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Some aspects of the role of organic matter in sustainable intensified arable farming systems in the West-African semi-arid-tropics (SAT)

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Abstract

In this paper the role of organic manure in intensified farming systems in the SAT of West-Africa is discussed. Different aspects are treated: its function as a source of plant nutrients, its effects on soil physical and on soil chemical properties. It is concluded that often the major effect is through increased nutrient supply, but that in combination with chemical fertilizer – particularly nitrogen – it serves to counteract the negative effects of these fertilizers, particularly acidification and the increased removal of nutrients other than the one applied in the fertilizer.

Insufficient organic material appears to be available to realize the required production increase and prevent the negative effects of nitrogen fertilizers. However, application of chemical fertilizer alone can lead to sustainable production systems provided export and losses of all nutrient elements are sufficiently compensated and acidification is avoided by using the correct type of nitrogen fertilizer, possibly in combination with liming.

Introduction

Intensified land use in the West-African SAT, associated with increasing population pressure, puts high demands on maintenance and improvement of soil fertility. The demands on traditional systems of shifting cultivation ('cultures itinérantes') have exceeded their limits due to shortage of land, hence they must be replaced by more intensive systems [9, 26].

This problem, which was first encountered in the 50's mainly in the vicinity of urban centres, led to research concentrating on the development of semi-intensive production systems, in which the fallow period was replaced by cultivation of a forage crop, either a perennial grass or a leguminous species. Morel and Quantin [28], summarizing experimental work in the Central African Republic, covering the period 1954–1963, concluded that continuous cultivation using external inputs (mainly chemical fertilizer) was more productive than those semi-intensive systems.

Application of organic manure, alone or in combination with chemical fertilizer, to increase production per unit area, had been considered as early as '46/'47, at several locations in Mali [45]. Long-term fertilizer experiments in which yields and 'soil fertility' were recorded for periods of at least ten years under different rotations and with different fertilizer regimes: without fertilizer, with chemical fertilizer, organic manure, or combinations in the SAT of W. Africa were initiated in the early '60's by the Research Institute for Tropical Agriculture (IRAT). The experiments in Saria (Burkina Faso) cover a period of 29 years [35].

Many of the results of these experiments have been summarized by Piéri [36, 37], who concluded that fertilizer application is an effective means to increase yields in arable farming systems without fallows. However, he cautions that in the long term problems may arise, especially in the drier areas. To substantiate that, he cites Pichot et al. [35]: 'Application of NP and NPK fertilizers results in increased yields for some years, but in the long run it leads to decreasing base saturation and acidification of the soil. These phenomena, associated with the use of N fertilizers, are characterized by increasing K-deficiency, decreasing pH and occurrence of Al-toxicity. Application of organic materials such as green manures, crop residues, compost or animal manure can counteract the negative effects of chemical fertilizers.' This leads Piéri [36] to conclude that soil fertility in intensive arable farming systems in the W.-African SAT can only be maintained through efficient recycling of organic material, in combination with effective use of N-fixing leguminous species and chemical fertilizers. Crop residues should be composted or recycled through the animal, as direct application of material with a high C/N ratio may have negative effects due to immobilization of N during its decomposition (Fig. 1). Application of animal manure or compost, however, generally has a positive effect, also in combination with chemical fertilizer (Table 1).

Annual applications of at least 5 t ha^{-1} of compost or animal manure appear necessary to maintain a constant production level after clearing fallow land, while higher applications are necessary to achieve increased yields [35]. However, limited availability of crop residues is a serious constraint for the production of such quantities of compost, as straw is generally used for other purposes. Evaluation of availability of straw for composting in different regions of Senegal, showed that only in the south a surplus existed of 1 to 2.5 ton ha^{-1} [1]. In all other regions all the straw is being used as animal feed, construction material and fuel. Similar analyses for Burkina Faso led to the same conclusions [41]. Even if all the straw being produced would be used as animal feed, manure production would still be insufficient, and substantial areas of natural pasture would be required to produce the necessary 5 ton of manure per ha of arable land. Quilfen and Melville [38] observed that in the present production systems in the north of Burkina Faso, only 2.5 to 4 ton of animal manure per hectare of arable land is applied. Breman and Traoré [6, 7, 8] showed that feed availability from natural pasture and crop by-products at the present animal density, is insufficient for the production of the manure required to maintain the present production levels in arable farming in Niger, Burkina Faso and Mali, even if all feed would be used for that purpose.

Hence, if on the one hand, compost or animal manure are indispensable to maintain soil fertility, and on the other hand insufficient organic manure is available, it would imply that sustainable arable farming systems, characterized by stable high yields, cannot be developed in the semi-arid tropics of West Africa.

