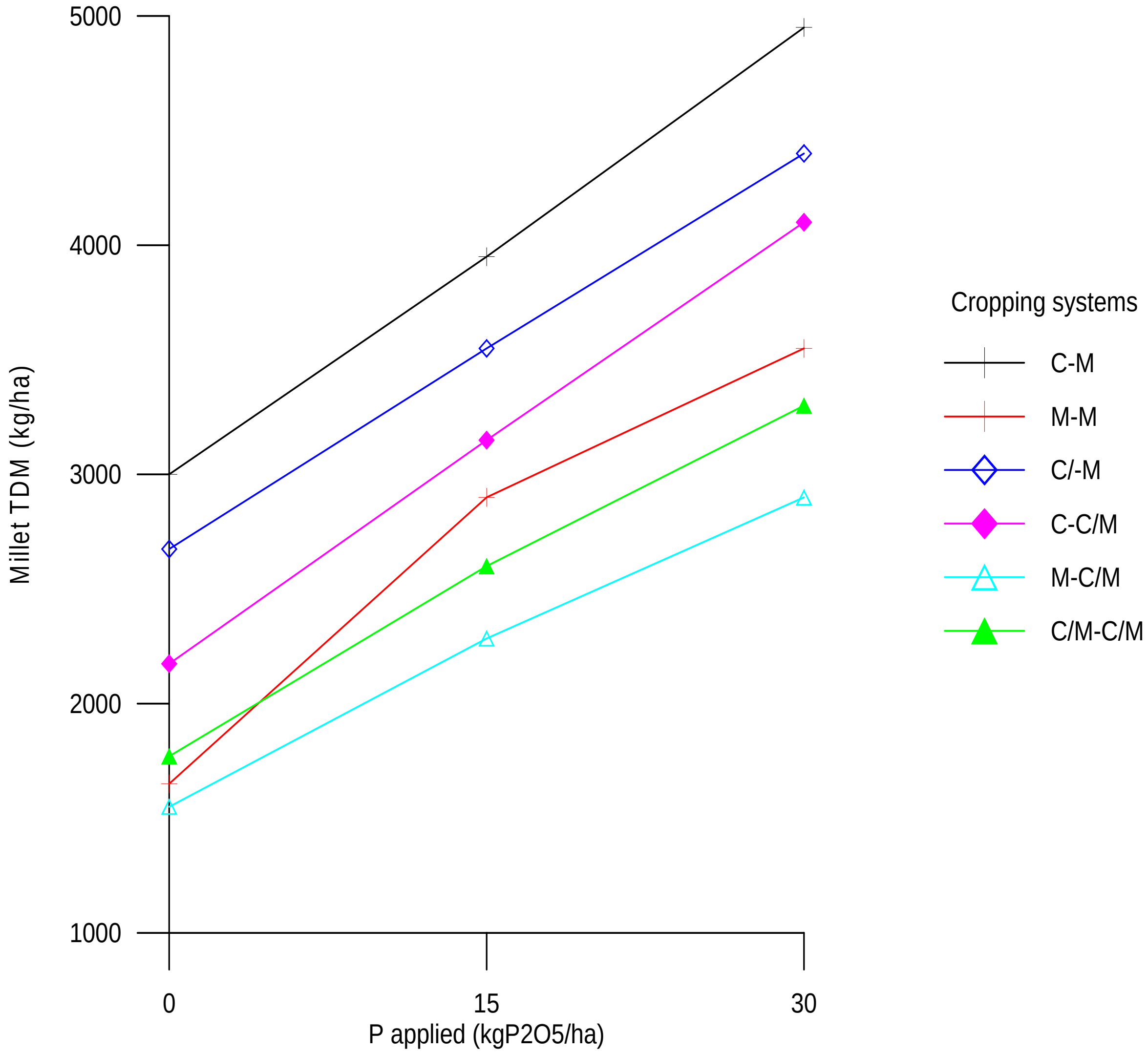
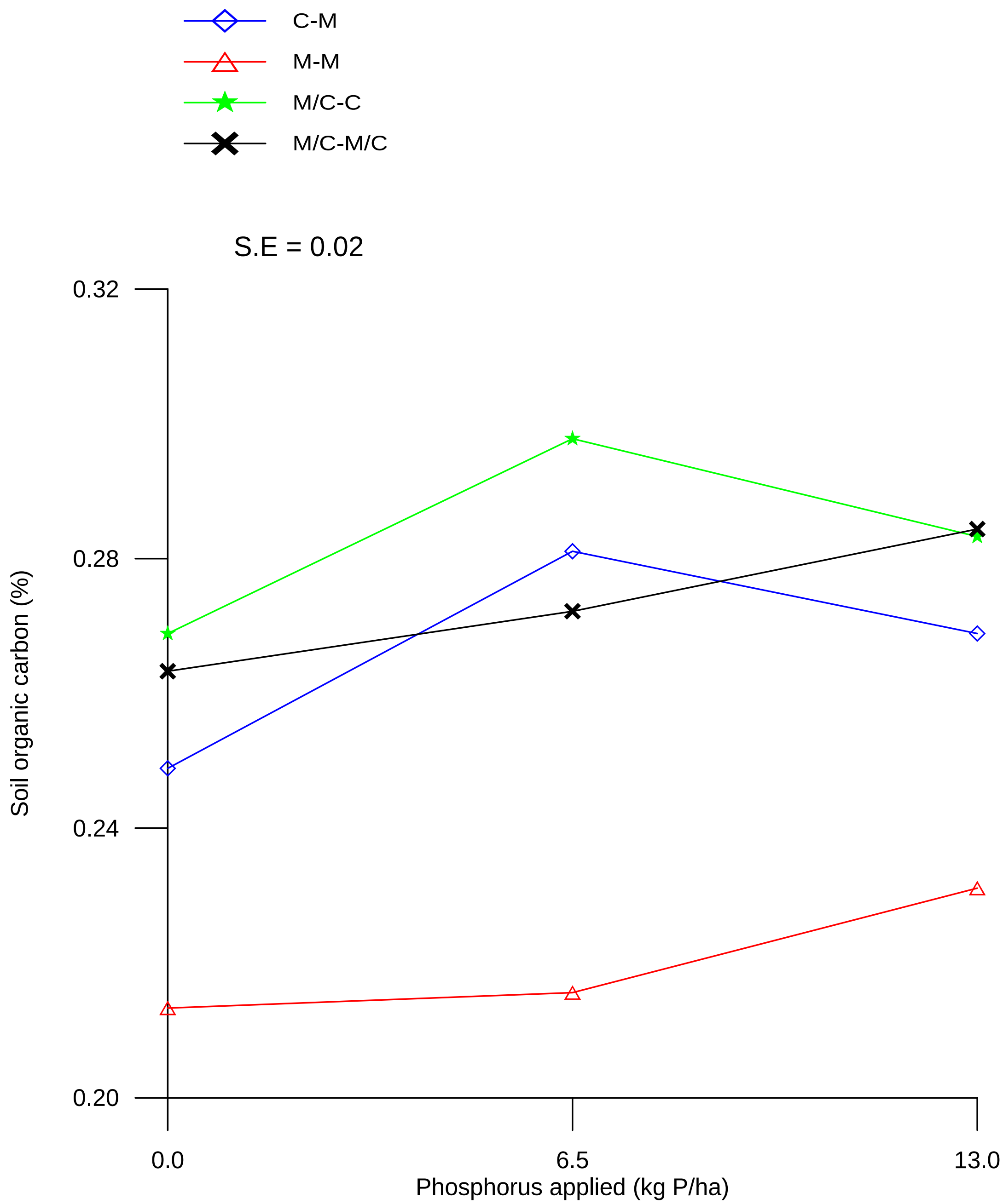


Figure 20: Effects of Phosphorus and Nitrogen on different cropping systems over 4 years, Sadore, Niger



C-M = Millet following Cowpea,
M-M = continuous millet,
M/C-M = Millet following Millet intercropped with Cowpea,
M/C-M/C = continuous Millet-Cowpea intercropped

Figure 21: Effect of phosphorus and cropping system on soil organic carbon, Sadore, Niger 1995

Draft

Sustainable intensification of crop livestock systems through manure management in Western and Eastern Africa: lessons learned and emerging research opportunities

Bationo, A.[1]; Nandwa, S.M.[2]; Kinyangi, J.M.[1]; Bado, B.V.[4]; Lompo, F.[5]; Kimani, S.[6]; Kihanda, F.[7] and S. Koala[8]
[1]Tropical Soil Biology and Fertility Programme, P.O. Box 30592, Nairobi, Kenya.
[2]Kenya Agricultural Research Institute, National Agriculturtal Reseach Laboratories, P O Box 14733, Nairobi, Kenya.
[4] INERA, P.O. Box 910, Bobo-Dioulasso, Burkina Faso.
[6]Kenya Agricultural Research Institute, National Agricultural Resarch Center (Muguga), P.O. Box 30148, Nairobi, Kenya.
[7]Kenya Agricultural Res. Institute, Regional Research Centre (Embu), P.O. Box 27, Embu, Kenya.
[8]International Crop Research for the Semi-Arid Tropics, B. P. 12404 Niamey, Niger.

