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ORIGINAL PAPER

Effect of manure application on crop yield and soil chemical properties in a long-term field trial of semi-arid Kenya

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Abstract The sustainability of cereal/legume intercropping was assessed by monitoring trends in grain yield, soil organic C (SOC) and soil extractable P (Olsen method) measured over 13 years at a long-term field trial on a P-deficient soil in semi-arid Kenya. Goat manure was applied annually for 13 years at 0, 5 and 10 t ha^{-1} and trends in grain yield were not identifiable because of season-to-season variations. SOC and Olsen P increased for the first seven years of manure application and then remained constant. The residual effect of manure applied for four years only lasted another seven to eight years when assessed by yield, SOC and Olsen P. Mineral fertilizers provided the same annual rates of N and P as in 5 t ha^{-1} manure and initially ,gave the same yield as manure, declining after nine years to about 80%. Therefore, manure applications could be made intermittently and nutrient requirements topped-up with fertilizers. Grain yields for sorghum with continuous manure were described well by correlations with rainfall and manure input only, if data were excluded for seasons with over 500 mm rainfall. A comprehensive simulation model should correctly describe crop losses caused by excess water.

Keywords Manure application · Phosporous · Nitrogen · Soil organic matter · Semi-arid Kenya

Introduction

In semi-arid sub-Saharan Africa (SSA) it is usual to find great variability of rainfall and low accessibility to technical information and markets, so the early and widespread adoption of fertilizers has not occurred. Manure application is one of the most effective ways of improving fertility in tropical soils. As an example, the production, distribution and application of manure is a vital part of sustainable smallholder arable farming around Kano in northern Nigeria, a semiarid area with a high population and a long history of arable farming (Dennison 1961; Harris and Yusuf 2001). But organic nutrient sources have their own problems, such as limited supplies and the work of handling bulky materials. The effects and costs of organic and inorganic nutrient sources are different, but may be complementary. Thus the combined use of organic and inorganic nutrient sources is now considered a better way to maintain soil fertility, but comparative information on their long-term effects is scarce.

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Both organic and inorganic sources have residual effects in the field. These effects are a vital component of sustainability because they smooth season-to-season variations in soil fertility and crop productivity, but they are difficult to assess quantitatively. Therefore, it is advantageous to undertake well-characterized medium-to-long term experiments rather than single-season trials, and to detail the interactions rather than averaging the responses over different seasons and environments (Tandon and Kanwar 1984). Long-term implies that primary objectives, treatments and management are not changed during the period under consideration, often regarded as at least 10 years, but unfortunately there is a paucity of long-term experiments in the semi-arid tropics (Laryea et al. 1995). However, long-term information on soil fertility can still be obtained by monitoring trends in the soil nutrient status even though the pattern of crops may change. The work described here is a development of work at one site of the multi-site experiment first reported by Gibberd (1995).

In 1993, it was clear that manure at 5 t ha^{-1} was widely beneficial, so advantage was taken of the significant soil fertility differences established by then (Warren et al. 1997) to examine residual and long-term effects of soil fertility management.

The general objective of this work was to assess the sustainability of cereal/legume intercropping in semi-arid conditions, by assessing trends in crop yield and soil chemical data collected during more than ten years. Specific objectives were (i) to identify trends in crop performance and soil nutrient status, (ii) to assess the residual value of manure and (iii) to assess the relative value of manure and fertilizer at the same rates of N and P addition.

Materials and methods

Field site

The experimental site was at Machang'a, Mbeere District (0°47′ S, 37°40′E; 1050 m altitude). It was cleared from. native bush at the end of 1988, cropping was started in March 1989 and the manure treatments commenced in September 1989. The soil was a sandy clay loam containing 56.5%, 12.7% and 30.8% of sand, silt and clay, respectively, with a pH of 6.55 (1:2.5 in water) and provisionally classified as a Chromic Cambisol, (Kenya Soil Survey, personal communication). Meteorological data (rainfall and temperatures) were manually collected at the site. The two major seasons are the long rains (LR) which occur between April to June and the short rains (SR) between October and December.

Agronomy

The original experiment had nine treatments comprising three crop rotations and three fertility managements in factorial combination, each with three replicates laid out in randomized blocks. The crop rotations compared intercropping and two sole crop rotations. The fertility treatments were annual (a) additions of goat manure at 0, 5, and 10 t ha^{-1} yr^{-1}. The results from 1989 to 1993 are given by Gibberd (1995), In February 1993, soil was sampled from all plots, and it was found that the different crop rotations had not created any significant differences in soil organic C (SOC), total N, extractable P (Olsen P) or exchangeable cations (Warren et al. 1997). The intercropped rotation was continued without alteration to manure rates. The sole crop rotation with cereals planted in March and legumes planted in October was discontinued in order to create three new soil fertility treatments with intercropping as described below. The other sole crop rotation continued unchanged and will be reported separately.