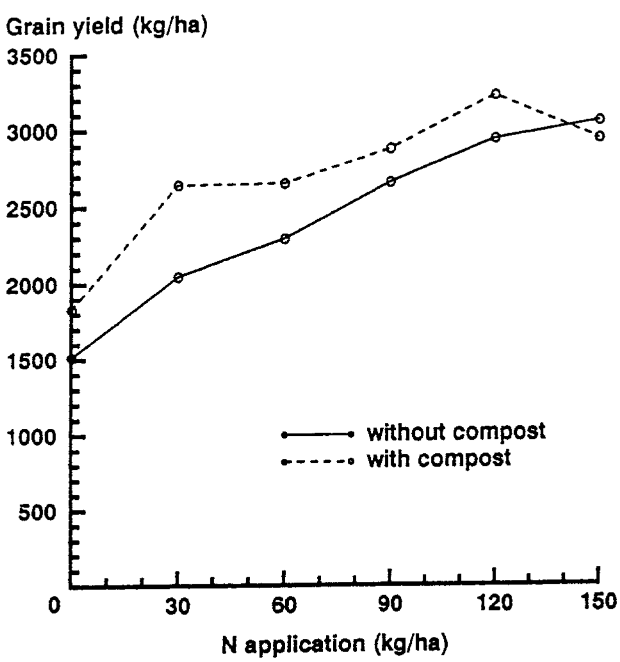


Fig. 1. Grain yield of millet as a function of nitrogen fertilizer application, with (10 t ha^{-1}) and without straw application (Source: Traoré, 1974).

Table 1. Effect of application of different types of organic manure (10 t ha^{-1}) with and without fertilizer N on grain yield (kg ha^{-1}) of millet (Source: Sedogo, 1981)

Treatment	Fertilizer N (kg ha^{-1}) 0	60
no organic manure	1831	2796
sorghum stover	1652	3427
animal manure	2409	3591
compost	2505	3688

In this paper the role of organic manure in maintaining soil fertility is critically evaluated and possible alternatives to avoid the negative effects of chemical nitrogen fertilizers are discussed.

Effects of organic manure

Application of organic manure generally aims at two major goals: (i) increased supply of nutrient elements to the crop and (ii) increased organic matter contents in the soil, resulting in more favourable soil physical and chemical properties. These two goals are conflicting, as release of nutrient elements requires decomposition of the organic material, which is thus lost for the formation of soil organic matter. First the role of organic manure in the supply of plant nutrients will be discussed and subsequently the effect on soil organic matter content will be treated.

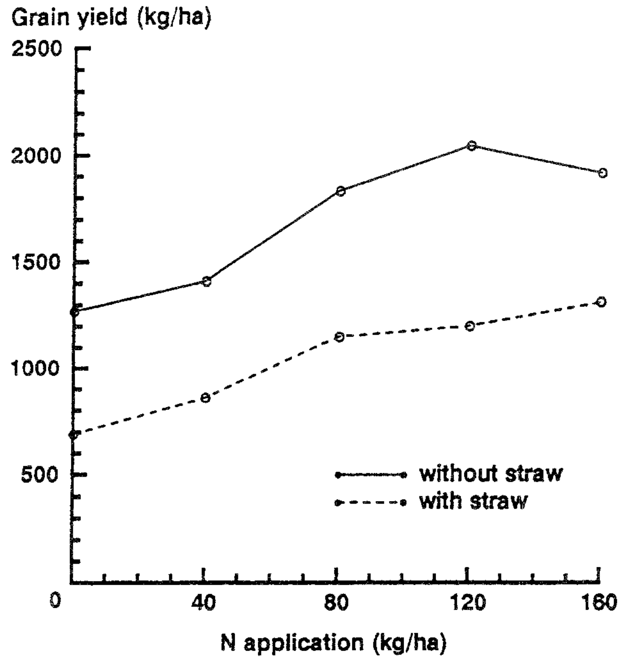


Fig. 2. Grain yield of millet as a function of nitrogen fertilizer application with (11 t ha^{-1} in the first year, 15 t ha^{-1} in the second year, year of observation) and without compost application (Source: Ganry et al., 1974).

Organic manure as a source of plant nutrients

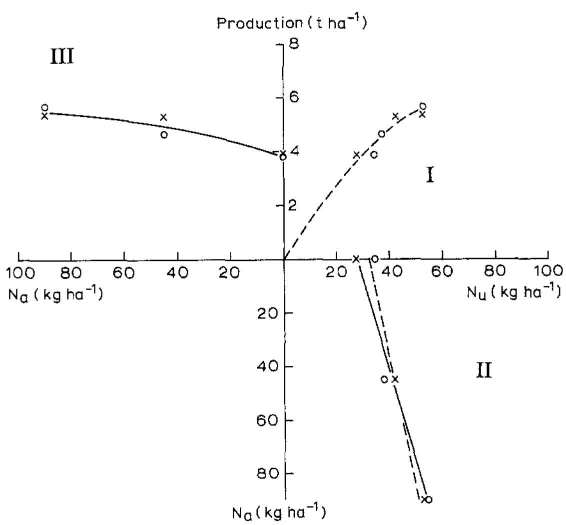
In the last decades, many experiments have been carried out in West Africa to determine crop yields as affected by fertilizer application, with or without organic manure. In analyzing these experiments, generally yields at a certain level of fertilizer application, with and without organic manure application are compared, as illustrated in Figure 2. The yield increase, in this case grain yield of millet, is attributed to the combined positive effects of organic manure on crop growth. The observed variability in response in different experiments is attributed to differences in the quality of organic manure.