Abstract
In the mixed farming system that characterises the Semi-Arid zone of Eastern and Western Africa, low rural incomes, high cost of fertilizers, inappropriate public policies and infrastructural constraints prevent the widespread use of inorganic fertilizers. Under this situation and as population pressure increases and fallow cycles are shortened, organic sources of plant nutrients such as manure, crop residue and compost remain the principal sources of nutrients for soil fertility maintenance and crop production. Estimates of the nitrogen contribution from manure to the total N input budget suggest that up to 80 percent of N applied to crop is derived from manure in both the extensive and the intensive grazing systems.

In this paper, we first discuss the effect of manure on soil productivity and on ecosystem functions and services. This is followed by highlights of the management practices required to increase manure use efficiency before tracking the emerging new research opportunities in soil fertility management to enhance the crop-livestock integration.

Although the application of manure alone produces a significant response, it cannot be proposed as an alternative to mineral fertilizers. In most cases the use of manure is part of an internal flow of nutrients within the farm and does not add nutrients from outside the farm. Furthermore quantities available are inadequate to meet nutrient demand on large areas. Research highlights have indicated that different management practices including time and methods of manure application, sources and method of application, and integrated nutrient management enhance its efficiency.

Research opportunities include ecosystem functions and services of manure use, the establishment of fertilizer equivalency of different manure sources, the assessment of the best ratios of organic and inorganic plant nutrient combinations, the crop livestock trade-offs to solve conflicting demands for feed and soil conservation and the use of legumes directly for soil fertility and for animal feed. The establishment of Decision Support Guides and assessment of the economic viability of manure-based technologies in farmers-focussed research is presented as a powerful management tool intended to maximize output while preserving the environment in the mixed farming system of the semi-arid zones.

Introduction

Rapid rural and urban population growth, changes in agroecosystems and increased market access in Western and Eastern Africa provides a stimulus to drive agriculture towards intensification, whereby continuous cropping increasingly replaces pasture and fallows; and manure, forages and crop residue become more valuable as part of the intensification-oriented technologies, with increasing off-take from a fixed land base. The ultimate result of this dynamism is the emergent and evolution of mixed crop-livestock systems. This is currently perceived as the most efficient and sustainable means of food production. The evolution process often include paddocking of livestock on cropland in high potential areas; shift to the system of collection, processing, storage and application of animal dung and urine; shift from field grazing of crop residues and pastures to confined livestock feeding; replacement of hand labor with animal traction and mechanization; and intensification through growing of multipurpose legumes and forages. This calls for new research approach that allows replacement or refinement of old paradigms with new principles notably identification of "best-bet options" and strategies using "whole farm" or holistic approach to working with farmers. Such an approach has resulted in new lessons and insights in management and augmentation of nutrients through crop residue and manure management including livestock-mediated nutrient cycling, crop combination and crop geometry, livestock feeding studies, effect of livestock component on the soil fertility (chemical, physical and biological properties), and also gender, policy and institutional issues.

The major challenge facing researchers attempts to contribute towards sustainable intensification of the crop-livestock systems in SSA, is that of soil degradation whereby poor quality and low inputs of crop residues and boma manure leads to soils of low productivity. Inorganic inputs are often too expensive for the low-resource endowed farmers. In such systems, the demand for organic inputs e.g. manure is likely to increase in response to system intensification. The contribution of manure management to enhance soil productivity is unquestionable (Murwira *et al*., 1995; Pankhurst, 1990). However, there is need for such research to be viewed realistically, especially in the context of the evolving farming systems in the arid and semi-arid lands, notably integrated systems in terms of crops and livestock units which may hinder or compliment each other. There is a growing recognition of the need to develop technologies and policies which ensure optimization enterprises. Implicit in this strategy is the maximization of the contribution of the livestock unit to soil fertility improvement while addressing challenges of increasing intensity of crop-livestock systems.

In this paper we will first discuss the effect of manure on soil productivity and ecosystems services. This is followed by highlighting the management practices to increase manure use efficiency before elaborating on the emerging new research opportunities in soil fertility management to enhance the crop-livestock integration.

II. Effect of manure on soil productivity and ecosystems services

In the mixed farming systems that characterizes the semi-arid zone of Africa, low rural incomes, high cost of fertilizer, inappropriate public policies and infrastructural constraints prevent the widespread use of inorganic fertilizers. Under this situation and as population pressures increases and fallow cycles are shortened, organic sources of plant nutrients such as manure, crop residue and compost remain the principal sources of nutrients for soil fertility maintenance and crop production (William *et al*., 1985). Estimates of the nitrogen contribution from manure to the total N input budget suggest that up to 80% of N applied to crops is derived from manure in both extensive and intensive grazing systems in East and Southern Africa.

Several scientists have reported the effect of manure on crop yield increases in Western and Eastern Africa (Bationo and Mokwunye, 1991; Bationo *et al*., 1998; Mokwunye, 1980; Pichot *et al*., 1981; Padwick, 1983; Pieri, 1986; de Ridder and van Keulen, 1990; Abdulahi and Lombin, 1978; Powell, 1986; Murwira *et al*., 1995; Pankhurst, 1990; Kihanda, 1996; Kihanda and Gichuru, 2000; Lekasi *et al*., 1998; Probert et al., 1995; Kanyanjua and Obanyi, 1999; Gibberd, 1995; Kihanda and Warren, 1998.

Most of the studies in the literature have focussed on the responses of crops to farmyard manure (FYM) applications. One of the earliest reported increases to FYM application in sub-saharan Africa was by Hartley (1937) in the Nigerian Savannah. It was observed that application of 2 t ha^{-1} FYM increased seed cotton yield by 100%, equivalent to fertilizers applied at the rate of 60 kg N and 20 kg ha^{-1}. In Embu, Kenya, FYM significantly increased maize and potato yields in a long-term trial (Gatheca, 1970). The data in Table 1 summarizes the results of a number of trials on manure conducted in research stations in West Africa. The data shows that manure collected from stables and applied alone produces about 20 to 60 kg N/ha in cereal grain and 70 to 178 N kg/ha in stover per tonne of manure.

In Kenya, Kanyanjua and Obanyi (1999) observed that within the Fetilizer Use Recommendation Project (FURP) sites (averaged over several sites and seasons) the response to manure application was in the order cabbages>potatoes>maize>cowpea and nitisols gave a higher response than acrisols (Table 2). Kihanda *et al*. (1988) while evaluating the effects of inorganic fertilizers, lime, FYM and crop residues on the yield of maize in acidic andosol of Central Kenya found that FYM increased maize biomass by 210%, while lime and P increased yields by 115 and 57%, respectively. They concluded that the large response to FYM application might have been due to a reduction in exchangeable aluminium and manganese allowing the plant to establish better rooting system in addition to providing nutrients, particularly potassium.

In the Sahelian zone of West Africa, Bationo and Mokwunye, 1991, found no difference between applying 5 t ha^{-1} of FYM as compared to the application of 8.7 kg P ha^{-1} as Single Superphosphate and a further application of FYM at 20 t ha^{-1} only doubled pearl millet grain a compared to the application of 5 t ha^{-1} (Table 3).

Gatheca, 1970 reported that an annual application of 5 to 6 t ha^{-1} of manure gave higher yields of maize in Kenya than heavy applications of 20 to 30 t ha^{-1} applied at intervals of four to five years. In the acidic soils of Central Kenya, Mugambi (1978, 1979) noted that application of FYM at 5 t ha^{-1} increased the potato tuber yield by more than 50% above the control. A combination of the same rate of FYM and P at 100 kg P ha^{-1} increased potato yield by more than 100% above the control, an indication that P was also limiting in that soil. The data in Table 4 indicates that the application of 3 t ha^{-1} of manure plus urine produced grain and total bio-mass that were higher as compared to when only manure was applied and crop response to sheep dung was greater than to cattle dung. Research studies indicate that approximately 80-95% of the N and P consumed by livestock is excreted. Whereas N is voided in both urine and faeces, most P is voided in faeces (ARC, 1980; Termouth, 1989). Dar *et al*., 2001 clearly indicated that in the P deficient soils of sandy sahelian soils, the addition of P fertilizer will increase the efficiency of FYM and hill placement of both FYM and P fertilizer was better than broadcasting (Fig. 1).

The data in Tables 5 and 6 respectively from eastern and Western Africa give the variation in the nutrient concentration of manure samples from different sites, indicating that even on the same soil type and rainfall, the response to manure application will greatly depend on the source of manure.

Pieri (1986, 1989) and Sedogo (1993) summarized the results of the long-term soil fertility experiments initiated since the 1960's. One important conclusion that emerged from the experiments is that application of mineral fertilizers is an effective technique for increasing crop yields in the Sudanian zone of West Africa. However, in the long-run the use of mineral fertilizers alone will decrease crop yields but sustainable and higher production is obtained when inorganic fertilizers are combined with manure (Fig. 2).