The soil fertility treatments are summarized in Table 1. Treatments C, Al and A2 were maintained throughout from 1989 to 2002. The goat manure was obtained from the same source every year and a sample taken, air dried and analyzed for N, P and K contents prior to application. The manure was then broadcast and immediately incorporated by hand digging into the top 10 cm soil layer. Treatments B1 and B2 assessed the residual effects after a final manure application in 1992 and treatment F assessed the effectiveness of mineral fertilizers on cropped and previously unfertilized soil. In the four years from 1993 to 1996, the manure was sampled and analyzed for

Table 1 Soil fertility treatments applied at the Maching'a trial. Manure was applied annually in September and fertilizer was applied every season (from October 1993) at approximately 51,12 and 30 kg ha^{-1} of N,P and K respectively

Code	Treatment	
	1989 to 1992	1993 to 2002
A1	5 t ha^{-1} yr^{-1} manure	5 t ha^{-1} yr^{-1} manure
A2	10 t ha^{-1} yr^{-1} manure	10 t ha^{-1} yr^{-1} manure
B1	5 t ha^{-1} yr^{-1} manure	None
B2	10 t ha^{-1} yr^{-1} manure	None
C	None	None
F	None	NPK fertilizer

total C, N, P and K. In these years, the rates of fertilizer N and P in the new treatment F were adjusted in the April season so as to provide equal amounts of N and P in treatments F and Al. From 1997, the fertilizer treatment was N (51 kg ha^{-1}), P (12 kg ha^{-1} and K (30 kg ha^{-1}) each season, providing approximately the same annual inputs of N and P as 5 t ha^{-1} of manure, which were on average 101.5 kg N ha^{-1} a $^{-1}$ and 23.7 kg P ha^{-1} a^{-1} from 1993 to 1996.

The crops were (i) sorghum *(Sorghum bicolor*, cv. 954066), intercropped with cowpea *(Vigna unguiculata*, cv. M66); (ii) Pearl millet *(Pennisetum glaucum*, cv. KPM1), intercropped with green gram *(Vigna radiata*, cv. N26) and (iii) maize *(Zea mays*,cv. Katumani) intercropped with long duration pigeon pea *(Cajanus cajan*, cv. Kimbeere), the latter being a local variety. Cereals were planted in rows 70 cm apart at a spacing of 25 cm within rows, and the associated legume was planted at the same density in extra rows midway between the cereal rows, From 1989 to 1993, the treatments C, Al and A2 carried a pattern of sorghum/cowpea for two seasons followed by millet/green gram for two seasons as described by Gibberd (1995). From October 1993 this was amended to a rotation (sorghum/cowpea sown in October and millet/gram sown in March) that closely follows typical local farming practice. From October 1999, cropping was to maize/pigeon pea. The first pigeon pea crop was sown in October 1999, grain harvested in May–August 2002 and the plots then cleared. The second pigeon pea crop was sown in October 2000 and harvests made in May–August 2001 and 2002 from the same plants. The intercropped maize was sown every October and March. The plots that were converted to soil treatments B l, B2 and F carried a rotation of sorghum; cowpea; millet; green gram, with cereals planted in March from 1989 to 1993. From October 1993 they carried the same rotation as treatments C, Al and A2. At harvest, the grains and above-ground residues (leaves, stalks and threshing residues) were collected separately for each crop. They were air-dried and weighed at the site.

Soil sampling and analysis

Sampling of the soil commenced in February 1993 and was carried out at intervals of approximately six or twelve months, from the 0–20 cm horizon of all plots. Pits were dug 30 × 30 *times* 20 cm within steel frames driven into the soil, sub-sampled, air-dried and ground by hand to pass a 2-mm aperture sieve, as described by Warren et al (1997). Three sampling pits per plot were dug at the first (1993) and last (2002) sampling occasions and duplicate pits in 1997, but for reasons of economy, only a single sampling pit was used at the other occasions. Olsen P was measured colorimetrically after extraction for 30 min at 20°C and 1:20 w/v soil:-reagent ratio with 0.5 M $NaHCO_3$ adjusted to pH 8.5. SOC was measured by heating finely-ground soil for 2 h at 130–135°C with H_2SO_4/ H_3PO_4 /$K_2Cr_2O_7$ mixture and back-titration with $(NH_4)_2{\cdot}Fe(SO_4)_2$. When required, results of soil analysis were also calculated as amounts in kg ha^{-1} using the soil mean bulk density of 1.39 in the 0–20 cm horizon.

Statistical methods

Season-to-season variability in the results makes it difficult to discern the differences and trends which may indicate the stability and sustainability of the cropping systems. Therefore the grain yield, Olsen P and SOC data were analyzed statistically by analysis of variance for each season individually, and also by linear regression over sequences of seasons to search for trends. Statistical calculations were performed with INSTAT (Stern et al. 1990).

