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THE ROLE OF CATTLE MANURE IN ENHANCING ON-FARM PRODUCTIVITY, MACRO- AND MICRO-NUTRIENT UPTAKE, AND PROFITABILITY OF MAIZE IN THE GUINEA SAVANNA

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SUMMARY

An on-farm trial was conducted in the northern Guinea savanna of Nigeria, over a period of five years, with the objectives of quantifying the effects on maize of applying cattle manure in combination with synthetic fertilizer with regard to soil characteristics, yield, plant nutrition and profitability. Maize grain yield was significantly increased by the annual application of cattle manure, compared to maize receiving an equal amount of N through synthetic fertilizer, but only from the third year of the experiment. The application of manure resulted in higher soil Kjel N, Bray-I P and exchangeable K values, and an increased N utilization efficiency by maize, suggesting that yield-limiting factors other than N deficiencies were of lesser importance than in the treatment receiving sole inorganic fertilizer. Nutrients other than N applied via the manure, particularly P, K and/or B, may have contributed to the higher grain yields in treatments receiving manure. A partial budgeting analysis revealed that, over a 5-year period, investments in the application of manure, in combination with synthetic fertilizer, resulted in higher margins than the application of fertilizer alone. However, analyses of marginal rates of return of changes from low urea N to high urea N or additional manure applications suggested that it was more profitable to invest in additional urea than in organic manure in the first two years of the experiment. The results suggested that manure applications, even when applied at relatively high rates, did not serve as a quick fix to on-farm soil fertility problems, but over a longer period, manure applied in combination with synthetic fertilizers did provide a significant and profitable contribution to enhanced cereal production.

INTRODUCTION

In many parts of the Guinea savanna of West Africa, the intensification of cereal-based farming without the application of appropriate nutrient inputs has led to stagnating or declining productivity of staple cereals such as maize (*Zea mays*), sorghum (*Sorghum bicolor*) and millet (*Pennisetum glaucum*) (Bationo *et al.*, 1998). Increased application of organic inputs, along with appropriate rates of synthetic fertilizers, is considered key to maintaining soil fertility and productivity in intensifying cropping systems. The application of organic inputs alone is not a feasible option to combat poor soil fertility.

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Besides the limited availability of organic inputs, these inputs are not full substitutes for synthetic fertilizers (Vanlauwe and Giller, 2006).

Plant residues that can serve as organic input are generally scarce in the Guinea savanna. Over the dry season, most plant biomass left in the field from the previous cropping season is lost due to strong winds, free-roaming ruminants, bush fires and termites (Schulz *et al.*, 2001). Agro-forestry systems, having the potential to provide large quantities of plant biomass at the start of the cropping season, have never been widely adopted in the savanna due to labour constraints (Douthwaite *et al.*, 2002). Animal manure represents the main source of organic inputs for many farmers in the Guinea savanna. With a rapidly growing demand for livestock products, livestock production by mixed crop–livestock farmers has increased in areas that have access to urban markets, providing opportunities for increased manure field applications (Tarawali *et al.*, 2004; Tiffen, 2004). Consequently, many agricultural development organizations and other extension groups in the area consider promoting the use of manure among farmers a priority.

Studies have frequently reported that the combined application of organic inputs and synthetic fertilizer in cereals, as compared with the application of synthetic fertilizers alone, result in synergistic, positive effects on cereal yield and soil fertility status (Agbenin and Goladi, 1997; de Ridder and van Keulen, 1990; Iwuafor *et al.*, 2002; Vanlauwe *et al.*, 2001, 2002). These synergistic effects are likely to be the result of a combination of factors, although the exact mechanism often remains uncertain. Applications of organic inputs affect the availability of N for plant uptake. Part of the N supplied through organic inputs is immobile and not directly available for plant uptake. Organic inputs, especially those with a high C/N ratio, may immobilize some of the N supplied through synthetic fertilizers. When immobilized N is mineralized over the course of the growing season, an improved synchrony between soil N availability and plant uptake may result in a higher N use efficiency of applied fertilizer (Powell *et al.*, 1999). Organic inputs may also enhance crop yield by providing nutrients that are in short supply and provided insufficiently by synthetic fertilizers. Nutrients other than those usually supplied by synthetic fertilizers, such as S, Zn and Ca, are likely to limit cereal production in parts of the Guinea savanna (Agbenin, 2003; Friesen, 1991; Kang *et al.*, 1981; Ojeniyi and Kayode, 1993). However, the extent to which these nutrients limit crop yields, and the role organic inputs may play in relieving them, are poorly documented. Another benefit associated with the use of organic inputs is the build-up of soil organic matter, resulting in improved physical and chemical characteristics of the soil. The build-up of the soil organic matter pool may lead to improved moisture retention, higher cation exchange capacity and a higher soil pH, which may mitigate acidifying effects of synthetic fertilizer (de Ridder and van Keulen, 1990). Many of these potential benefits, related to soil organic matter dynamics, are difficult to quantify, as the effect of applying organic inputs on the soil organic matter pool is usually small.