At Kabete in Kenya, Nandwa (1997), obtained higher yields of maize in a long-term soil fertility management experiments when mineral fertilizers are combined with crop residue and FYM (Fig. 3).

For a modest yield of 2 t/ha of maize the application of 5 t ha^{-1} of high quality manure can meet the N requirement but this cannot meet the P requirements in areas where P is deficient (Palm, 1995). Organic inputs such as manure are often proposed as alternatives to mineral fertilizers, however, it is important to recognize that in most cases the use of manure is part of an internal flow of nutrients within the farm and does not add nutrient from outside the farm and also quantities available is inadequate to meet nutrient demand over large areas because of the limited quantities, the low nutrient content, and the high labour demands for processing and application. The availability of manure for sustainable crop production has been addressed by several scientists. De Leeuw *et al*. (1995) reported that with the present livestock systems in West Africa the potential annual transfer of nutrient from manure will be 2.5 kg N and 0.6 kg P per hectare of cropland. Although the manure rates are between 5 to 20 t/ha in most of the on-station experiments, quantities used by farmers are very low and ranged from 1300 to 3800 kg ha^{-1} (Williams *et al*., 1995). Hiyami and Ruttan (1985) reported that exclusive use of inorganic fertilizers in Africa will increase food production at best by 2% yr^{1}, well below the population growth rate, and not even close to 5 to 6% required to reduce poverty and secure food security. Organic sources of nutrients, however, will be complementary to the use of mineral fertilizers (Quinones *et al*. 1997). Despite its vital role the quantities of manure are not available on-farm for a number of factors. There are simply insufficient number of animals to provide the manure needed. This problem becomes more pronounced especially in post drought years (Williams *et al*. 1995). The amount of livestock feed and land resources available are also limited. Depending on rangeland productivity, it will require between 10-40 hectares of dry season grazing land and 3-10 hectares of rangeland of wet season grazing to maintain yields on one hectare of cropland using animal maure (Fernandez *et al*. 1995).

Manure production by zero-grazing cattle in Kenya has been estimated as 1 to 1.5 t $animal^{-1}$ yr^{-1} (Strobel, 1987). Two animals will be needed to supply a 2 t ha^{-1} of crop, if the manure were of high quality, but eight animals are required if the quality is low.

Ecosystem services are broadly defined to include nutrient cycles, water movement and storage, soil erodibility, pest control and chemical detoxification. These services are key determinants of agricultural productivity and sustainability. Therefore the application of manure and increase in system carbon can be considered to be a major component of sustaining the crop-livestock production systems. Recognition of this fact has led to investment in research on carbon sequestration in tropical agricultural landscapes.

The data in Table 7 in the Sahelian zone of Niger clearly indicates that manure application will not only improve the organic carbon of the soil but by complexing iron and aluminium it will also increase P availability. In the long-term soil fertility management trials, although soil organic carbon decrease in all treatments overtime, the organic carbon value was higher in the treatment where crop residue and manure was applied (Fig. 4).

Past and on-going research has been focussed on the assessment of the relationship between land management practices and carbon storage. Our current understanding is that the carbon sequestration potential of different organic inputs is an analogous index to that of fertilizer equivalency. Further studies are directed at the assessment of the trade-offs between the use of soil carbon for agricultural productivity and its value for carbon sequestration potential and environmental conservation. This is a relatively new area of research especially on assessing the effect of quantity and quality of organics on soil organic matter fractions and crop yields.

Expected benefits from manure application in the context of ecosystem functions include non-nutritional effect on soil physical properties that in turn influence nutrient acquisition and plant growth. The resource, through interactions with the mineral soil in completing toxic cations helps to reduce the phosphorus (P) sorption capacity of the soil.

III. Management practices to improve manure efficiency

1. Improvement of manure quality

Manure quality varies widely and clear indices of quality determination are sometimes difficult to apply widely. Past research has been focussed on evaluating different ways of managing manure to improve its quality. Preliminary studies suggest that feeding of concentrates; zero-grazing rather than traditional boma; manure stored under cover instead of in the open, concrete floor rather than soil floor results in higher quality of manure (Lekasi *et al*., 1998).

(a) Animal type and diet

The quality of manure has been observed to vary with types of animals and feeds, collection and storage methods (Mueller-Saemann and Kotschi, 1994; Mugwira, 1984; Ikombo, 1984; Probert *et al*., 1995; Kihanda, 1996). A study in Ethiopia showed that the quality of manure declined in the order of chicken > sheep/goat > horse/donkey > cattle manure with respect to % N (1.5, 0.7, 0.5 and 0.4), % P (0.4, 0.4, 0.3 and 0.2) % K (0.8, 0.3, 0.3 and 0.2) and % organic matter (29, 31, 22 and 16), respectively. In a related study conducted in Kenya, Lekasi *et al*. (1998) observed that the nutrient contents (especially N and P) of manure decreased in the order of chicken, pig, rabbit, goat and cattle, with manure mixed with urine having a higher quality than dung alone. Nevertheless, current characterization studies indicate that manure quality is very variable e.g. % N 0.23-1.76; % P 0.08-1.0; % K 0.2-1.46; % Ca 0.2-1.3 and % Mg 0.1-0.5. High quality manure has been defined as that with % N>1.6 or C:N ratios of <10; while low quality manure has <0.6% and C:N ratios of >17. Recent studies have shown poor correlation between manure quality and lignin, polyphenols and soluble fractions of carbon (Kihanda and Gichuru, 2000). Fig. 5 shows the effect of C:N ratio on N mineralization of manures. Fig. 6 shows that the N fertilizer equivalency increases with high N content.

Besides animal type, quality of manure can be enhanced through feed manipulation which is more favourable in intensive grazing systems (eg. stall or zero-grazing units) rather than extensive grazing systems (eg. communal or range etc.). In a study carried out in East Africa, it was reported that manure N concentration increased by more than two fold when the basal diet of barley straw animal feed was supplemented with poultry waste and high quality forage shrubs, *Calliandra* and *Macrotylama* (Delve, 1998). In another study, manure from animals that received P supplements of Busumbu (0.70% P) and Minjingu rock phosphate (0.45% P) increased by two to four-fold above the basal diet of napier (0.24% P), bone meal (0.50% P). However, feeding animals with “unga” commecial feed resulted in much higher values of P in manure (0.95% P).

(b) Composting techniques and materials

While the quality of materials used to make compost manures determines its quality, composting techniques are equally important. High quality manures is often obtained from covered shed composting compared to open-shed composts; and similarly from pit composts compared to heap or surface composting. Furthermore crop residue incorporation has been found to minimize nutrient losses through aerobic volatilisation or anaerobic dentrification. For example, in a study in Kenya it was reported that composting low quality manure with different proportions of either tithonia or lantana, the N content of manure was increased by between 10 and 40 per cent depending on the treatment but no changes in P concentration was found (Kihanda and Gichuru, 2000).

In a study conducted in Zimbabwe, investigating manure nitrogen changes during storage, Nzuma and Murwira (1998) showed that total N measured in anaerobic manure composts at the end of storage was significantly higher than in aerobic manure composts. This aerobic manure compost incorporated with maize straw was 0.9 and 0.6% N for April and July samples respectively, while the values in the absence of straw incorporation were 1.4 and 1.2% N (due to lack of N immobilization). The results also showed that the pH in anaerobic manure compost system ranged from 6.5 to 6.9 while the anaerobic manure composts were more alkaline with pH range of 8.2 to 8.6 (Fig. 7).

The effect of composting on the phosphate rock (PR) dissolution has been study by Bado (1985) and Lompo (1984) in Burkina Faso. The local phosphate rock of Kodjari alone or combined with urea was incorporated in two low quality organic materials for composting during 6 months. The RP and the urea were incorporated in the organic materials at the rates of 4kg of PR (25% P2O5) for 100kg and 12 kg of urea for 1000 kg dry organic matter according to the recommended rates (Lompo, 1984). The organic material was a mixture of 75% of sorghum straws and 25% of cattle manure (using as an inoculums). The effect of composting on the water-soluble phosphorous (WSP) balance before and after composting was evaluated.

The results (Table 8) indicated that the composting of the organic materials with PR involved an enhancement of the total WSP balance. The total WSP was positive for all treatments. A positive balance of 67% to 796% of the total WSP was observed after 6 months of composting. The augmentation of the total WSP may be explained by an increase of the soluble phosphorous from organic matter. It may also due to a probable dissolution of the P of the PR by the organic acids during the composting. May be the two process took place during the composting time.