Regression modelling of grain yields

Empirical equations of the following form were fitted to grain yield (Y) for the continuous treatments (C, Al, and A2):

$$Y = a + bR + cM^x + dR \times M^x \quad (1)$$

where R was the seasonal rainfall (mm), M was the annual manure rate (t ha^{-1}) and a, b, c, d and x were fitted parameters. A preliminary matrix of correlation coefficients showed that Y was always correlated much more closely with $R \times M$ than either R or M alone. Then parameter x was selected to give the highest correlation between Y and $R\times M^x$, and the significant terms and regression coefficients were obtained using stepwise multiple regression.

Trends over time in soil properties under continuous manure

For soil data, the trend over several seasons for each measurement and treatment was described by linear regression with time (T) in years as the explanatory variable. Soil data for continuous manure treatment were considered in two phases, 1993 to 1997 and 1997 to 2002. 1997 was chosen as the dividing year because of the more intensive soil sampling carried out in that year. For 1989 to 1997, the value T = O was set to 1 January 1989, approximately the start of the experiment, and for 1997 to 2002, T = 0 was set to 1 January 1997. Comparisons between continuous manure treatments were then made by pooling the data for these treatments and a set of joint regression lines, either parallel to each other or diverging from a common origin at 1989, was fitted using multiple regression with factors (Draper and Smith 1981).

Assessment of manure residual value

For each season from 1993 to 2002, the residual value (RV) of manure for grain yield was assessed by the response to residual manure divided by the response to continuous manure, calculated as follows:

$$\mathrm{RV}_i = \frac{\mathrm{Yield}(\mathrm{B}_i)}{\mathrm{Yield}(\mathrm{A}_i)} - \frac{\mathrm{Yield}(\mathrm{C})}{\mathrm{Yield}(\mathrm{C})} \quad (2)$$

where A_i denotes continuous manure at rate i , B_i denotes residual manure at rate i and C denotes the no manure treatment. RV should therefore vary between 1.0 for a residual effect as good as fresh manure and 0.0 when there is no residual effect. Residual values also were assessed by the responses in Olsen P and SOC, calculated by Eq. 2, with the substitution of yield by Olsen P or SOC values. The trends in yield and soil data were assessed by linear regression with time (T) in years as the explanatory variable. The value T = O was set to 1 January 1993 since the new treatments commenced during 1993.

Comparison of fertilizer and manure

For each season from 1993 to 2002, the relative effect of fertilizer in comparison with manure was assessed by the fertilizer to manure ratio (FMR) for cereal grain yields calculated as follows:

$$\mathrm{FMR} = \frac{\mathrm{Yield}(\mathrm{F})}{\mathrm{Yield}(\mathrm{A1})} \quad (3)$$

FMR was also assessed for Olsen P and SOC, calculated by Eq. 3, with the substitution of yield by Olsen P or SOC values. The trends in yield and soil data were assessed by linear regression with time (T) in years as the explanatory variable. The value T = O was set to 1 January 1993.

Results

Weather

From 1990 to 2002, the mean annual rainfall was 789 mm, bimodally distributed with peaks in November and April (Fig. 1). Seasonal rainfall varied from 100 to 1030 mm and appeared more variable from 1997 onwards (Fig. 1). Mean annual class 'A' pan evaporation was 1993 mm, and the mean daily maximum and minimum temperatures were 29.0°C and 16.6°C, respectively.

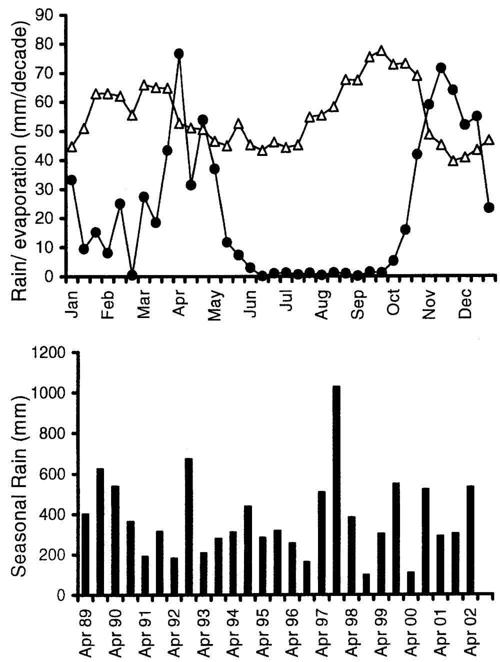

Fig. 1 Mean rainfall (●) and class 'A' pan evaporation (△) in "decades" (10-day periods), averaged over the period 1990-2002, and rainfall during each cropping season, assessed by summation of the rainfall from 1 October to the following 31 January for each November season and from 1 March to 30 June for each April season