In most cases, in the analyses no attempts are being made to differentiate between the quantitative effects of organic manure as a source of additional nutrient elements and possible other positive effects. Such a differentiation is facilitated if, in addition to fertilizer application and crop yield, the chemical composition of organic manure and harvested products have been determined. Availability of those data allows analysis and comparison of application/uptake and yield/uptake relations for different combinations of organic manure and fertilizer application in so-called three quadrant figures [46]. In those figures, the upper left hand side presents the relation between application of a nutrient element and production, the upper right hand side presents the relation between uptake of a nutrient element and production, while in the lower right hand side the relation between application rate and uptake is presented.

To illustrate the method, the results of a nitrogen fertilizer experiment in Niger [34] are presented in Figures 3a-c. The data refer to an experiment with millet, executed during three consecutive seasons on the same plots. The treatments consisted of application of 0, 45 and 90 kg N ha^{-1} as urea, with and without application of 10.000 kg of straw per ha, containing 35 kg of nitrogen. Annual rainfall in the three years of 339, 283 and 296 mm was well below the long-term average of 600 mm yr^{-1}.

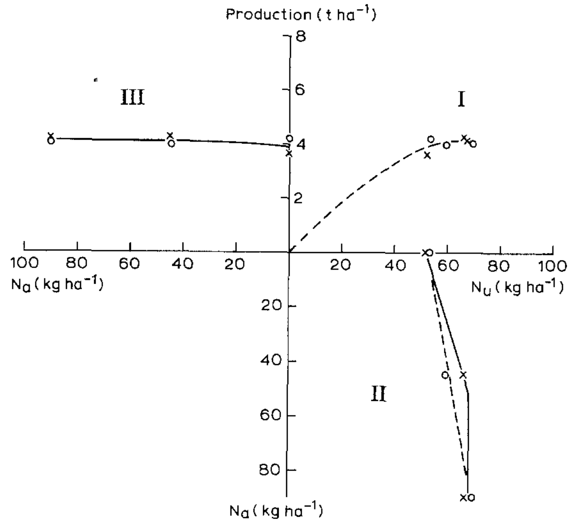
In the first year a linear relation is found between nitrogen uptake and aboveground dry matter production, almost till the highest uptake level (Fig. 3a, II). The relation between application and uptake is linear, both with and without straw, as often found in experiments involving nitrogenous fertilizers [27], but the recovery of fertilizer N is slightly lower (0.21 vs. 0.28) in the presence of straw. Presumably, a larger part of the fertilizer N is not available for uptake, which may be due to immobilization by straw decomposing micro-organisms.

In the second season (Fig. 3b) production hardly responds to increased nitrogen uptake, while the maximum yield is substantially lower than in the preceding season. Apparently, nitrogen availability was not the growth-limiting factor as also witnessed by the very high concentration of N (17.2 g kg^{-1}) in the tissue at harvest at the highest application rates. The presence of straw again affects the relation between application and uptake: uptake at zero fertilizer application is slightly higher in the presence of straw, while the recovery fraction is lower. Without straw, increased fertilizer application from 45 to 90 kg ha^{-1} does not result in higher uptake, presumably because the crop was 'saturated' with nitrogen throughout its growth cycle.

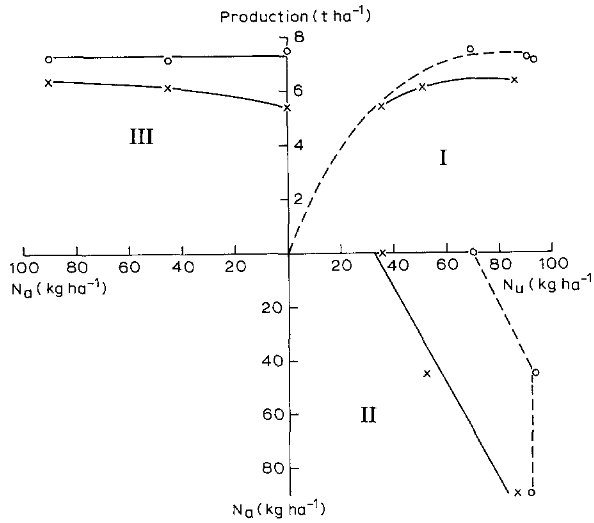


(a)

Fig. 3. The relation between (quadrant I) yield and N application (Ni); that between (quadrant II) N uptake (Nu) and yield and that between (quadrant III) N application and N uptake for millet in three consecutive years, 1971 (a), 1972 (b) and (1973) (c) (Source: Pichot et al., 1974).



(b)



(c)

Fig. 3. (*continued*).