Most studies in the Guinea savanna on the impact of applications of organic inputs, often along with synthetic nutrient sources, on cereal yield and soil characteristics have been conducted on-station (Agbenin and Goladi, 1997; Heathcote, 1969; Jones, 1971, 1976; Vanlauwe *et al.*, 2002), and only few on-farm (Franke *et al.*, 2004; Iwuafor *et al.*, 2002). In this region, crop yields on farmers' fields are generally far below yields observed in on-station trials. Also, the response of cereals to the application of synthetic fertilizer and organic inputs on farmers' fields is generally far below that obtained on-station, which affects the profitability of investments in nutrient inputs. Therefore, it is necessary to test nutrient management strategies under realistic on-farm conditions. Furthermore, the role of nutrients other than N, P and K has often been neglected in studies on the impact of organic inputs on cereal yields in the Guinea savanna. Also, the reported experiments did not include economic analyses of nutrient management strategies. This is especially relevant since manure is not regarded as a free commodity, as reflected by the growing role of manure sale and exchange between farmers in the area.

The present trial was conducted on the performance of maize on farmers' fields with typical infertile lixisols, over a period of five years. The objectives were to quantify the effects of applying cattle manure in combination with synthetic fertilizer on (i) soil characteristics, (ii) maize yield, (iii) maize nutrient uptake and (iv) profitability, as compared with maize receiving sole synthetic fertilizer and farmers' traditional practice.

MATERIALS AND METHODS

The experiment was established on eight farmers' fields in Mahuta village (11°11′N, 07°38′E), Kaduna State, Nigeria, in the northern Guinea savanna, from 1999 to 2003. This intensively farmed area is situated near the urban centres of Kaduna and Zaria. The growing season in this area typically lasts 150–180 days from late May until October, and the long-term mean annual rainfall is 1050 mm. The soil type is a sandy loam and is classified as a Haplic Lixisol (six blocks) and Ferric Lixisol (two blocks) (FAO, 1988). The number of participating farmers went down from eight to seven in 2000 and to five in 2003 (Table 1). Reasons for abandoning the trial included sickness of the farmer and the desire to grow crops other than maize at the experimental site. The experimental design was a randomized complete block design with every farmer having a set of five treatments (T1–T5), as well as an adjoining farmers' practice (FP). Prior to the establishment of the trials, plots were cultivated with cereals for at least three years, occasionally followed by tomatoes or cowpea as a relay crop. During the experiment, maize was grown annually on all experimental plots, receiving 50, 100, or 150 kg N ha^{-1} as cattle manure and/or urea. In the FP, farmers were free to decide on fertilizer use. The treatments were:

FP Farmers' practice
T1 50 kg N ha^{-1} as urea (50N urea)
T2 100 kg N ha^{-1} as urea (100N urea)
T3 150 kg N ha^{-1} as urea (150N urea)
T4 50 kg N ha^{-1} as urea and 50 kg N ha^{-1} as cattle manure (50N urea + 50N CM)
T5 50 kg N ha^{-1} as urea and 100 kg N ha^{-1} as cattle manure (50N urea + 100N CM)

Table 1. Number of participating farmers, planting and harvest periods of maize in Julian day numbers, and mean application rates of N, P and K in the farmers' practice (FP), with minimum and maximum values given in parentheses.

Year	No. of farmers	Planting period	Harvest period	Fertilizer rate in FP (kg ha^{-1}) N	P	K
1999	8	157–165	302–311	31.3 (14.4–53.3)	5.1 (1.6–9.8)	10.1 (3.1–18.8)
2000	7	152–161	315	48.9 (7.9–118.5)	4.7 (0.8–6.5)	8.3 (0–18.8)
2001	7	142–144	284–293	25.8 (15.3–57.0)	3.9 (1.6–9.8)	7.5 (3.1–18.8)
2002	7	161–171	319	27.3 (11.4–49.3)	4.3 (2.4–11.4)	8.3 (4.7–21.9)
2003	5	170–176	288–289			

All treatments, except for the FP, received a blanket application of P as triple super phosphate and K as muriate of potassium at 17 kg P ha^{-1} and 33 kg K ha^{-1}. These fertilizers were broadcast manually before ridging and planting. In T4 and T5 manure was applied in the furrows of the old ridges and covered with soil when new ridges were formed. N in the form of urea was spot-applied in two applications: 50% at two weeks after planting (WAP) and the remaining at 6 WAP. The participating farmers provided cattle manure from their homesteads for application in T4 and T5. This manure was produced over the dry season and stored in bags until planting time. In 2002, the manure originated from lot-fed cattle from the National Animal Production Research Institute (NAPRI). The quantity of cattle manure applied varied from year to year, depending on its N concentration. Plots were 72 m^2 in size (12 rows of 8 m length). Maize was grown with an inter-row distance of 0.75 m and a plant-to-plant distance of 0.25 m ($\sim$ 53 333 plants ha^{-1}). The maize variety, Across97 TZL Comp. 1-W, is an open-pollinated, long-duration variety recommended in this area as tolerant to infestations of the weed *Striga hermonthica*. Plots were weeded at 2 and 5 WAP using ox-drawn implements. Planting and harvest dates are given in Table 1.