Continues manure

Grain yields

For the unmanured plots (treatment C), the first season gave the highest yields of cereals and legumes (Fig. 2) and from then on, yields remained low every year. For the continuously manured plots (A1 and A2), yields were higher in the earlier years (approximately 1989–1995), when manure gave significant increases in cereal yield in almost every season and legume yield in three seasons (SR90, 92 and LR02)However 10 t ha^{-1} manure did not give any significant extra grain yield compared to 5 t ha^{-1} manure (Fig. 2). In the period 1996–1998, all yields were low. For the cereals, this is attributed mainly adverse weather conditions, for example the November seasons of 1996, 1997 and 1998 provided the highest and the two lowest rainfalls on record for that season (Fig. 1). Yields could be depressed by high rainfall. In the November 1992 season, rainfall was the second highest on record but the sorghum yield was only about half that of the best season. In the extreme case of January and February 1998, an exceptionally extended rainy season caused complete loss of the November 1997 season's grain harvest, which rotted in the field and the yield had to be recorded as missing data. For the legumes, yields declined after 1992 (Fig. 2) and this was caused by an increasing incidence of disease. Cowpeas usually failed to set seed after 1995 because of root rot, which became endemic in the plots. After the intercropped plots were converted to the maize/pigeon pea system, grain yields were generally better (Fig. 2), although it is likely that this was in part due to more favourable rainfall patterns.

The relationships between grain yield and seasonal rainfall were plotted for each rate of manure (Fig. 3). For sorghum, it appeared that the yield was correlated with rainfall up to about 500 mm of seasonal rain, and that the response to extra rain was greater if manure was applied. An empirical regression equation gave a close description of the sorghum grain yield data for eight seasons in a period of nine years, excluding (i) the initial season before manure was first applied (4/89); and (ii), the two seasons when rainfall exceeded 500 mm. The term for rainfall (R) in Eq. (1) was not significantly different from zero, and a very highly significant ($p < 0.001$) relationship was found as follows:

$$Y = a + bM^{0.3} + cR \times M^{0.3} \tag{4}$$

where a=146.7, *s.e.* 78.9; b=–867, *s.e.* 92,7; c=5.89, *s.e.* 0.29 and r^2=0.963. This equation can be written in the following alternative form:

$$Y = 146.7 + (5.89.R - 867)M^{0.3} \tag{5}$$

This suggests that (i) a certain minimum rainfall (R = 867/5.89 = 147 mm) is essential for grain production, which is otherwise negative according to this equation, and (ii) that above the minimum rainfall, yield depends on the product of R and M, showing that there is a strong positive interaction between rainfall and soil fertility.

For millet, cowpea and green gram, the yields in relation to rainfall were much more scattered

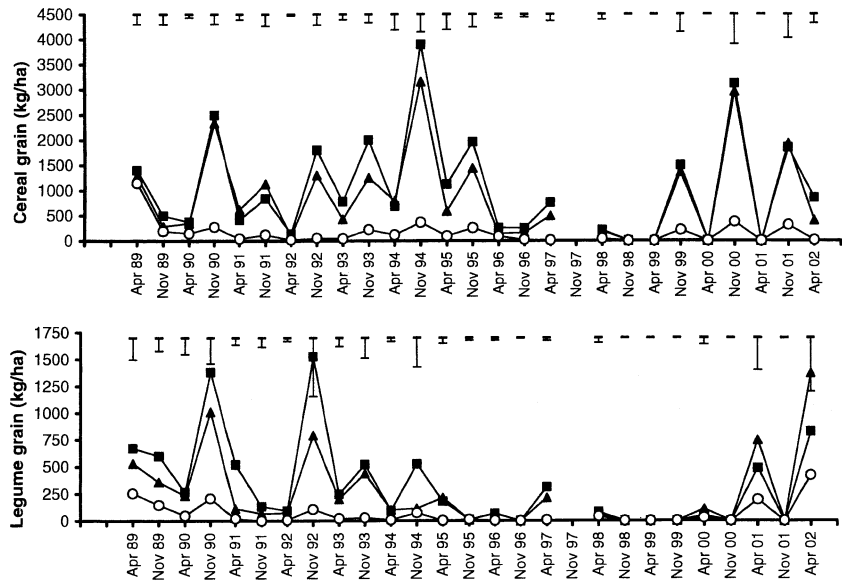

Fig. 2 Grain yields of cereals (maize) and legumes (green grams) in each season with intercropping and soil fertility treatments C (○), Al (▲) and A2 (■), in which 0,5 and 10 t $ha^{-1}a^{-1}$ manure respectively were applied. Vertical bars equal the *s.e.d.* for each season