(c) Handling and storage techniques

Besides heaps and pits, manure may be collected and stored in cattle kraals, bomas, open areas etc. Recent research shows that quality of manure may be affected depending on prevailing conditions. Murwira (1993) reported that under aerobic and high pH conditions in the Kraal, volatilisation of ammonia may occur while the wet soggy anaerobic conditions may lead to dentrification and leaching losses. Such losses are minimized under intensive grazing system such as zero-grazing units with concrete floor and covered roof. In such systems provision of low quality organics as bedding helps to trap the nutrients from the urine. Lekasi *et al.* (1998) reported that manure removed from grazing units with a soil floor had a much lower N and P and higher ash content than manure removed from grazing units with a concrete floor. Factors responsible for enhanced gaseous N loss in composting include increased total N of the material; high temperatures, low pH and frequent turning (Dewes and Hunsche, 1998). On the other hand high dentrification loss are often associated with increased pH and not increase of insoluble carbon compounds as opposed to reducing sugars under anaerobic conditions. Run-off and nitrate leaching losses can also be substantial.

(d) Integrated nutrient management

The beneficial effects of combined manure and inorganic nutrients on soil fertility have been repeatedly shown, yet there is need for more research on the establishment of the fertilizer equivalency of the manures and also determining the optimum combination of these two plant nutrients (INM) taking into account the high variability in the quality. Such information is useful in formulating decision support systems and establishing simple guidelines for management and utilization of the resources. Studies investigating the benefits of sole versus combined application of manures and inorganic fertilizers have given variable and sometimes inconsistent results. At Chisunga N in 100% inorganic and 100% organic have yield of maize lower than combining the two plant nutrient. For example, the application of 100 kg N/ha in the inorganic farms have maize yields of about 3.2 t ha^{-1} but the application of the same quantity with half inorganic form and the other half in inorganic form gave maize yield close to 6 t ha-1. In Manjoro there was no advantage to combine organic and inorganic plant nutrients (Fig. 8). For example, studies in Tanzania indicated that there was no significant difference in maize yields between sole and combined application of 5 t ha^{-1} of manure and 60 kg N ha^{-1} of mineral fertilizer (Richard, 1967). But at a different site in the same country, combination of manure at 5 t ha^{-1} with 40 kg N ha^{-1} mineral fertilizer gave similar maize yield with either manure at 10 t ha^{-1} or mineral fertilizer at 80 kg N ha^{-1} (Kalumuna *et al*., 1999). Disparities in such responses are partly due to addition of different rates and quality of nutrients through compared treatments; and also due to differences in the limiting nutrients and soil moisture at the test sites. For example, in Madagascar, Rabeson (1992) observed that supplementing manure with inorganic N fertilizer, the rice yield increased by more than 100% but supplementing with P did not improve the crop yield, suggesting that N was the most limiting nutrient in that soil. Another cause of inconsistent results may be due to depressing or antagonistic effects of the nutrient source combinations. For example, a study in Zimbabwe showed that while increasing rates of manure, lime and NPK mineral fertilizers increased growth of pearl millet, however, lime had a depressing effect on the effectiveness of manure while the NPK fertilizers increased the effectiveness of manure (Mugwira, 1985). Also, short-term trials do not give a true picture of the long-term effects of the treatments. Additionally, higher fertilizer equivalencies have been observed in less moist and less fertile soils e.g. sandier and drier soils (Kimani *et al*., 2001). Using data collected in different sites, Mutuo *et al*., 2001 found a linear relationship between the percent fertilizer equivalency and the N content. This linear function indicates that increase of 0.1% N in the tissue of organic amendment, there is a 6% increase in the fertilizer equivalency value and the critical level of N content of organic material for net immobilization or mineralization was found to be 2.2%. This is an agreement with the one of the 2.2% suggested by Palm *et al*. (1995) and Palm *et al.* (1997) in the decision tree for the selection of organic materials (Fig. 9).

(e) Time frequency and method of application

Low quality manure is often observed to depress crop yields. This deleterious effect can be overcome through application of manure ahead of planting time to overcome this effect. In some cases, surface application has resulted in better results than incorporation. In many cases, this depends on the quantity of manure applied. Some studies have investigated the potential to overcome this problem through megadose application instead of annual applications. But such studies from Zimbabwe suggest that there are no differences in crop yields between the two application regimes eg. 7 t ha^{-1} annual application, 14 t ha^{-1} applied every second year and 28 t ha^{-1} applied every fourth year (Mugwira and Murwira, 1997).

(f) Fortification and pelleting

The bulky nature of manures and low quality constraint its transportation and returns to application. To make manure as a biofertilizer easily handleable (less bulky) and applicable, some studies have shown granule pelleting to be a farmer user-friendly packaging system. Other studies have demonstrated that the quality and return to such biofertilizers can be improved through fortification with the addition of inorganic nutrient sources; composting under cover to minimize leaching and loss of nutrients via gases; and the use of high quality biofertilizers on high value crops solely or in combination with inorganic fertilizers.

In high external input systems, large quantities of maize stover or wheat straw can be generated (8–10 t ha^{-1}), and this is either burnt or partly grazed, resulting in large nutrient off-takes unless the manure is recycled. To overcome this constraint, fortification trials have been conducted. Okalebo *et al.* (2000) found that combined application of composts of 2 t ha^{-1} of wheat straw or soybean trash with 80 kg N ha^{-1} of mineral fertilizer resulted in higher maize yields (grain and stover) than from application of 80 kg N ha^{-1} of mineral fertilizer alone. Sole application of residue depressed yields. In related studies Muasya *et al*. (2000) found that wheat straw composted with inorganic fertilizer (80 t ha^{-1} compost) resulted in slightly higher wheat yields (3.6 t ha^{-1}) than with the same rate of normal compost (3.0 t ha^{-1}).

2. Strategies to increase manure quantity

In both regions, manure is produced abundantly under extensive systems eg. in pastoralists and transhumant systems. As these systems decrease, settled arable agriculture increases. In the latter systems farmers own cattle either under confinement or paddocking systems. Lots of manure is accumulated in cattle boma in the East African region. In West Africa, kraaling eg. keeping of livestock on selected areas over a given period of time, helps increase and accumulate manure through urine and dung voided in the field. Recent studies have shown that two nights kraaling results in between higher yields than in unkraaled fields (Powell *et al*., 1998).

IV. New Research Opportunities

1. "Best-bet" manure-based technologies

Past reviews of research on the use of organics (with or without mineral fertilizers) for soil fertility management in tropical agroecosystems (CABI, 1994; Padwick, 1993; Nandwa and

Bekunda, 1998; Palm *et al*., 1997; Palm *et al*., 2001) have shown widespread non-adoption or low adoption of emerging technologies. It has been reported that often the use of organic materials is based on trial and error (Palm *et al*., 2001). At the research and development level, presently and in future, there is a need for priority setting (Kilambya *et al*., 1999) and targeting of a potential “best-bet” technology for smallholder farmers in the form of an agronomic superiority, economic viability, environmentally friendly and culturally acceptable options.

2. Multidisciplinary/interdisciplinary research agenda

Wider adoption of soil productivity technologies requires that their profitability for smallholder farmers be carefully evaluated. The imperative for future manure research is to adopt a holistic framework for closer interaction between soil productivity subject matter specialists, economists, environmentalists, extensionists and policy makers. There is a need for more horizontal and, above all, vertical networking to create momentum and synergy in soil productivity management research. Lack of multidisciplinary research has been reported to lead to inadequate discounting of soil quality by economists in the context of a “future generations sustainability quest” (Young, 1998). Furthermore, other workers have reported a poor relationship between farm product price and nutrient withdrawal (mining) in the context of nutrient replacement cost. Recent work in Kenya showed that 32% of the average net farm income amounted to the replacement of mined nutrients of many farms and farmers, 54% of whom are estimated to live below the poverty line, i.e. on one US dollar per day (de Jager *et al*., 1998). The proposed new approach should provide synergies between applied or strategic research to adaptive research, and also between farmers’ indigenous technical knowledge and their main scientific knowledge, and therefore result in higher rates of technology adoption. Future multidisciplinary research should also investigate yield depression attributed to phytotoxicity associated with manure management (Elliott *et al*., 1978), plant diseases (Cook *et al*., 1978) and pests (Musiek and Beasley, 1978).

3. Farmer/client participatory research approach and methodologies

There is a need for a shift from a top-down to bottom-up research approach because the use of the former approach in soil productivity management consultative/collegial research in the past has proved retrogressive, especially for heterogeneous, risk-averse farm households. Future manure and other nutrient input management research should use participatory research approaches eg. farmer’s field school, participatory learning action research (Defoer et al., 1998), in the context of the target farming systems, integrating different disciplines and with participation of farmers (Martin and Sherington, 1997; Haverkort *et al*., 1991).

4. Guidelines on the use of manures

A majority of manure are often characterized as intermediate–low-quality resources and hence are prescribed to be used in a mixture with mineral fertilizer (Palm *et al*., 2001). Future research is required to identify the “best-bet” low-quality manure that can be mixed with high-quality organic resources to satisfy the short-term goal of nutrient availability and the long-term goal of building SOM. Such research should come up with cases for proper discounting of resource conservation estimates (Smaling *et al*. 1997).

5. The benefits of manures, like other organics, over mineral fertilizers is both the short-term effects and residual or long-term effects. Future research opportunities include the development of guidelines that link quality of manure to their short-term fertilizer equivalency value and longer-term residual effects through SOM turnover and formation.