In the experimental plots, maize yield was determined by harvesting 10 centre rows of 7 m length, leaving 0.5 m at both ends of the row. Plant density was assessed. Cobs were removed from the harvested plants, weighed and shelled. The fresh weight of stalks, empty spindles and grain was determined. Four random subsamples of maize stalks, empty spindles and grain were used for dry matter determination through oven drying at 65 °C to constant weight. After harvest, crop residues remaining in the plots were removed.

The FP was assessed from the field surrounding the experimental block. All farmers cultivated a main crop of maize on the surrounding field, but were free to select the variety, to relay cowpea into the maize at the end of the season, and to choose the type and quantity of organic inputs and synthetic fertilizers. All cultural operations were done by farmers following standard practice. This involved ridging and twice remoulding the ridges for weed control during the season. Yield and other crop parameters were measured in six randomly selected subplots of 4 m × 4 m. The entire subplot was harvested and subsequently analysed using a similar method to the experimental block. After harvest, crop residues remained on the field, but much

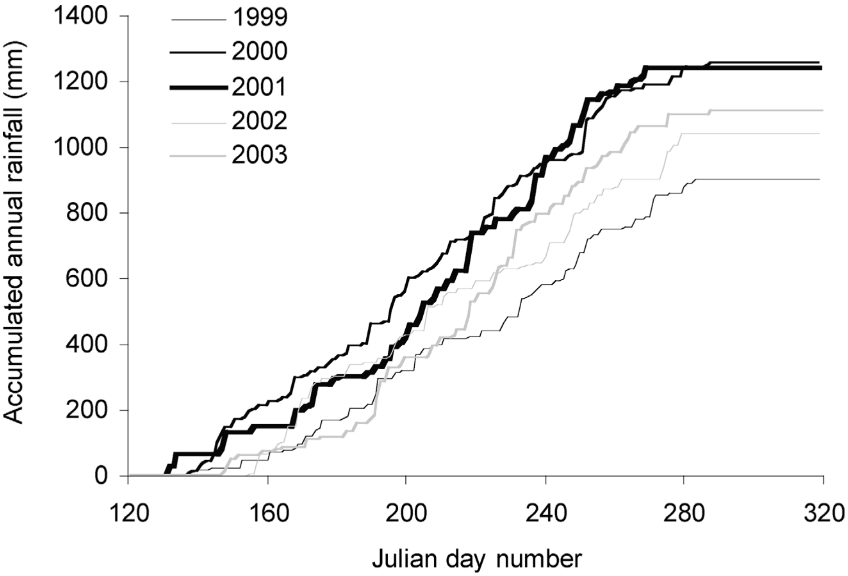

Figure 1. Accumulated annual rainfall in 1999–2003.

of the residues disappeared over the dry season. Annual interviews with farmers provided data on nutrient management in the FP. In 2003, four farmers decided to grow sorghum instead of maize on their FP, because fertilizer prices were relatively high and farmers reckoned sorghum performs better than maize on poorly fertilized soil. Therefore, no data on maize yield could be obtained from the FP in 2003.

Plant and soil analyses

Total plant N concentration was determined from grain and stover samples harvested in 2003 using hot acid digestion (Novazamsky *et al.*, 1983) followed by colorimetric analysis using the indophenol blue method (Searle, 1984). The concentrations of nutrients other than N were assessed from composite samples of grain and stover harvested in 2003 using radial CIROS inductively coupled plasma atomic emission spectrometry (ICPAES) by Waite Analytical Services, University of Adelaide, Australia, in 2005. Nutrient concentrations of cattle manure applied in the experiment was analysed using ICPAES in a similar manner. Soil samples were taken in May 2004 at the end of the experiment. In each plot, 12 subsamples were taken halfway up the slope of the ridges of the previous year at depths of 0–12 cm and 12–24 cm using a soil auger 22.5 cm in diameter. Soil pH (H_2O, 1:1 soil to water ratio), soil organic C (Walkley-Black method), total N (Macro-Kjeldahl method), Bray-I available P, exchangeable K, Ca and Mg and soil particle size were determined at the International Institute of Tropical Agriculture's analytical services laboratory (IITA, 1981). Soil nutrient and organic C content ($\mathrm{g\,kg^{-1}}$) were converted to a soil mass basis (Ellert and Bettany, 1995) with soil reference mass of 1950 $\mathrm{t\,ha^{-1}}$, representing an average soil layer down to a depth of 15 cm. Rainfall was recorded daily at Mahuta village (Figure 1).

Table 2. Farm gate prices of fertilizer, manure and maize grain, and manure application costs, used in the partial budgeting study.