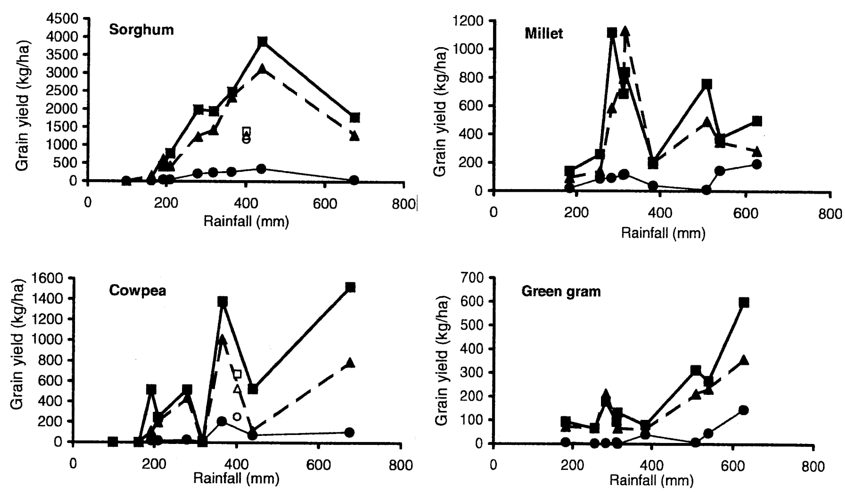

Fig. 3 Relationships between grain yield of sorghum, cowpea, millet and green gram, and seasonal rainfall, with intercropping and soil fertility treatments C(●), A1 (▲) and A2 (■), in which 0, 5 and 10 t ha^{-1} a^{-1} manure respectively were applied. Yields for the season before manure application started (April 1989) are shown in open symbols (○, △, □) for treatments C, Al and A2, respectively

(Fig. 3). For the legumes, it still appeared that the response to extra rain was better in the manured treatments. Close correlations of yield with *M* and $R \times M$ were not found, although for millet at rainfall less than 350 mm, the following relationship was significant:

$$Y = a + bM^{0.1} + cR \times M^{0.1} \quad (6)$$

where a = 85.8, *s.e.* 92.2, b=–994, *s.e.* 313, c=5.18, *s.e.* 1.11 and r^2=0.774.

Maize and pigeon pea yields were obtained in four and three seasons respectively, which were not enough data to obtain meaningful relationships between yield and rainfall.

Olsen P

Significant increases in Olsen P were caused by manure application. Compared to the control, treatment A2 caused significant increases in Olsen P at almost every sampling (Fig. 4), but the increase caused by treatment A1 was never large enough to be significant in any one season. Olsen P in treatment A2 was significantly more than in Al in nine out of 13 sampling occasions. In 1993

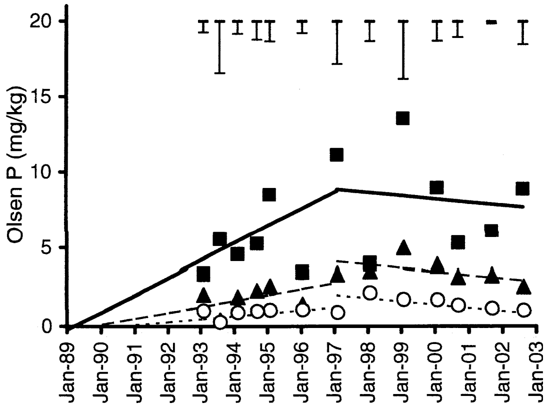

Fig. 4 Soil Olsen P for intercropped treatments C (○), A1 (▲) and A2 (■), in which 0, 5 and 10 t ha^{-1} a^{-1} manure respectively were applied. Vertical bars equal the *s.e.d.* for each season. Fitted joint regression lines (*s.e* of parameter) for 1993 to 1997 were: treatment C (......) P = 0.277(1.533) +0.188(0.267) *T*; treatment Al (- - -) P = 0.277(1.533) +0.383(0.267) *T*; and treatment A2 (—) P = 0.277(1.533) +1.112(0.267) *T*. Fitted joint regression lines for 1997 to 2002 were: treatment C (......) P = 2.06(1.06)–0.211(0.245) *T*; treatment Al (– – –) P = 4.17(1.06)–0.211(0.245) *T*; and treatment A2 (—) P = 8.92(1.06)–0.211(0.245) *T*

and 2002, Olsen P values were unchanged in C with 1.0 mg kg^{-1}, compared with increase in treatment Al from 2.1 to 2.6 mg kg^{-1} and in treatment A2 from 3.3 to 8.9 mg kg^{-1} and A2 (Warren et al. 1997) (Fig. 4). This suggested that trends in Olsen P should be observable.