6. Future research opportunities exist on building on past Organic Resource Database (ORD) to develop Decision Support System (DSS) guides and simple tools, based on both scientists and

farmer perspectives to guide the choice and utilization of manure depending on their varied quality and quantities. This will require research that correlates scientific indicators (chemical content and nutrient release) with farmers indicators of manure quality (texture, colour, smell, white fungi/sand, homogeneity and longerity of composts).

7. Research opportunities exist on the establishment of the relationship between manure quality and a number of variables that influence quality eg. feeds manipulation, composting techniques, manure handling and storage method. These type of research should include determination of strategies that minimize nutrient losses and leaching, erosion, volatilisation and dentrification.

8. Future research opportunities include the development of a systematic framework for investigating integrated nutrient management based on fertilizer equivalence values and pertinent ecosystem services and functions. This research should conduct the determination of economic and social trade-offs of improved soil fertility management alternatives to manures eg. legumes, high quality organics, green manures, forage legumes in traditional mixed farming systems.

9. There are future research opportunities on the determination of the biophysical and socio-economic boundary conditions for the adoption of manure management-based techniques.

Conclusion

There is considerable information on manure management in Western and Southern Africa. The results of the comparative analysis from the regions suggest that different lessons can be learned from each stakeholder. As an example, it is clear that scientists in West Africa can benefit by learning more of the technologies developed in West Africa where compost with manure is fortified with phosphate rock and scientists in West Africa can also learn on the work done in East Africa on the assessment of manure fertilizer equivalency, the technologies based on the identification of the best combination ratios of organics and inorganics and the systematics characterization of manure for its nutrient contents and lignins and polyphenols in order to apply the organic matter decision tree.

Crop response to manure or in combination with inorganic fertilizers is variable and site specific. The difference in response may be due to several factors eg. soil fertility status quality of manure and environmental factors. This means that modelling and decision support systems will have an important role in future research. Other new research opportunities include topics such as the crop livestock trade-off by developing new strategies that minimize competition between crops and livestock such as conflicting demands of crop residue for feed and soil cpnservation, the legume for soil fertility management per se of feed for livestock the increase of inorganic fertilizer use efficiency, due to better management of manure, the relationships between manure quality and build-up of soil organic matter, the other benefits of manure use and the socio-economic and policy implications.

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Table 1: Results of manuring experiments at three sites in semi-arid West Africa

Panel A: Manure only

Location	Amount of manure applied (t/ha)	Crop	Crop response[1] (kg of DM/t manure) Grain	Stover	Reference
M Pesoba, Mali	10	Sorghum	35[2]	n.s.	1
Saria, Burkina Faso	10	Sorghum	58	n.s.	2
Sadore, Niger 1987	5	Pearl millet	38	178	3
	20	Pearl millet	34	106	3

Table 1: Results of manuring experiments at three sites in semi-arid West Africa (cont.)

Panel B: Manure with inorganic fertiliser

	Amount of			Crop response[1] (kg of DM/t manure0	
Location	Manure (t/ha)	Fertiliser (kg/ha)	Crop	Grain	Stover
M Pesoba, Mali	5	NPK: 8-20-0	Sorghum	90[4]	n.s.
Saria, Burkina Faso	10	Urea N: 60	Sorghum	80	n.s.
Sadore, Niger					
1987	5	SSP P: 8.7	Pearl millet	82	192
1987	20	SSP P: 17.5	Pearl millet	32	84

1. Responses were calculated at the reported treatment means for crop yields as: (treatment yield - control yield)/quantity of manure applied.
2. Response of sorghum planted in the second year of a 4-year rotation involving cotton-sorghum-groundnut-sorghum. Manure was applied in the first year.
3. Manure plus urine
4. Estimated from visual intrapolation of graph
n.s. implies not specified

References: 1. Pieri (1989); 2. Pieri (1986); 3. Baidu-Forson and Bationo (1992)

Source: Williams et al. 1995

Table 2: Crop yields (averaged over several sites) as influenced by levels of FYM application

Crop	FYM rates and crop yields (t ha^{-1})				Response equation	R^2
	0	2.5	5.0	7.5		
Nitisols						
Maize	3.72	4.00	4.34	4.76	Y = 3.68 + 0.138 FYM	0.99
Potatoes	9.12	10.20	10.60	11.80	Y = 9.16 + 0.337 FYM	0.98
Cabbages	13.70	21.20	27.60	29.30	Y = 14.97 + 2.128 FYM	0.97
Acrisols						
Maize	1.88	2.00	2.00	2.07	Y = 1.90 + 0.021 FYM	0.93
Cowpeas	0.77	0.78	0.83	0.82	Y = 0.77 + 0.079 FYM	0.88

(Source: Kanyanjua and Obanyi (1999).

Table 3: Effects of manure and phosphorus from different sources on Pearl Millet grain yield, at Sadore, Niger, 1988

Treatments	Grain yield (tons ha^{-1})
Control	0.362
8.7 kg P ha^{-1} as single superphosphate (SSP)	0.734
5 tons manure ha^{-1}	0.723
8.7 kg P ha^{-1} as SSP + 5 tons manure ha^{-1}	1.093
39.3 kg P Parc W phosphate rock ha^{-1}	0.485
39.3 kg P Parc W phosphate rock ha-1 + 5 tons manure ha^{-1}	0.952
17.5 kg P ha^{-1} as SSP	0.851
20 tons manure ha^{-1}	1.457
17.5 kg P ha^{-1} as SSP + 20 tons manure ha^{-1}	1.508
SE	±0.089
CV (%)	27.9

Note: The manure had 0.405% total P and 1.21% total N
Source: Bationo and Mokwunye 1991

Table 4: Effect of cattle and sheep dung and urine on pearl millet grain and total above-ground biomass, Sadore, Niger 1991

Type of manure	Dung application rate kg/ha	With urine		Without urine	
		Grain yield (kg/ha)	Total biomass (kg/ha)	Grain yield (kg/ha)	Total biomass (kg/ha)
Cattle	0	-	-	80	940
	2990	580	4170	320	2170
	6080	1150	7030	470	3850
	7360	1710	9290	560	3770
	s.e.m.	175	812	109	496
Sheep	0	-	-	80	940
	2010	340	2070	410	2440
	3530	1090	6100	380	2160
	6400	1170	6650	480	2970
	s.e.m	154	931	78	339

Adapted from Powell et al. 1998

Table 5: Nutrition content of FYM samples collected from different parts of Sub-Saharan Africa (mainly Eastern and Southern Africa)

	Nutrient content (%)				
Country (Reference)	N	P	K	Ca	Mg
UK (Hemingway, 1961)	1.76	0.24	1.29	0.74	0.34
Kenya (Ikombo, 1994)	1.62	0.50	1.34	0.26	Nd*
Kenya (Kihanda, 1996)	1.19	0.24	1.46	0.97	0.26
Zimbabwe (Mugwira, 1984)	0.6-1.3	0.1-0.2	0.7-1.0	0.2-0.3	0.1-0.2
Ethiopia (Mueller and Kotschi, 1994)	0.3	0.2	0.2	nd	nd
Kenya (Probert *et al*., 1995)	0.23-0.70	0.08-0.22	0.28-1.14	0.58-2.02	nd
Madagascar (Rabeson, 1992)	0.8-1.7	0.6-1.0	0.7-1.4	0.5-1.3	0.3-0.5
Chicken manure: Mueller-Saeman and Kotshi, 1994	1.5	0.4	0.8	-	-
Sheep/goat manure: Mueller-Saeman and Kotshi, 1994	0.7	0.4	0.3	-	-
Cattle manure: Mueller-Saeman and Kotshi, 1994	0.3	0.2	0.2	-	-
Horse/donkey manure: Mueller-Saeman and Kotshi, 1994	0.5	0.3	0.3	-	-

nd* not determined

Source: Adapted from Kihanda and Gichuru 2000

Table 6: Nutrient composition of manure at selected sites in semi-arid West Africa

Location and type of manure	Nutrient composition (%)			Reference
	N	P	K	
Saria, Burkina Faso				
Farm yard manure	1.5 - 2.5	0.09 - 0.11	1.3 - 3.7	1
Northern Burkina Faso				
Cattle manure	1.28	0.11	0.46	2
Small ruminant manure	2,20	0.12	0.73	2
Senegal				
Fresh cattle dung	1.44	0.35	0.58	3
Dry cattle dung	0.89	0.13	0.25	3
Niger				
Cattle manure	1.2 - 1.7	0.15 - 0.21	-	4
Sheep manure	1.0 - 2.2	0.13 - 0.27	-	4

Source: Williams et al. 1995`

Table 7: Changes in soil nitrogen, pH, organic matter, and Bray P_1 in 1987 after additions of manure in 1984 and 1986