	1999	2000	2001	2002	2003
Fertilizer farm gate price (US \$ kg^{-1})					
N	0.28	0.29	0.30	0.34	0.45
P	0.65	0.67	0.69	0.78	1.04
K	0.34	0.35	0.36	0.41	0.54
Maize grain farm gate price (US \$ kg^{-1})	0.15	0.17	0.23	0.17	0.16

Partial budgeting study

A partial budgeting study was conducted by comparing the value of the grain produced in 1999–2003 and subtracting the costs that varied among treatments; these were fertilizer, manure and manure application costs. Other costs, such as seed, crop protection and labour for operations other than manure application, were assumed to be similar among treatments. Since this assumption was invalid for the FP, and 2003 yield data from the FP were lacking, this treatment was excluded from the economic analysis. Crop values were based on the mean farm-gate price of grain in the three months after harvest (Table 2). Grain prices generally increase later after harvest, but few farmers are able to store their produce and sell when market prices are higher. Fertilizer prices were based on farm-gate prices at planting (Table 2). An economic analysis of farming systems in nine villages in Kaduna State (Wallays, 2003) was used to estimate cattle manure farm-gate price (10.4 US \$ t^{-1}) and application costs (5.2 US \$ t^{-1}). In the present analysis, manure N concentration was assumed to be 1.3%, which equalled the mean concentration of farmers' manure in the experiment, giving an application rate of 3.8 t ha^{-1} y^{-1} in T4 and 7.7 t ha^{-1} y^{-1} in T5. In the base case scenario of the partial budgeting study (Table 9), the 2003 crop and fertilizer prices were used. Marginal rates of return of changes from T1 (50N urea) to the other treatments are presented. In addition, a sensitivity analysis was conducted to assess the effects of the availability of free manure (including manure application costs only), changing maize and fertilizer prices, and discounting future costs and benefits. Maize and fertilizer prices in the sensitivity analysis were both varied by 40%, reflecting the observed price variation in 1999–2003 (Table 2). Discount rates were set at relatively high annual rates of 10 and 30% reflecting farmers' reluctance to invest resources in farming methods that do not provide a rapid return. All costs and benefits were converted to 2003 US dollars.

Data analyses and presentation

Maize yield, harvest index, soil parameters and plant nutrient concentration and uptake were statistically analysed using analysis of variance techniques with the software package of SAS, version 8 (SAS Institute, 1989). The fertilization regime was treated as a fixed effect, and year and replicate (nested in year) as random effects. Contrast probabilities based on least square means were calculated to allow pair-wise comparison of treatments. Variations between treatments were considered significant

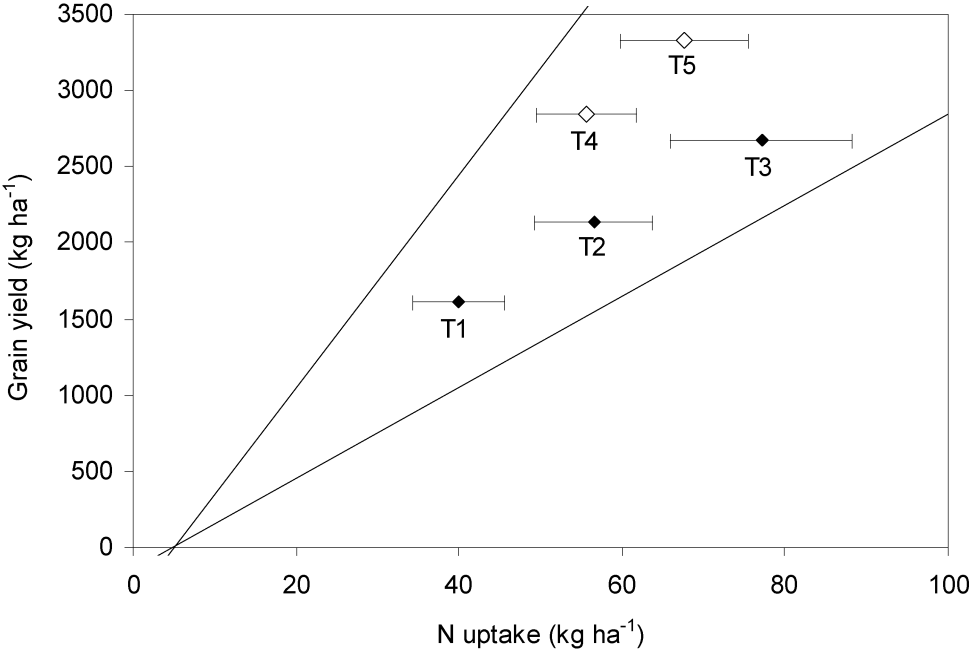

Figure 2. Relationship between maize grain yield and N uptake in 2003 and the standard errors associated with N uptake. The upper line in the graph represents the theoretical yield with maximum dilution of N and the lower line that with maximum accumulation of N (Janssen *et al.*, 1990).

at a confidence level of $p < 0.05$. Variability of means is presented in graphs and tables as standard error of the means (*s.e.*), unless stated otherwise. Grain yields were converted to 12% moisture. N utilization efficiency by maize was assessed by relating N uptake to grain yield and comparing this relationship with the theoretical limits of maximum dilution and maximum accumulation of N in maize (Figure 2) (Janssen *et al.*, 1990).

RESULTS

In the FP, all farmers applied the synthetic fertilizers urea and NPK 15-15-15; sometimes single super phosphate, and no organic inputs were used. The rates of fertilizer applied in the FP (Table 1) were generally below those applied in other treatments. The mean N concentration of cattle manure applied in T4 and T5 was low (13 g N kg^{-1} dry matter), except for 2002 (Table 3). Large differences in the N concentration of manure provided by the individual farmers were observed. In 2002, the cattle manure originated from NAPRI and its N concentration (25 g N kg^{-1} dry matter) was higher than in other years. The quantity of manure applied varied between 3.6 and 4.1 t ha^{-1} in T4 and between 7.2 and 8.3 t ha^{-1} in T5, except for 2002 when the quantity of applied manure was lower (Table 4). Besides N, considerable amounts of P, K and other nutrients were applied through the manure in T4 and T5 (Table 4).