From 1993 to 1997, the trends in Olsen P shown by regressions on time were small for treatment C, a little upward in Al and distinctly upward in treatment A2 (Fig. 4). But, because of the variability of results, no trend line gradient for an individual treatment was significantly different from zero, although Olsen P must have been the same in all treatments in 1989 and a significant difference between treatments C and A2 had developed by 1993. When projected backwards to 1989, the fitted Lines tended to a common origin as should be expected. Therefore, data for the three treatments were pooled and a set of joint regression lines was fitted, each of the following form, one equation for each treatment:

$$\text{Olsen P}(\text{mgkg}^{-1}) = a + bT \quad (7)$$

They started at a common origin with *T* = O set to 1 January 1989, and had separate slopes. A good fit was obtained (r^2=0.782), shown in Fig. 4. The rate of increase of Olsen P was highly significant in treatment A2 but not in treatments C and Al, in agreement with the significant differences between treatments at each of the 1993 to 1997 samplings (Fig. 4).

From 1997 to 2002, the trends in Olsen P were slightly downward in all treatments (Fig. 4). The downward trends of individual treatments were not significantly different from zero or each other, but treatment effects in each season were consistently in the order C < Al < A2. These results were pooled and three parallel lines (each as Eq. 7) with separate intercepts were fitted by joint regression, with *T* = O set to 1 January 1997. The joint downward slope was not significantly different from zero and Olsen P in treatment A2 was significantly more than in treatment Al (p=0.01). The difference between treatments C and Al was not quite large enough to be significant at the 5% level.

Soil organic C

Compared to the control, treatments Al and A2 caused significant increases in soil organic C (SOC) at almost every sampling (Fig. 5), but the difference between treatments Al and A2 was never significant.

From 1993 to 1997, the trend in SOC was small for treatment C and distinctly upward in treatments Al and A2 (Fig.5). But because of the variability of results, none of the gradients of the individual trend lines was significantly different from zero, although the initial SOC must have been the same in all treatments and a significant difference between treatments C and the manured treatments had developed by 1993. The initial SOC would be the same in all plots and when projected backwards in time, the trend lines tended to a common origin as might be expected. These data were pooled and set of joint regression lines based on a common origin and separate slopes were fitted to the equation:

$$\text{SOC}(\text{gkg}^{-1}) = a + bT \quad (8)$$

where a=6.28, *s.e.* 0.891, and b=–0.053, 0.296 and 0.328, for treatments C, Al and A2, respectively,

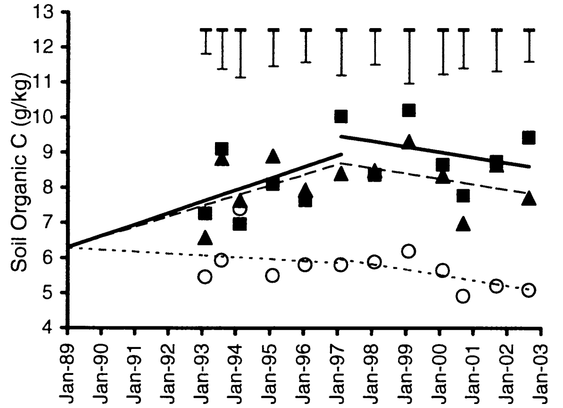

Fig. 5 Soil organic C for intercropped treatments C (○), Al (▲) and A2 (■), in which 0, 5 and 10 t ha^{-1} a^{-1} manure respectively were applied. Vertical bars equal the *s.e.d.* for each season. Fitted joint regression lines (*s.e* of parameter) for 1993 to 1997 were: treatment C(......) SOC = 6.28(0.891) –0.053(0.155) *T*; treatment Al (- - -) SOC = 6.28(0.891) + 0.296(0.155) *T*; and treatment A2(—) SOC = 6.28(0.891) + 0.328(0.155) *T*. Fitted joint regression lines for 1997 to 2002 were: treatment C(......) SOC = 5.98(0.35) – 0.154(0.081) T;treatment Al (—) SOC = 8.72(0.35) – 0.154(0.081) *T*; and treatment A2(—) SOC = 9.48(0.35) – 0.154(0.081) *T*

s.e. 0.155, (F=8.98; r^2=0.658). The rate of decline of SOC in the Control treatment was not significant, while in the manured treatments, the rate of increase was not quite large enough to be significant and there was no significant difference between treatments Al and A2. The data for treatments Al and A2 were combined, and a regression line (Eq. 8) was estimated, where a=6.28, *s.e.* 0.865, and b=0.312, *s.e.* 0.145, in which the rate of increase of SOC was significant (p=0.05). These results are in agreement with the individual differences between treatments for the 1993 to 1997 samplings and show that annual manure application increased SOC up to 1997, but there was no difference between treatments A1 and A2.