In the third year (Fig. 3c), the highest yield is achieved, with again at the highest application rates no response to increased nitrogen uptake: another factor (nutrients other than N or water availability) appears yield-determining. At the highest uptake levels, production in the combined straw/fertilizer treatments seems somewhat higher than in the fertilizer only treatments, a phenomenon also frequently observed under Dutch conditions with application of organic manure to silage maize [40]. This suggests that the situation with respect to the production-determining factor has improved. This could be the result of the higher organic matter content in the soil under the straw treatments with its associated higher water holding capacity, more favourable pH, improved availability of nutrient elements other than nitrogen, etc. This may be deduced from the results of chemical soil analyses: higher values for organic C, total P, CEC, and base saturation in the soils amended with straw.

The relation between application and uptake shows that in the presence of straw, uptake without fertilizer application is higher by about 35 kg ha^{-1}, while the recovery of fertilizer N differs only slightly (0.56 vs. 0.51). Presumably, some of the nitrogen immobilized in organic material in the preceding seasons is mineralized in this season.

N uptake at zero fertilizer application without straw is intermediate between the first and the second year.

Other fertilizer experiments reported in the literature (not only involving nitrogen, but also phosphorus) have been analysed in a similar way [3, 16, 22, 23, 25, 29, 44, 45]. They are not treated in detail in this paper, but on the basis of those analyses the following conclusions can be drawn:

- higher nutrient uptake due to fertilizer application generally leads to higher yields;
- higher yields obtained with combined application of organic manure and fertilizer, compared to fertilizer alone, can in first instance be explained by the additional supply of the limiting nutrient element. Higher yields obtained with combined application of organic manure and fertilizer, at similar non-limiting uptake levels, may be attributed to the supply with organic manure of nutrient elements other than the one applied in fertilizer or more favourable soil physical or chemical properties;
- recovery of N from fertilizer in the first years is higher in the absence than in the presence of organic manure probably due to immobilization. Part of that N may, however, be released in subsequent years;
- uptake of N from organic manures varies strongly from year to year and is dependent on the quality of the organic material and environmental conditions.

Soil organic matter build-up

Increasing soil organic matter content in cultivated soils in the semi-arid tropical zones of West Africa is tedious, as illustrated, for example, by the results of the long-term experiment in Saria (Burkina Faso). After 18 years of annual applications of 60 t ha^{-1} of animal manure, in combination with 60 kg N, 45 kg P and 25 kg K per hectare, organic C content has increased from 2.5 to about 6.6 g kg^{-1} (or from 4.5 to 12 g organic matter per kg) [35]. Similar conclusions follow from the results of an experiment with a rotation of millet and groundnut, started in 1972 in the north of Senegal. Annually, either chemical fertilizer alone (100 kg NPK, 14-7-7 and 100 kg N as urea) or in combination with 10 ton ha^{-1} of animal manure was applied. In 1983 the soils in this experiment were analysed, showing that organic carbon content in the soils that had received organic manure, was 0.3 g kg^{-1} higher in the upper 10 cm and 0.15 g kg^{-1} in the 10–20 cm layer and was identical below that depth compared to the soils that had received chemical fertilizer only [12]. A further example refers to an experiment in which annual applications of 11.5 ton ha^{-1} of compost and 150 kg fertilizer N ha^{-1} were compared with only return of the millet stover produced. After 4 years, organic carbon was 2 g kg^{-1} higher in the top 20 cm of the soil under the former treatment [19].

To put these results in perspective, in Table 2 an approximate calculation is presented of the amounts of organic material necessary to increase the organic carbon content in the top 20 cm of a soil with a bulk density of 1.4 g cm^{-3} in one year by 1 g kg^{-1}. In the calculations, it is assumed that the relative rate of decomposition of soil organic matter is 0.06 yr^{-1} [24]. Hence, if the original carbon content is 3 g kg^{-1}, 500 kg C ha^{-1} is required to maintain organic carbon at that level. To increase the carbon content by 1 g kg^{-1} an additional 2800 kg ha^{-1} of C is required. The rate of decomposition of organic material added to the soil depends on its quality

Table 2. Schematic calculation of the amounts of straw, animal manure or compost necessary to increase organic C in the top 20 cm of a soil by 1 g kg^{-1} (for details see text)

C loss from existing organic material (kg ha^{-1} yr^{-1}):		500
Required C for increasing carbon content by 1 g kg^{-1}(kg ha^{-1}):		2800
Total C required (kg ha^{-1}):		3300
Relative rate of decomposition of organic material (kg kg^{-1} yr^{-1}):		
- straw	0.5	
- animal manure	0.7	
- compost	0.8	
C content (kg kg^{-1}) in:		
-straw	0.45	
- animal manure	0.35	
- compost	0.30	
Organic material required (t ha^{-1}):		
- straw		14.7
- animal manure		31.4
- compost		55.0