Table 3. N concentration of the manure applied in T4 and T5 (g N kg^{-1} dry matter). Values between brackets are the minimum and maximum N concentration of the manure provided by the individual farmers. Manure in 2002 came from NAPRI as one load.

Year	N concentration
1999	12.1 (8.1–15.0)
2000	12.1 (5.7–18.7)
2001	12.6 (6.3–19.1)
2002	25.2
2003	13.9 (6.1–20.9)

Table 4. Quantity of dry manure (t ha^{-1}) annually applied in T4 and T5 and the quantity of nutrients applied through manure in these treatments (kg ha^{-1}).

Year/ treatment		Dry manure	N	P	K	S	Zn	B	Ca	Mg
1999	T4	4.1	50	8.1	78	6.3	0.25	0.06	32	15
	T5	8.3	100	16.2	156	12.7	0.49	0.11	63	30
2000	T4	4.1	50	9.1	87	7.6	0.31	0.07	50	19
	T5	8.3	100	18.3	174	15.3	0.61	0.15	100	37
2001	T4	4.0	50	10.3	103	8.3	0.26	0.08	43	20
	T5	7.9	100	20.5	205	16.6	0.52	0.17	86	40
2002	T4	2.0	50	16.6	80	8.2	0.23	0.04	17	15
	T5	4.0	100	33.2	160	16.4	0.46	0.08	34	30
2003	T4	3.6	50	8.3	76	7.2	0.32	0.06	45	15
	T5	7.2	100	16.6	151	14.4	0.64	0.12	89	30
Total	T4	17.8	250	52.4	424	37.7	1.36	0.31	186	84
	T5	35.7	500	104.7	847	75.4	2.73	0.62	373	167

In 2002, the quantity of P applied through manure was higher than in other years, while that of B and Ca was less.

Soils in layer 0–12 cm contained on average 47% sand, 42% silt and 11% clay particles. Site soil characteristics showed that soils were slightly acidic with pH values of plots varying between 4.6 and 5.7 (Table 5). Soil organic C content and Kjel N values were generally low, while Bray-I P and exchangeable K values were intermediate. The characteristics were in line with the common perception that soils in this area are low in fertility. At the end of the experiment, treatments receiving manure had an increased organic C content, especially T5 which had received the highest dose of manure, but the differences with other treatments were insignificant. Also, Kjel N, available P and exchangeable K, Ca and Mg values were increased in treatments receiving manure, relative to the other treatments. This increase was significant for available P and exchangeable K values ($p < 0.02$), and for Kjel N values at $p < 0.1$. The C/N ratio was unaffected by treatments. pH values showed a small, but significant increase in treatments receiving manure. In the FP, the available P was well below that of other treatments. Other soil parameters in the FP were within the range of values found in the other treatments.

Table 5. Soil characteristics at the end of the trial in May 2004, using a soil reference mass approximately equivalent to soil layer 0–15 cm; pH was assessed in soil layer 0–12 cm.

Treatment	pH (H_2O)	Org. C (t ha^{-1})	Kjel N (kg ha^{-1})	C/N ratio	Bray-I P (kg ha^{-1})	Exchangeable cations (kg ha^{-1}) K	Ca	Mg
Farmers' practice (FP)	5.01	11.5	947	12.4	7.6	196	935	219
50N urea (T1)	5.01	11.7	964	12.3	13.4	200	834	200
100N urea (T2)	5.01	12.2	964	12.9	17.3	217	890	190
150N urea (T3)	4.98	12.4	1035	12.1	17.9	219	909	190
50N urea + 50N CM (T4)	5.16	12.5	1057	12.1	21.0	269	928	220
50N urea + 100N CM (T5)	5.21	13.9	1161	12.1	30.9	338	969	231
s.e.	0.141	1.56	158.3	0.527	4.86	32.8	98.9	27.8

Table 6. Maize grain yields in 1999–2003, including the associated mean and *s.e.* (t ha^{-1}).

Treatment	1999	2000	2001	2002	2003	Mean
FP (1999–2002)	1.6	2.5	2.1	3.0		2.3
50N urea (T1)	3.2	3.0	2.2	4.5	1.8	2.9
100N urea (T2)	3.8	4.1	2.3	4.9	2.4	3.5
150N urea (T3)	3.7	3.7	2.3	5.1	3.0	3.6
50N urea + 50N CM (T4)	3.6	3.8	2.9	6.3	3.2	4.0
50N urea + 100N CM (T5)	4.1	4.5	3.2	6.4	3.7	4.4
s.e.	0.29	0.63	0.40	0.53	0.42	0.45