Treatments	Total N (%)	pH H2O	pH KCL	Organic matter (%)	Bray P1 (ppm)
Control	153	4.98	3.88	0.29	5.33
5 tons manure ha-1	202	5.37	4.25	0.39	10.31
17.5 kg P ha-1 as SSP	148	5.05	4.03	0.30	15.50
20 tons manure ha-1	285	6.21	5.03	0.58	22.90
SE	15	0.14	0.16	0.06	2.58
CV (%)	18.7	5.18	7.42	29.63	37.46

Source: Bationo and Mokwunye 1991

Table 8: Percentage change of water soluble phosphorus after 6 months of composting

Treatments	(%)
Sorghum Straw(75%) +Manure(25%)	67
Sorghum Straw(75%)+Manure(25%) + PR	172
Sorghum Straw(75%) + Manure(25%) +PR+ Urea	196

+

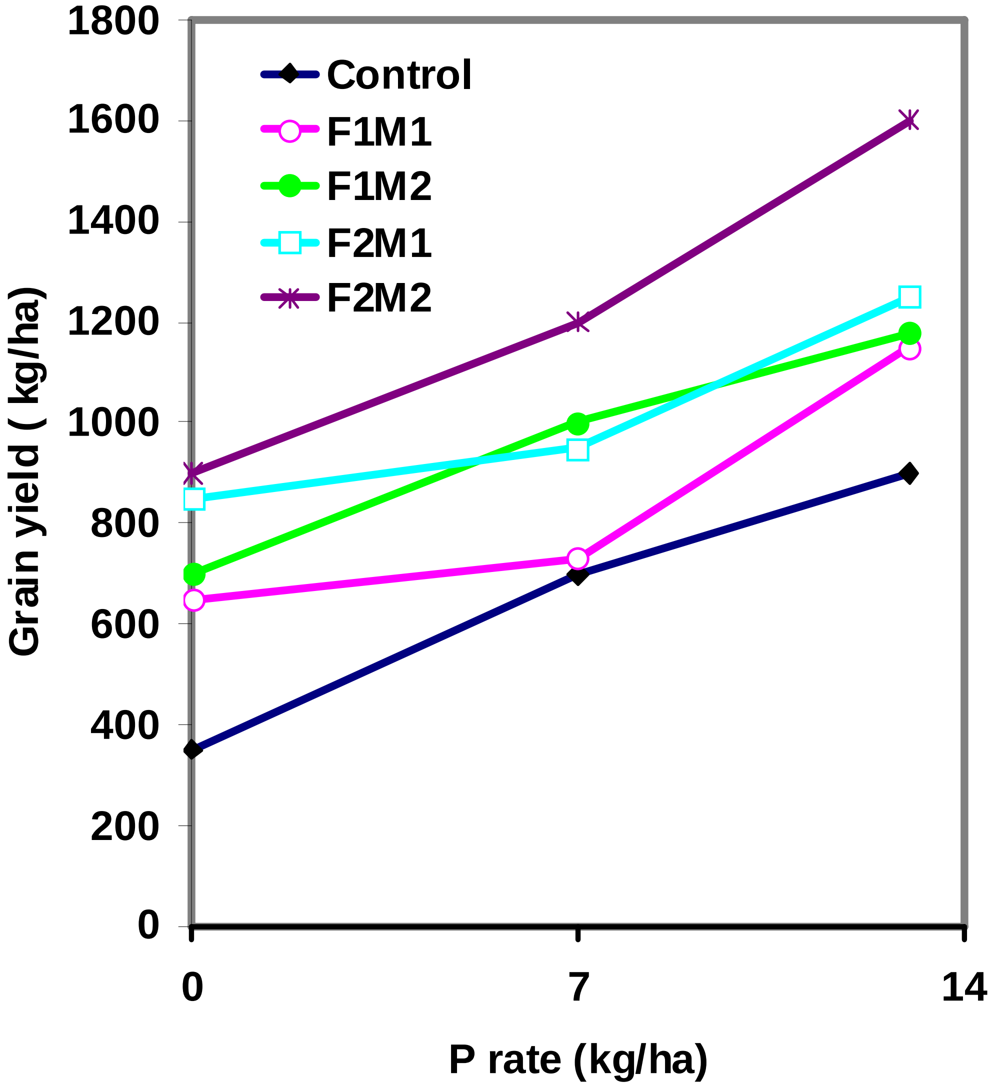

Fig 1. Effects of manure placement methods and P fertilizer on milllet grain yield
F = Manure1 = 3 ton, 2 = 6 ton
M = Methods of application 1 = broadcast, 2 = hillplaced

Source: Dar et al., 2000

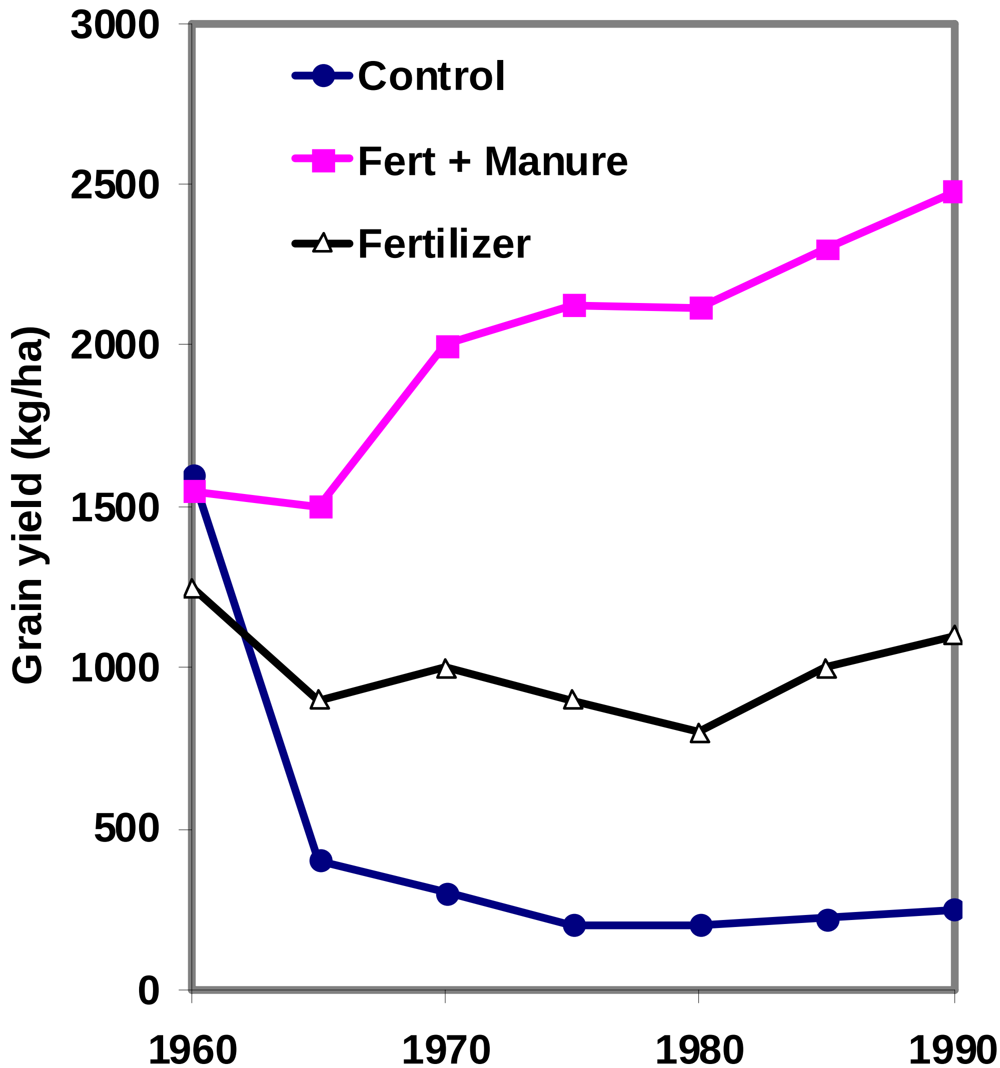

Fig 2. Sorghum grain yield as affected by mineral and organic fertilizers over time.