From 1997 to 2002, the trends in SOC were slightly downward in all treatments (Fig. 5). The downward trends were not significantly different from zero or each other and treatment effects in each season were consistently in the order C < A2~Al (Fig. 5). These results were pooled, three parallel lines were fitted by regression, with T = 0 set to 1 January 1997. The set of regression lines was described by Eq. (8), where a=5.98, 8.72 and 9.48 for treatments C, Al and A2, respectively, *s.e.* 0.35, and b=–0.154, *s.e.* 0.081. (F=692; r^2=0.994). The combined downward slope was still not significantly different from zero, SOC in treatments Al and A2 was significantly more than in treatment C (p=0.001), and there was no significant difference between treatments Al and A2. These results suggest that in the manure treatments after 1997, a new dynamic equilibrium had been reached between C inputs and decomposition.

Residual manure treatments

Grain yields

The assessment of manure residues started in November 1993, and significant differences between continuous and residual manure treatments were not normally found in any one subsequent year because of the variability. In many years there were no significant effects of manure, either continuous or residual, on crop yields. Only cereal yield data were used because legumes were affected by disease. Residual Value (RV) could not be calculated for seasons of severe drought or missing data and the values were rather scattered (Fig.6). Nevertheless, the linear regression between RV and time showed a highly significant (p=0.001) downward trend, described by the following equation, where time (T) was zero for 1 January 1993.

$$RV = a + bT \tag{9}$$

Where a=0.820, *s.e.* 0.087, and b=–0.0727, *s.e.* 0.0157 (r^2=0.495). The confidence limits ($p < 0.05$) for the fitted mean regression line were plotted and projected back to April 1993 (Fig. 6). They showed that (i) from April 1993 to December 2001, RV was significantly less than one but more than zero, (ii) at April 1993, RV was not significantly different from one (this should be the case since the last manure application was the previous year), and (iii) by January 2002, RV was not significantly different from zero. These data suggest that the effects of manure lasted approximately eight years, from the first residual effect season (November 1993) until December 2001.

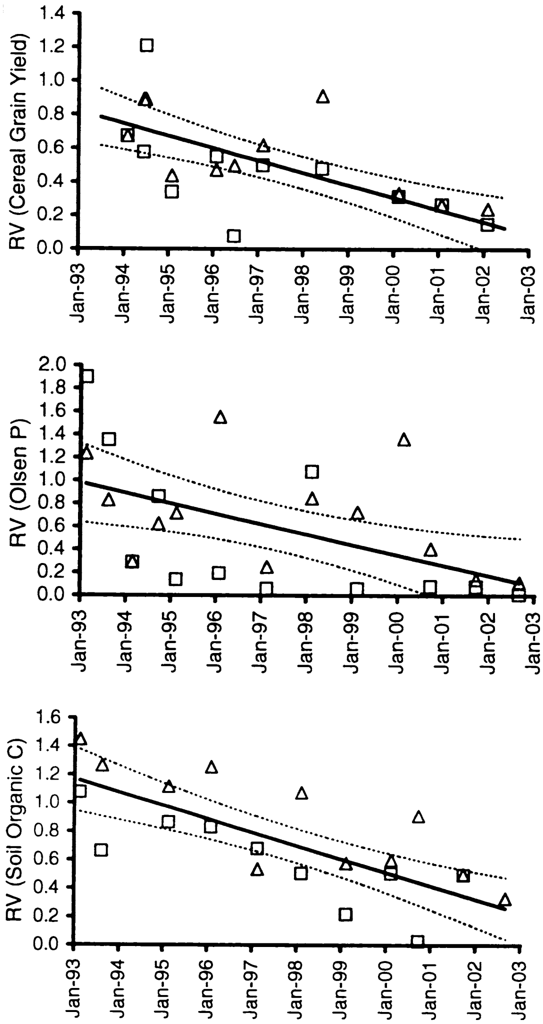

Fig. 6 Residual value (RV) of manure, calculated as response to residual manure (treatment B) divided by the response to continuous manure (treatment A), at 5 t ha^{-1} manure and 10 t ha^{-1} manure (□) for cereal grain yield, Olsen P and SOC. Solid lines show the fitted linear regression of RV with time (*T* years, starting 1 January 1993). Fitted lines (*s.e* of parameters): RV (Grain Yield) = 0.820(0.087)–0.0727(0.0157) *T* (r^2 =0.495); RV (Olsen P) = 0.980 (0.165)–0.0897(0.0305) *T* (r^2 =0.265); and RV (SOC) = 1.169(107)–0.0941(0.0183)T (r^2=0.568). Dotted lines delimit the 95% confidence intervals of the fitted lines

Olsen P

Residual Value data were rather scattered (Fig. 6), but the linear regression of RV with time showed a highly significant (p=0.01) downward trend, described by Eq. 9, where a=0.980, *s.e.* 0.165, and b=–0.0897, *s.e.* 0.0305 (r^2=0.265). The confidence limits ($p < 0.05$) for the fitted mean regression line were wider than for grain yield data (Fig.6) and showed that by about September 2000, RV was not significantly different from zero. These data suggest that the residual effects of manure on Olsen P lasted approximately seven years, until eight years after the final manure application.