A large year-to-year variation in maize grain yield was observed with a minimum mean annual yield in 2001 of 2.5 t ha^{-1} and a maximum of 5.0 t ha^{-1} in 2002 (Table 6). Maize in the FP achieved lower yields than the other treatments. In treatments receiving sole urea (T1, T2 and T3), an increase from 50 to 100 kg N ha^{-1} y^{-1} resulted in a significant yield gain, while a further increase to 150 kg N ha^{-1} y^{-1} only marginally increased mean grain yield. In treatments receiving manure (T4 and T5), grain yields improved over the duration of the experiment, relative to the treatments receiving sole synthetic fertilizer at similar N rates (T2 and T3). In 1999–2000, no significant difference in yield was found between treatments receiving manure and the corresponding treatment with sole synthetic urea, while yield was significantly enhanced in T4 and T5 in 2001–2003. Thus, a significant impact from the annual application of manure on grain yield was observed only from the third year of the experiment. Maize yield varied significantly between experimental blocks (farmers) in all years. These variations in yield could not be related to differences in soil site characteristics between blocks.

Mean stover yield over 1999–2003 followed the same trend as grain yield, with the highest stover yield in treatments receiving manure (Table 7). Differences in stover yield between treatments were significant in 1999, 2002 and 2003. Also the mean harvest index was increased by the application of manure (Table 7), but this difference was significant only in 2002. Thus, both an enhanced dry matter production and a higher harvest index contributed to the greater grain yield observed in plots receiving

Table 7. Maize stover yield and harvest index at harvest, mean over 1999–2003.

Treatment	Stover yield ($t\ ha^{-1}$)	Harvest index (% dry matter)
FP (1999–2002)	3.6	36.6
50N urea (T1)	4.2	39.1
100N urea (T2)	4.9	39.4
150N urea (T3)	4.9	39.8
50N urea + 50N CM (T4)	5.3	40.7
50N urea + 100N CM (T5)	5.7	41.6
s.e.	0.45	2.10

Table 8. Concentration and uptake of nutrients in above-ground maize parts in 2003. Zn and B concentration and uptake were multiplied by 1000.

	N	P	K	S	Zn	B	Ca	Mg
Concentration ($g\ kg^{-1}$ dry matter)					(× 1000)	(× 1000)		
50N urea (T1)	8.2	1.24	8.7	0.56	42	2.6	1.19	1.07
100N urea (T2)	9.2	1.05	9.3	0.61	13	2.5	1.37	1.18
150N urea (T3)	10.3	1.31	8.4	0.66	15	2.6	1.43	1.14
50N urea + 50N CM (T4)	7.5	1.31	10.5	0.59	36	2.7	1.07	1.07
50N urea + 100N CM (T5)	7.6	1.48	12.4	0.55	21	3.0	1.02	1.11
s.e.	0.57	0.161	1.26	0.052	13.5	0.21	0.194	0.097
Uptake ($kg\ ha^{-1}$)					(× 1000)	(× 1000)		
50N urea (T1)	40	6.3	44	2.8	220	13	5.7	5.2
100N urea (T2)	57	6.4	56	3.7	82	15	8.6	7.3
150N urea (T3)	77	10.2	63	5.0	122	19	10.3	8.4
50N urea + 50N CM (T4)	56	10.2	75	4.4	299	20	7.7	8.0
50N urea + 100N CM (T5)	68	13.1	113	4.8	180	26	9.0	9.9
s.e.	7.6	1.80	13.3	0.59	93.5	2.6	1.52	1.05

manure. Mean plant density at harvest was lower in the FP (34 100 plants ha^{-1}) than that in the researcher-managed treatments (43 300 plants ha^{-1}). This plant density was well below the sowing density of 53 333 plants ha^{-1} in the researcher-managed treatments due to plant losses during the growing season caused by drought, water-logging and other factors.

In 2003, N concentration and uptake by above-ground maize parts were significantly increased with higher application rates of sole urea (T1, T2 and T3) (Table 8). In treatments receiving manure, N concentration was reduced and N uptake was not significantly different, relative to the corresponding treatments receiving synthetic fertilizer only. In Figure 2, treatments receiving manure were plotted close to the line representing maize yield with maximum dilution of N, indicating a high N utilization efficiency. This suggests that in treatments receiving manure, N was a relatively important yield-limiting nutrient, while other yield-limiting factors played a minor role. Treatments receiving synthetic fertilizer only were closer to the line representing maize yield with a maximum accumulation of N. These treatments had

Table 9. Base case scenario of the partial budgeting study: mean crop yield, crop value, inorganic fertilizer and manure costs, total costs that vary, and margin of crop value over total costs that vary, 1999–2003 (US \$ ha^{-1} y^{-1}).

			Variable costs			
Treatment	Crop yield (t ha^{-1})	Crop value	Synthetic fertilizer	Cattle manure	Total	Margin over costs
50N urea (T1)	2.94	488	147	0	147	341
100N urea (T2)	3.50	579	203	0	203	376
150N urea (T3)	3.55	586	260	0	260	327
50N urea + 50N CM (T4)	3.96	657	147	60	207	450
50N urea + 100N CM (T5)	4.37	725	147	121	268	458

Table 10. Annual and mean marginal rates of return of changes from T1 (50N urea) to the other treatments in the base case scenario of the partial budgeting study (%).