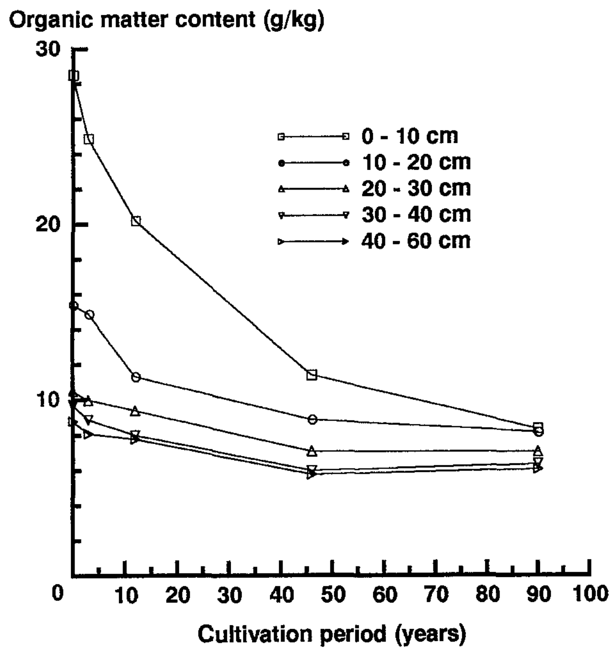


Fig. 4. Organic matter content in various soil layers for soils after different periods of cultivation.

as shown by Van Duivenbooden and Cissé [15], who established losses of 0.4 and 0.6 kg C kg^{-1} over a 90-day period in the growing season, for millet straw and animal manure, respectively. Feller et al. [20], following decomposition of compost in a rainy season of 120 days found a loss of 0.8 kg kg^{-1}. In the calculations of Table 2, relative decomposition rates of 0.5, 0.7 and 0.8 kg kg^{-1} during a 120-day rainy season have been used for straw, animal manure and compost, respectively. The amounts of these materials required to increase the organic carbon content by 1 g kg^{-1} are then 14.7, 31.4 and 55.0 t ha^{-1}, assuming carbon contents of 0.45, 0.35 [14] and 0.3 [18] g kg^{-1}, respectively.

To maintain these higher carbon contents in subsequent years, annual applications of 3000, 6425 or 11250 kg ha^{-1} of straw, animal manure or compost are necessary.

The large amounts of organic material necessary to increase the organic matter content of soils, are largely due to the high rates of decomposition under these conditions. This argument is supported by observations on the dynamics of organic matter following clearing of forest or savanna vegetations. These processes have been studied both in West Africa: Nye and Greenland [30] in Ghana, Brams [5] in Sierra Leone, Fauck et al. [17] and Siband [42, 43] in Senegal (Casamance) and in other parts of the world [39]. In the Casamance, soils under forest were compared with soils that had been under cultivation for periods from 3 to 90 years, with varying fallow periods. Soil organic matter was highest in the soils under forest and lowest in the soils cultivated for 90 years, the differences being most pronounced in the top 20 cm. Soil organic matter content rapidly declines in the first few years following clearing, after which the decrease proceeds more gradually (Fig. 4).

Effect of soil organic matter content on soil physical properties

Organic matter content especially affects the stability of the aggregates formed from the clay and loam particles. The degree of aggregation affects pore volume and pore size distribution, and hence infiltration capacity and soil moisture retention characteristics.

Aggregate stability also influences soil structure, which affects aeration and erosion susceptibility. These effects, however important they may be, are difficult to quantify and are therefore not further treated here.

Cissé and Vachaud [13] studying the water balance of the soils from the experiment in northern Senegal, referred to earlier, concluded that the differences in organic carbon content were too small to cause significant differences in soil hydraulic properties: infiltration capacity, soil moisture retention curve (Fig. 5) and hydraulic conductivity curve are similar for soils differing 0.15–0.3 g kg^{-1} in organic C.

More pronounced differences in organic C may not substantially affect moisture availability for a crop. The difference in available soil moisture between the forest soils and the soils long under cultivation (Fig. 4; [43]) is only some tenths cm^3cm^{-3} (Table 3). The differences in total available water probably are also related to the lower clay and loam contents in the upper layer of the soils under cultivation, as a result of migration to deeper layers.

Table 3. Moisture content ($cm^3\ cm^{-3}$) at pF 2.5, pF 3.0 and pF 4.2 and available soil moisture ($cm^3\ cm^{-3}$) between pF 2.5 and pF 4.2 and between pF 3.0 and pF 4.2 for forest soils and soils under cultivation for various periods (Source: Siband, 1974).