Source: Sedogo, 1993

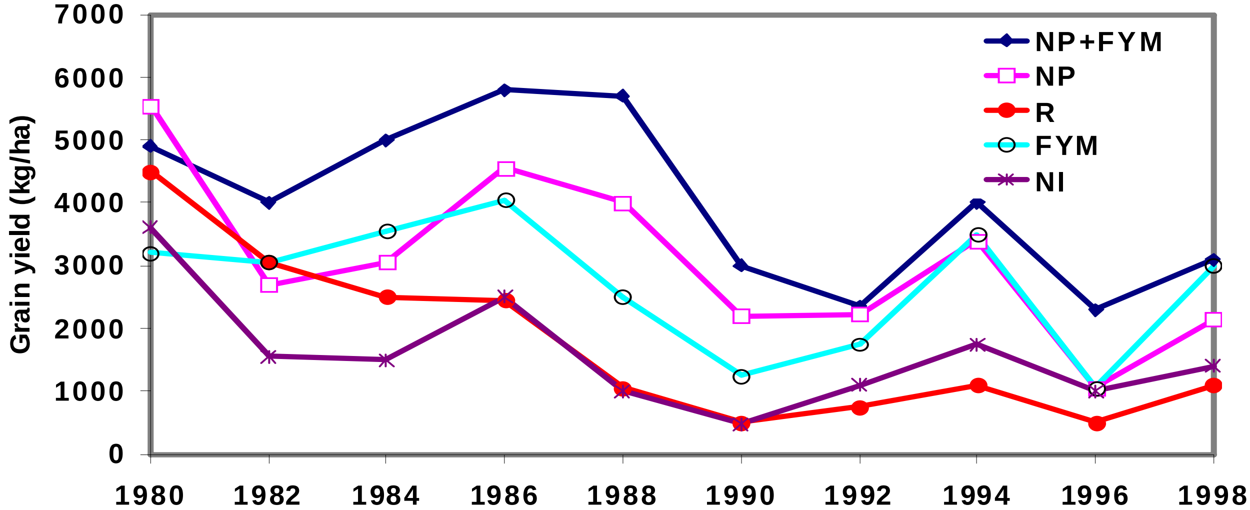

Fig 3. Maize yield trends for long-term trial for the period 1980 to 1998 at Kabete Nairobi, Kenya.

Source: Nandwa, 1997

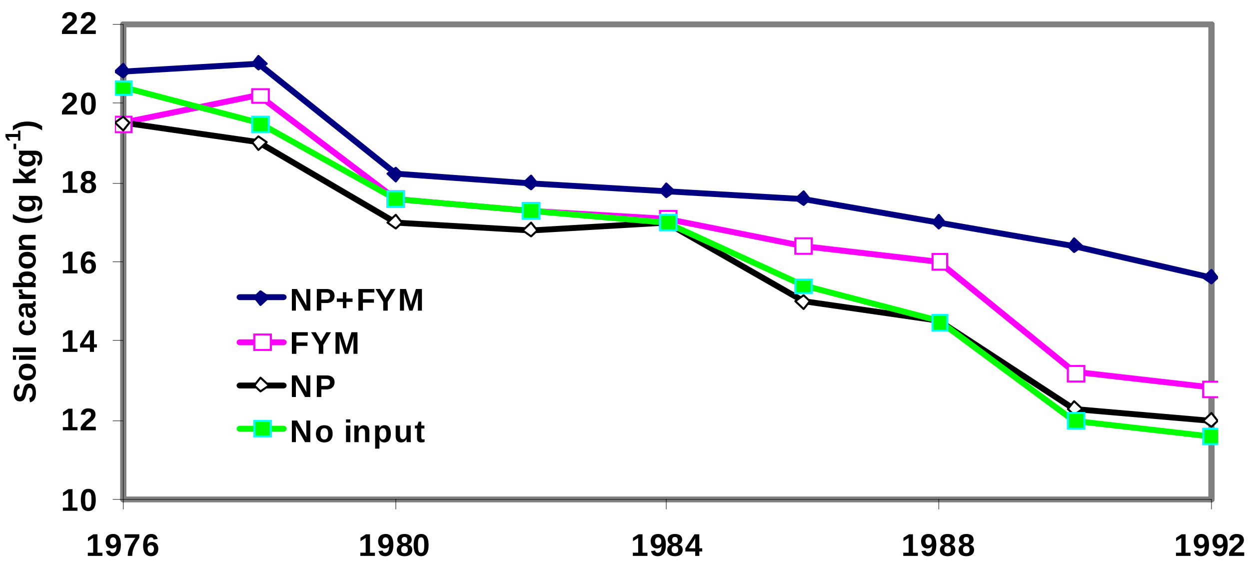

Fig 4. Effect of application of farmyard manure, mineral fertilizer on soil organic C at 0 to 25cm depth at Kabete, Kenya.

Source: Nandwa, 1997

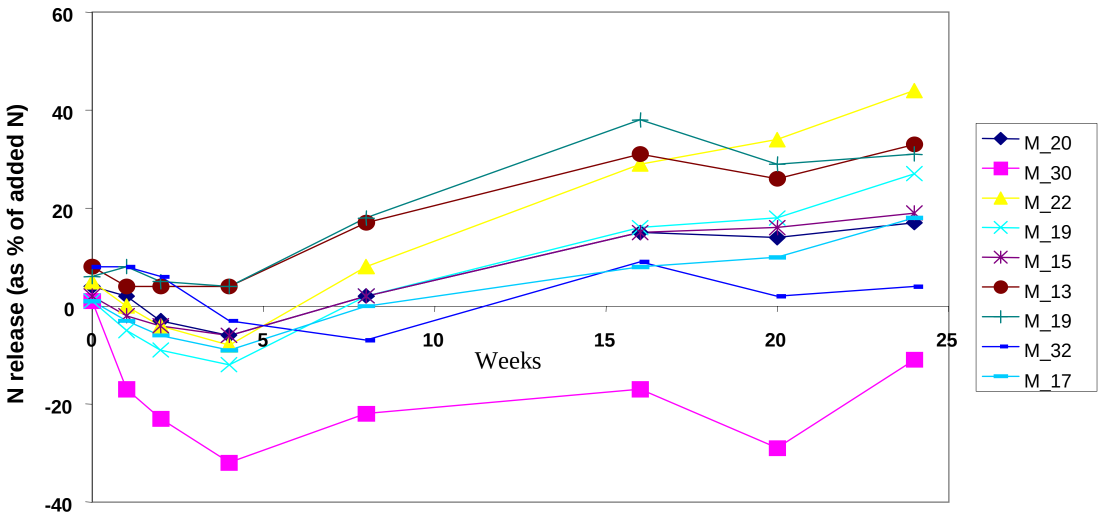

Figure 5. Nitrogen mineralisation of manures with different C:N ratios collected from cut and carry systems in Kenya. (numbers on right of legend indicate C:N ratio)

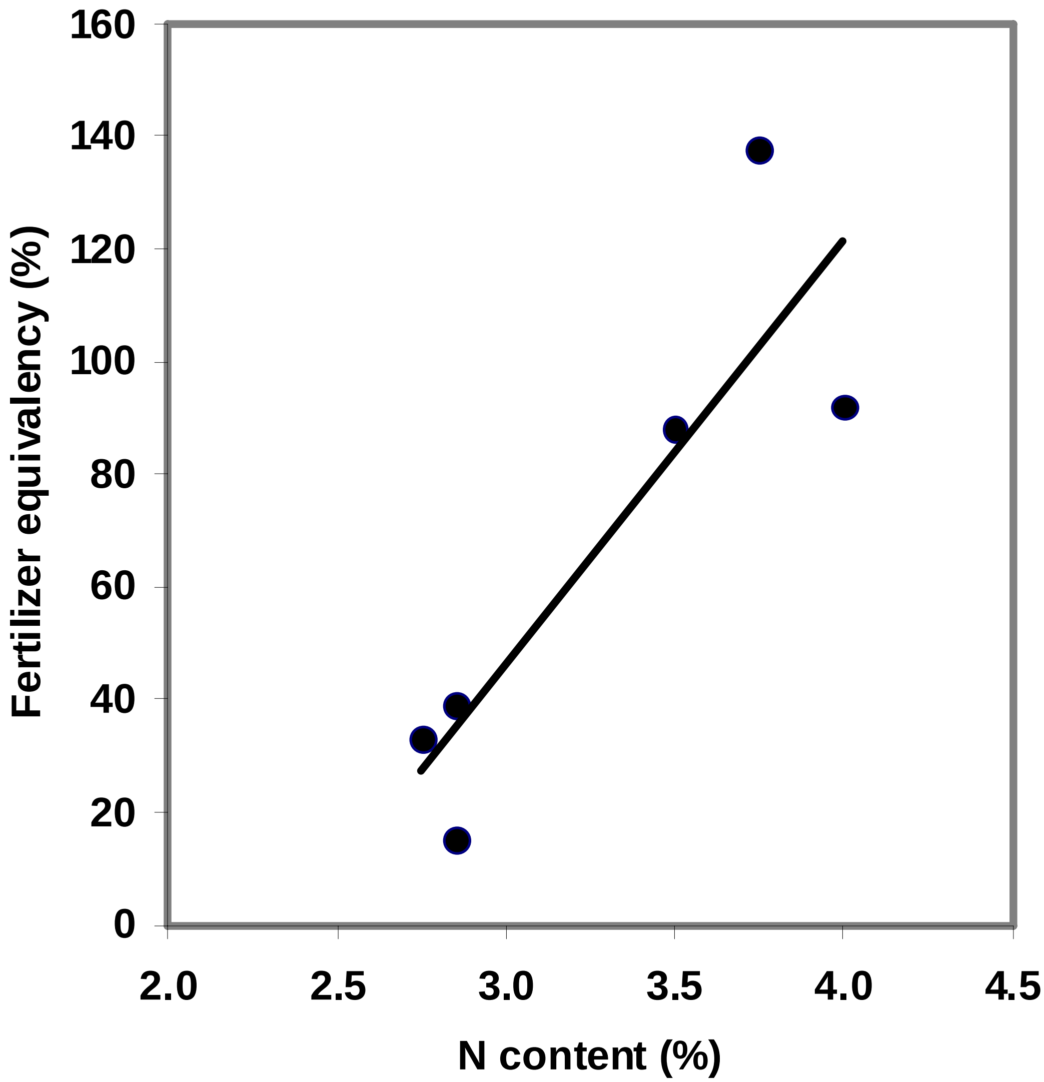

Fig 6. Relationship between percent fertilizer equivalencies and N content of organic materials