	1999	2000	2001	2002	2003	Mean
T1 to T2 (100N urea)	78	213	−58	17	61	62
T1 to T3 (150N urea)	−35	−3	−85	−9	69	−13
T1 to T4 (50N urea + 50N CM)	15	114	121	403	265	183
T1 to T5 (50N urea + 100N CM)	19	93	68	158	145	97

a reduced N-utilization efficiency, suggesting that yield-limiting factors other than N were relatively important here.

The concentration of nutrients other than N in above-ground maize was significantly affected by treatments for K and Ca only, while nutrient uptake by maize was affected by treatment for P, K, S, B and Mg (Table 8). Nutrient uptake was significantly increased for K and B in T5 and for P in both T4 and T5, relative to that of the corresponding treatments receiving sole urea (T2 and T3). K uptake of maize in treatments without manure exceeded K application rates (33 kg K ha^{-1}). The Ca concentration and uptake in T4 and T5 was reduced relative to that of T2 and T3. Zn concentration and uptake varied strongly between maize from different blocks, resulting in large standard errors associated with Zn. The amount of nutrients other than N applied as manure in 2003 in T4 and T5 (Table 4) was greater than the uptake by maize (Table 8). These data are discussed in more detail in the Discussion.

In the base case scenario of the partial budgeting study, a comparison between T1, T2 and T3 of the margin of crop values over total variable costs suggested that the application of 100N urea (T2) was more profitable than the other urea rates (Table 9). Furthermore, mean margins over the five-year period were increased by the use of manure, relative to the treatments receiving synthetic fertilizers only. Moreover, the marginal rates of return (MRR) of changes from T1 (50N urea) to the other treatments (T2–T5) were compared (Table 10). These analyses reflect a situation where a farmer has the opportunity to invest in additional nutrient inputs beyond the basic application rate of 50 kg urea-N ha^{-1}, and may choose between additional urea

Table 11. Effects of free manure, changes in fertilizer price, changes in maize price, and discounting future costs and benefits on the margin of crop value over total costs that vary (US \$ ha^{-1} y^{-1}).

Treatment	Base case	Free manure	Fertilizer price − 40%	Fertilizer price + 40%	Maize price − 40%	Maize price + 40%	Discounting	
							10%	30%
50N urea (T1)	341	341	400	329	146	536	282	194
100N urea (T2)	376	376	457	346	144	608	313	219
150N urea (T3)	327	327	430	273	92	561	267	180
50N urea + 50N CM (T4)	450	491	509	455	187	713	364	237
50N urea + 100N CM (T5)	458	540	516	469	167	748	371	244

or manure applications. Increasing urea N rates from 50 to 100 kg N ha^{-1} resulted in a positive MRR in most years. A further increase to 150 kg N ha^{-1} resulted in lower margins than in T1 and a negative MRR. Additional investments in the application of manure resulted in a higher MRR than investments in additional urea over the five-year period. However, in 1999 and 2000, additional investments in manure resulted in a lower MRR than investments in additional urea up to 100 kg urea-N ha^{-1} (Table 10). Thus, only from 2001, investments in manure were more profitable (a higher MRR) than investments in urea, which coincided with a significant increase in yield in treatments receiving manure. Adding 50 kg N ha^{-1} as manure (T4) resulted in a higher MRR than adding 100 kg N ha^{-1} as manure (T5).

The sensitivity analysis (Table 11) suggested that, if manure is freely available, the margins of crop values over variable costs improved in treatments receiving manure, especially in T5, in comparison with the base case scenario. A decrease in fertilizer prices reduced the difference in margins between treatments without manure and those with manure, while an increase in fertilizer prices enhanced this difference. This implies that high fertilizer prices would stimulate the use of manure as an alternative source of nutrients, provided that manure prices remain constant. Changing maize prices had a strong impact on the margins of all treatments, but did not greatly affect the relative differences in margin between treatments. Discounting future costs and benefits resulted in a relatively strong decrease of the margins of treatments receiving manure. The benefits of applying manure were visible only later in the experiment and therefore, discounting future benefits reduced the attractiveness of treatments receiving manure.

Group discussions with the participating farmers at the end of the experiment revealed that farmers' perception of the benefits of manure for maize production and the methods of manure application had changed over the experiment. This resulted in an increased use of manure on their own plots. The small numbers of livestock and consequently, the restricted availability of manure produced on-farm were mentioned as a key limitation for enhanced manure use, while *ex-situ* obtained manure was regarded as too expensive. Livestock densities, in turn, were constrained by a low availability of feed over the dry season. To a lesser extent, difficulties with the transportation of manure also discouraged its use.

DISCUSSION

While the N concentration in the manure donated by the participating farmers was generally low, the concentration varied greatly among farmers. Manure handling and storage methods were likely factors contributing to this variation and highlight the need to develop or promote more efficient technologies for manure handling, storage and application (Lekasi *et al.*, 2003). The manure from NAPRI in 2002 had a relatively high N concentration and a low C/N ratio, which may have favoured N uptake from manure by maize in 2002. Also, the P content of the manure applied in 2002 was high. In 2002, the yield difference between treatments receiving manure and those receiving sole urea was larger than in other years, which could be related to the characteristics of the manure applied in 2002. In our trial, maize might have responded more strongly, and perhaps also more rapidly, to manure applications if the applied manure had been of higher quality.