	Forest soil	Length of period under cultivation (yr)			
		3	12	46	90
pF 2.5:					
0–10 cm	11.4	10.4	9.7	7.5	7.2
10–20 cm	9.7	9.7	9.8	9.7	8.9
pF 3.0:					
0–10 cm	9.6	8.2	7.6	6.2	5.5
10–20 cm	8.0	7.5	8.1	9.7	7.1
pF 4.2:					
0–10 cm	7.5	5.9	6.0	4.6	3.9
10–20 cm	5.4	5.2	6.6	6.5	4.8
pF 2.5–pF 4.2:					
0–10 cm	3.9	4.5	3.7	2.9	3.3
10–20 cm	4.3	4.5	3.2	3.2	4.1
pF 3.0–pF 4.2:					
0–10 cm	2.1	2.3	1.6	1.6	1.6
10–20 cm	2.6	2.3	1.5	3.2	2.3

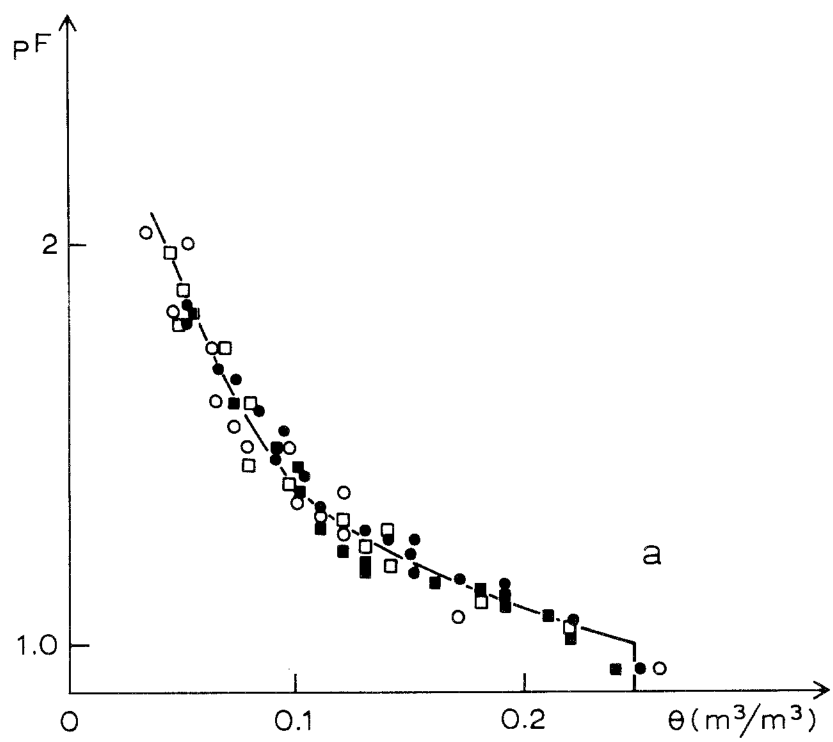


Fig. 5. Soil moisture retention curve for the top soil layers of sandy soils differing 0.3 (0–0.1 m) and 0.15 (0.1–0.2 m) g kg^{-1} in organic C content.

These considerations lead to the conclusion therefore, that the difference in maximum yield observed in the experiment in Niger (Fig. 3c, II), where the difference in organic C content was $1\,g\,kg^{-1}$ after 3 years, is not likely to be the result of differences in moisture availability.

Effect of organic matter content on soil chemical properties

The most important soil chemical characteristic affected by soil organic matter content is its cation exchange capacity (CEC), which in addition is determined by its clay content and the mineralogical composition of the clay fraction. In his review, Pichot [33] points out that in tropical soils, whose clay fraction is dominated by kaolinite and Fe and Al oxides and hydroxides, soil organic matter content is the major factor influencing cation exchange capacity. This conclusion is based on results from Senegal [42], Ivory Coast [10], the Central African Republic [32], Burkina Faso [2] and Niger [11, 34], where significant positive correlations were observed between organic matter content and CEC.

To quantify the effect of changing organic C contents in the soil, either through organic manuring, or through prolonged cultivation, on CEC, a relation between the change in C content and the associated change in CEC is necessary. For construction of that relation results from the north [12] and south [43] of Senegal, Niger [34] and Burkina Faso [35] were used, leading to a significant correlation (Fig. 6). A difference of $1\,g\,kg^{-1}$ in organic C results in a difference of $4.3\,mmol\,kg^{-1}$ in CEC (pH 7), a value within the range (3.64–5.46) presented by Bolt et al. [4]. The residual variability must be ascribed to differences in origin, nature and quality of the organic material.

At higher CEC values the buffering capacity for cations such as K, Mg and Ca is higher. Exchange of cations with Al^{3+} and H^+ lowers base saturation, but also counteracts decreasing pH. Hence, CEC serves as a buffer for pH changes.