Source: TSBF, 2000

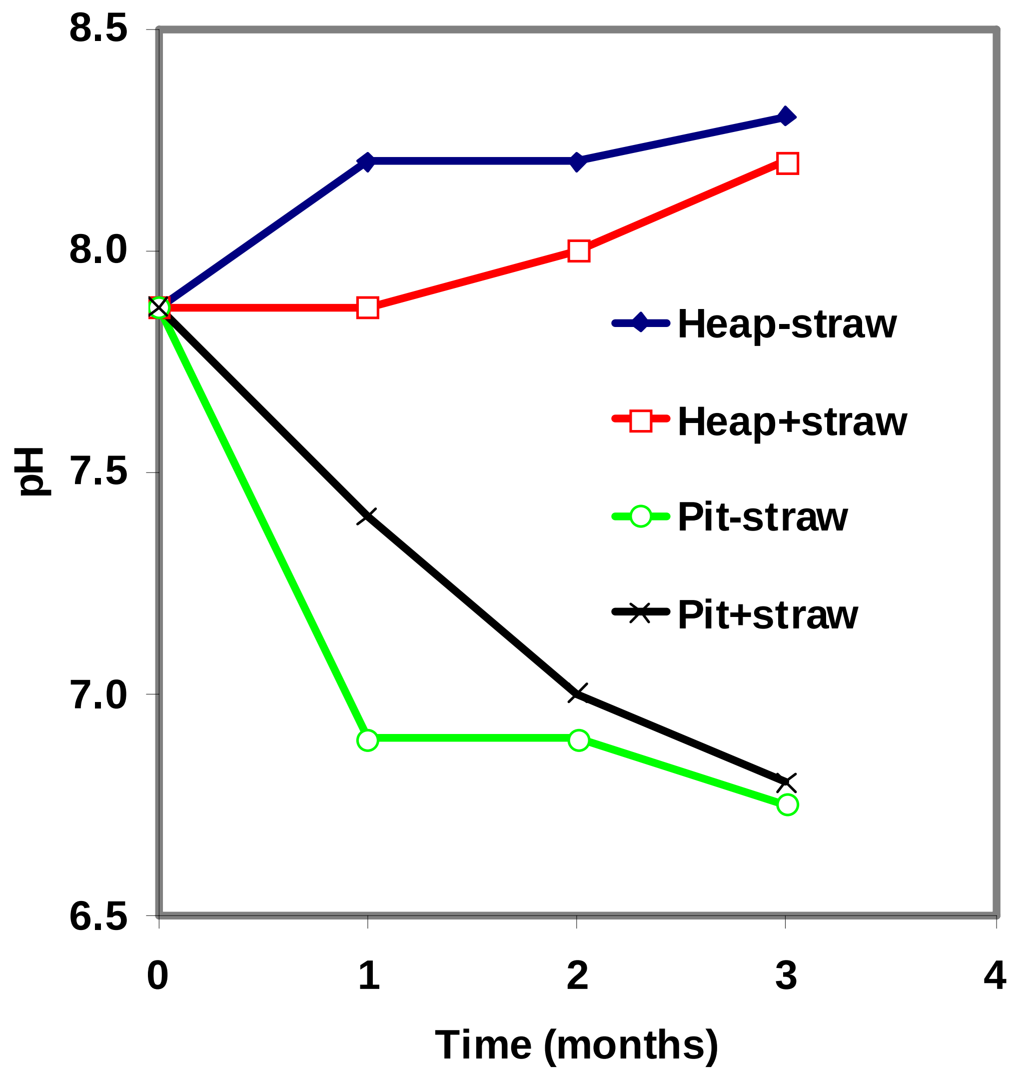

Fig 7. Effects of methods of manure storage and crop residue incorporation on soil pH.

Source: TSBF, 2000

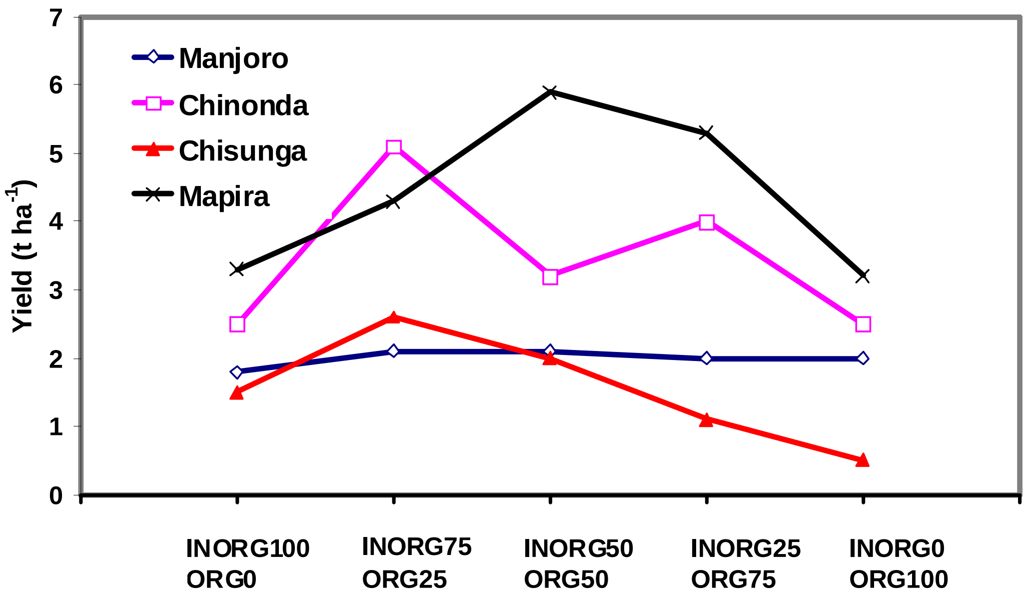

Fig 8. Grain yield obtained from 100kg N applied in different proportions of manure and inorganic fertilizers, Murewa, Zimbabwe.

Source: TSBF, 2000

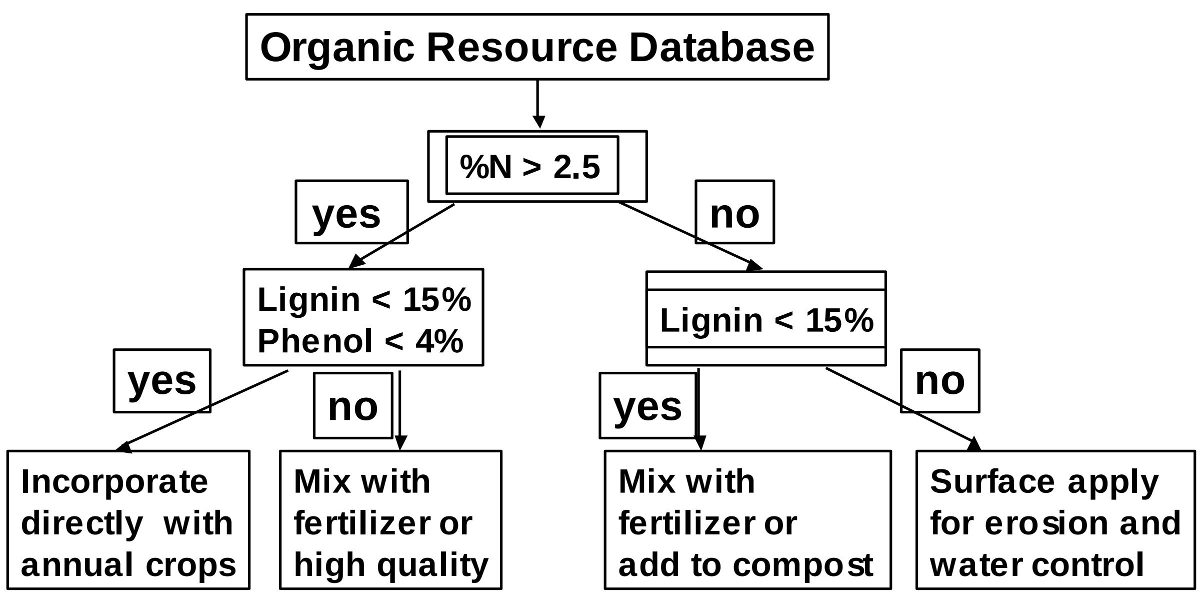

Fig 9. An Organic matter Management Decision Tree for Nitrogen

Source: Cheryl Palm, TSBF 1997