The observed large year-to-year variability in maize yield, irrespective of treatment effects, was probably caused by variations in environmental conditions, particularly in rainfall. Maize yield in 2002 may have been high because of favourable rainfall in the first 60 days after planting (Table 1; Figure 1). In 2001 and 2003, when maize yields were low, drought periods occurred soon after planting. Given the numerous possible interactions among the factors which affect yield, it is difficult to disentangle the exact reasons for the large variation based on the current data. Yield levels in the FP were below that of other treatments, due to differences in nutrient management, crop variety, planting density and other field management practices. Yield in the FP was, nevertheless, equal or above levels of on-farm, farmer-managed maize reported by other studies (Carsky *et al.*, 1998; Schulz *et al.*, 2003).

Manure applications resulted in a slight increase in soil organic C content at the end of the experiment. In T5, the application of 36 t manure over five years resulted in an increase in soil C content of about 1.5 t over the treatment receiving sole synthetic fertilizer (T3), equal to an increase in soil C concentration of around 0.1%. This impact of relatively large manure applications was small, but in line with results from long-term trials in the region reported by Agbenin and Goladi (1997) and Jones (1971; 1976). The build-up of soil organic C in T4 and T5 may have resulted in improved soil physical and chemical characteristics. The observed increase in pH values in T4 and T5, for example, may be related to the build-up of soil organic C, and was likely to benefit maize growth in the slightly acid soils of the trial. The observed greater harvest index in treatments receiving manure could be caused by reduced water stress during grain formation, which in turn may be related to higher organic C levels and an improved water-holding capacity of the soil.

In treatments receiving manure, N concentration was reduced and N uptake was similar (T4) or slightly reduced (T5), relative to the corresponding treatments receiving sole urea (T2 and T3). Soil Kjel N values were increased in T4 and T5 at the end of the experiment. These data indicate that N partly supplied as cattle manure was less readily available for plant uptake than N solely supplied as urea. Thus, the application of manure did not result in an improved synergy between N release and crop demand. Treatments receiving manure had higher N utilization efficiencies than treatments receiving sole urea (Figure 2). This indicated that the applied manure relieved yield-limiting factors other than N availability, such as a deficiency of one or more other nutrients. An increased uptake of P, K and B by maize was observed in treatments receiving manure. Maize P concentrations in treatments receiving sole synthetic fertilizer were low, relative to the ranges reported for West African maize (van Duivenbooden, 1996). Thus, the additional P supplied as manure could have enhanced maize growth. Maize K concentrations in treatments receiving sole synthetic fertilizer, on the other hand, did not indicate K deficiencies in maize (van Duivenbooden, 1996). The additional K uptake by maize in T4 and T5 was possibly luxury uptake, which can also explain the observed reduction in Ca uptake. While B uptake was also increased in maize receiving manure, no reference values for West African maize were available in the literature to assess if the observed B concentration or uptake in maize receiving only synthetic fertilizer indicated a deficiency. No evidence was found that manure applications relieved a deficiency of other nutrients that are known to limit maize growth in parts of the savanna, such as Zn or S (Agbenin, 2003; Friesen, 1991; Kang *et al.*, 1981; Ojeniyi and Kayode, 1993). Plant K uptake in treatments receiving sole synthetic fertilizer exceeded K input through fertilizer. Harmattan dust deposits may supply 15–20 kg K ha^{-1} y^{-1} (McTainsh, 1980; Von Jahn *et al.*, 1995). However, this additional K was insufficient to bridge the gap between K input and plant uptake, and soil K reserves probably complemented K supply to the crop. In the FP, a large part of the K taken up by maize may be returned to the soil when crop residues remained in the field after grain harvest.

Marginal rates of return of changes from sole 50 kg urea-N ha^{-1} to 100 kg urea N ha^{-1} suggested that it was more profitable to invest in additional urea than in organic manure in the first two years of the trial. Obviously, farmers will be reluctant to invest in manure inputs if there is a delay in returns, compared to investments in synthetic fertilizer. The base case scenario of the partial budgeting study was based on relatively expensive prices of *ex-situ* produced manure. In the sensitivity analysis, the availability of free manure increased the economic attractiveness of manure applications. The sale of manure by commercial livestock producers in the area and farmers' habit of trading manure within their village indicate that manure is not regarded as a free commodity. However, an increase in on-farm manure production would obviously reduce manure farm gate prices. The quantity and quality of manure produced on-farm could be enhanced in the area by improving nutrient cycling efficiencies and the integration of crop and livestock activities. For example, in the current zero-grazing farming system, incorporating new dual-purpose legume varieties in cereal-based rotations improves feed availability over the dry season (Sanginga *et al.*, 2003; Schulz *et al.*, 2001), providing opportunities to increase livestock densities. In conclusion, manure applications, even when applied at relatively high rates, did not serve as a quick fix to on-farm soil fertility problems, but over a longer period, manure applications combined with synthetic fertilizers did provide a significant and profitable contribution to enhanced cereal production.

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