Application of organic manures not only supplies N and P, but other important elements like K, Mg and Ca as well, which contribute to

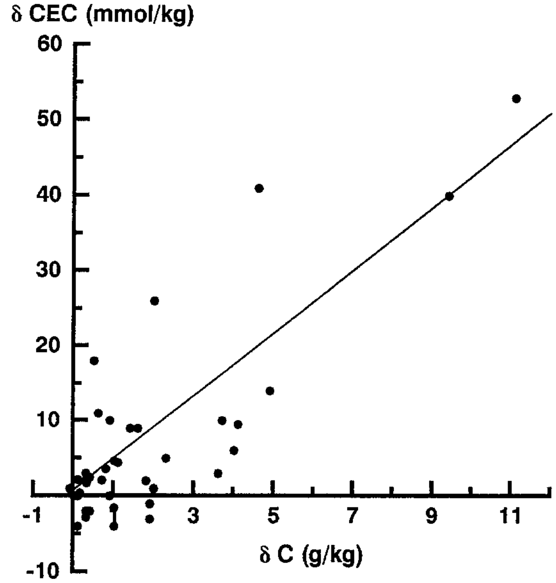


Fig. 6. Change in cation exchange capacity (δ CEC) as a function of change in organic C content (δ C) (Sources: Cissé, 1988; Pichot et al., 1981; Pichot et al., 1974; Siband, 1974).

maintaining base saturation at a high level. The positive relation between pH and base saturation has, among others, been illustrated by Pichot ([32], Fig. 7).

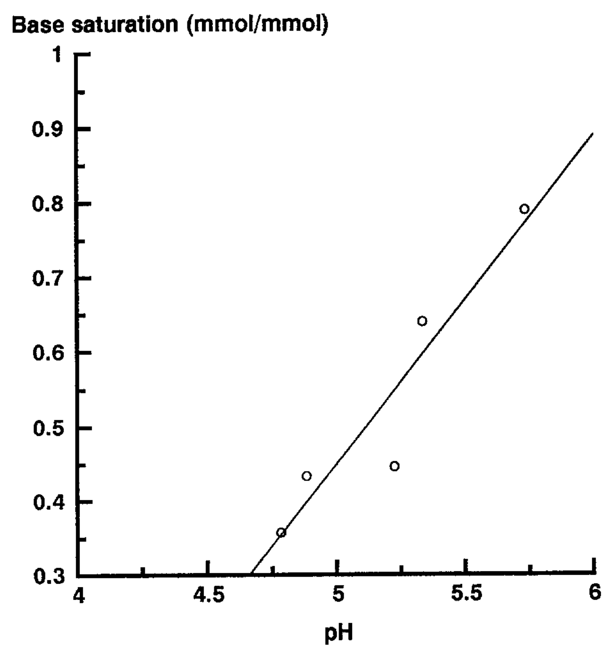


Fig. 7. Relation between pH and base saturation (Source: Pichot, 1971).

Long-term effects of fertilizer application

In a number of reported fertilizer experiments the positive response to increased nutrient availability declines with time when only chemical fertilizers are applied as demonstrated in the long-term experiment in Saria, Burkina Faso [35]. In that experiment, started in 1960, sorghum is cultivated in monoculture or in rotation with groundnut and niébé, under different fertilizer regimes: chemical fertilizer only (two levels), and in combination with 5, respectively 40 t ha^{-1} of animal manure. The amounts of N and P given annually, varied over the years, while since 1969 K fertilizer has been applied. Over the first 19 years, these amounts were on average 25 kg N, 30 kg P and 10 kg K per hectare at the lower level and 60 kg N, 45 kg P and 25 kg K at the higher level.

Sorghum grain yields in the control plots declined within a few years to about 150 kg ha^{-1}. After 1970, yields in the treated plots also decreased: first that in the high fertilizer only treatment, followed by the lower fertilizer only, and by the treatments with the low manure application rate. Only in the high manure/high fertilizer treatments yields remained stable.

Results of soil chemical analyses carried out in 1978 (some of which are given in Table 4) serve as the basis for the explanation of the yield decline [35]. Organic C content in the fertilizer only plots is lower than in the control, while in the plots receiving organic manure, it is much higher. CEC (pH 7) varies little among treatments, except for the plots with the highest application of organic manure. Base saturation clearly differs: in the fertilizer only treatments significantly lower than in the control, in the manure plots higher. pH is related to base saturation, hence lower than the control in the fertilizer only plots and higher in the animal manure plots. The lower pH and base saturation must be attributed to the acidifying effect of the fertilizer (most probably ammonium sulphate and/or ammonium phosphate).

Pichot et al. [35] explain the declining yields through these low pH values. Small differences in pH in the vicinity of pH 5 can have dramatic effects: Al ions can be liberated from the clay lattice, and preferentially be adsorbed at the exchange complex. At pH values below 5.2 the concentration of Al in the soil solution sharply increases (in the plots receiving only fertilizer, up to 50 mg l^{-1}), with toxic effects on the crop. Yield reductions of 80% have been observed at 50% Al at the complex [35].

Alternatively, the yield reduction could be due to K deficiency. The potassium supply with fertilizer may not have been sufficient to compensate for the export in grain and straw. An indication could be that exchangeable K is lower in the fertilizer only plots than in the control. Application of organic manure provides K and other cations, thus counteracting the decline in base saturation and preventing acidification and hence Al toxicity. However, large amounts of organic manure are required, as in the plots receiving 5 ton ha^{-1} of animal manure pH still approaches critical values of around 5.

The results of chemical analyses of the soils from the Niger experiment are comparable to those of Saria (Table 5): application of chemical fertilizer only (in this case urea) leads to a decline in pH (although the critical value of 5 is

Table 4. Organic carbon content (g kg^{-1}), CEC (mmol kg^{-1}), base saturation (fraction), exchangeable K, Ca en Mg (mmol kg^{-1}), and pH (water) for soils from experiments in Saria, Burkina Faso (Source: Pichot et al., 1981)

	C content	CEC	Base saturation	Exchangeable cations			pH
				K	Ca	Mg	
Control	2.5	26.5	0.63	1.6	11.5	3.5	5.2
Chemical fertilizer:							
low	2.4	26.5	0.37	0.9	6.6	2.2	4.6
high	2.4	25.0	0.38	1.5	6.0	2.1	4.4
5 t ha^{-1}: chemical fertilizer low	3.5	25.0	0.70	2.2	11.4	3.9	5.2
40 t ha^{-1}: chemical fertilizer high	6.6	39.4	1.00	5.0	23.7	10.7	5.9

Table 5. Organic carbon content (g kg^{-1}), CEC (mmol kg^{-1}), base saturation (fraction), exchangeable K, Ca en Mg (mmol kg^{-1}) and pH for soils from the experiments in Tarna, Niger (Source: Pichot et al., 1974)

	C content	CEC	Base saturation	Exchangeable cations			pH
				K	Ca	Mg	
Control	1.6	11.8	0.9	0.4	8.5	1.7	6.1
90 kg N ha^{-1}	1.8	12.1	7.2	0.5	6.8	1.4	5.5
10 t straw ha^{-1} + 90 kg N ha^{-1}	1.8	16.7	9.3	1.8	10.7	3.1	6.2

not yet reached). The differences in maximum yield between the fertilizer only plots and those receiving also organic manure could indicate that problems similar to those in Saria can be expected in the long run.

Discussion

To achieve food self-sufficiency for a growing population in West-Africa, the only solution is increased production per unit area. Agricultural research has shown convincingly that to achieve that goal, improved nutrient availability – in addition to other cultural measures – plays a key role [31].

Nutrient supply for the crop can be improved by applying either chemical fertilizer or organic manure, resulting in increased production of both marketable product (grains) and crop residues (stover, straw). Larger amounts of organic manure than of chemical fertilizer are required, as their element concentration is lower than that of chemical fertilizers. Moreover, the rate of nutrient supply from organic manures is slower, as the organic material must be decomposed to release the nutrient elements which also makes timing of nutrient availability uncertain. On the other hand, organic manures contain various nutrient elements, while most commonly used chemical fertilizers specifically supply only N and P, and sometimes K. Availability of organic manures is a limitation, while the price of chemical fertilizers may be prohibitive for application.

Agricultural research faces the challenge to answer the question which combination of fertilizers is most efficient for production increases. It is important to realize that intensive systems should also be sustainable. Considering the results presented earlier, two major problems appear:

- use of chemical NP fertilizers without organic manure, or without liming and K and possibly Mg fertilizer application, may result in acidification of the soil, with the associated risk of Al toxicity and deficiencies of other nutrient elements.
- availability of organic manures is insufficient to realize the required production increase and to prevent in combination with chemical fertilizers soil acidification.

In most of the fertilizer experiments cited in this paper it was common practice to remove in the fertilizer only treatments all the biomass from the field. That leads to declining organic C levels in the soil with the associated reduction in CEC. With the organic material substantial quantities of N, P and other minerals are removed, which is insufficiently compensated if only chemical NP fertilizers are applied. That results in decreasing base saturation and a lower pH. To assess which practices can result in sustainable production systems, quantitative assessment of the following aspects is necessary:

- Is the production increase in crop residues, associated with the use of chemical fertilizers sufficient and necessary to stabilize soil organic C content?
- Are the losses of C and nutrient elements incurred during transformation of crop residues to compost or animal manure compensated by the greater availability of the remaining elements and the added value of the material as animal feed or as a source of energy (biogas)?
- Does a minimum soil organic C content exist for a given level of fertilizer application and production?
- Which mixture of chemical fertilizers is necessary to maintain the base saturation at a

favourable level, taking into account possible supply of cations through crop residues, animal manure or compost?

- What is the optimum pH value for a given production systems and to what extent is liming necessary to maintain that pH?

To provide quantitative answers to these questions, determination of more nutrient response curves is hardly helpful. Target-oriented experiments are necessary in which production and nutrient uptake (of both grain and straw) are determined for different doses of various chemical fertilizers and organic materials, applied alone and in combination with lime application.

Evidently, in ensuring sustainability of intensified production systems, the equivalent acidity of fertilizers is a major consideration. If ammoniacal fertilizers are used, they must be combined with liming to maintain soil pH at a favourable level. Rock phosphates, with their inherent impurities, not only serve as a source of P, but may also help in maintaining a sufficiently high base saturation [21]. In combination with nitrate fertilizers also soil pH can be maintained. Hence, judicious application of chemical fertilizer may lead to sustainable intensified agricultural production systems in W. Africa, provided that their use is not prevented by economic considerations.

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