Soil organic C

The Residual Value data showed a clear downward trend (Fig. 6), and the linear regression of RV with time was very highly significant (p=0.001), described by Eq. 9, where a=1.169, *s.e.* 0.107, and b=–0.0941, *s.e.* 0.0183 (r^2=0.568). The confidence limits ($p < 0.05$) for the fitted regression line showed that by September 2002, RV had almost reached the point of being not significantly different from zero. These data suggest that the residual effects of manure on SOC lasted approximately eight years, until nine years after the final manure application.

Comparison of fertilizer and manure

Grain yields

Only cereal yields were considered because legumes were badly affected by disease in the period under consideration. In every season, there was no significant difference between treatments F and Al in grain yield. The relative effect of fertilizer in comparison with manure (FMR) showed a downward trend (Fig. 7), and the linear regression of FMR with time was significant (p = 0.05). The confidence limits ($p < 0.05$) for the fitted regression line showed that by the April 2002 season, FMR was significantly less than one. Therefore, by 2002, fertilizer was not as effective as manure even though the same amounts of N and P had been applied from 1993 to 2002.

Olsen P

During the period from 1993 to 2002, Olsen P was on average higher in treatment F (4.2 mg kg^{-1})

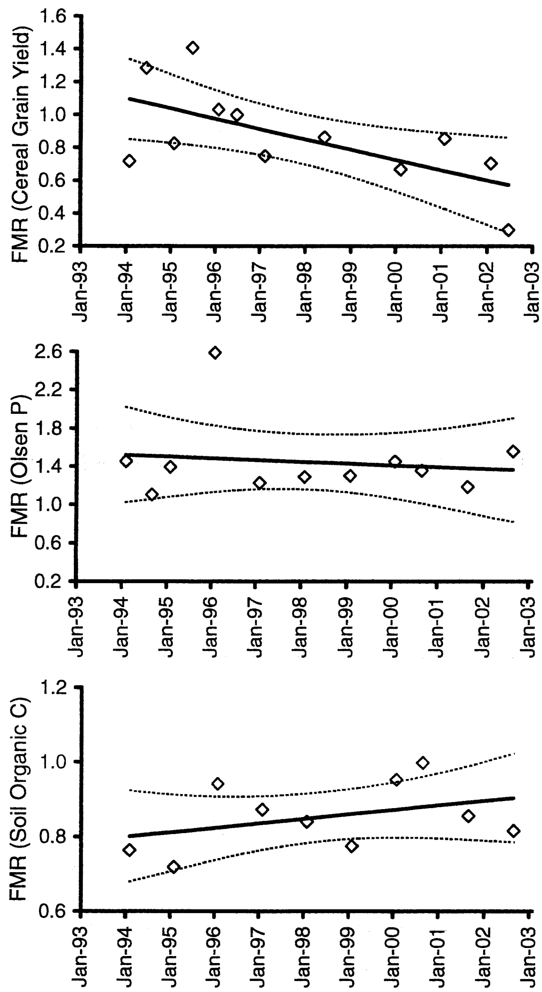

Fig. 7 Relative effect of fertilizer and manure (FMR; ◇), calculated as the ratio between the results for treatments F and Al (fertilizer and 5 t ha^{-1} manure respectively) for cereal grain yield, Olsen P and SOC. Solid lines show the fitted linear regression of FMR with time (*T* years, starting 1 January 1993). Fitted lines (*s.e* of parameters): FMR (Grain Yield) = 1.164(0.131)–0.0625 (0.0235) *T* (r^2=0.414); FMR (Olsen P) = 1.544(0.263)–0.0186(0.0448) *T* (r^2=0.019); and FMR (SOC) = 0.787 (0.063)–0.0121(0.0102) *T* (r^2=0.148). Dotted lines delimit the 95% confidence intervals of the fitted lines

than in treatment A1 (3.0 mg kg^{-1}) even though the total amount of P applied since the start of the experiment was greater in treatment Al than in treatment F, the quantities being approximately 261 kg ha^{-1} and 159 kg ha^{-1}, respectively. The slope of the regression of FMR with time was not significantly different from zero (Fig. 7), so fertilizer consistently increased Olsen P more than manure at the same rate of P application.

Soil organic C

There was no significant trend in FMR for SOC with time over the period 1994–2002 (Fig. 7) although the apparent trend was up rather than down. In 1994, SOC was significantly less in treatment F than in treatment A1, as would be expected since treatment Al had received five applications of manure at 5 t ha^{-1}, while treatment F had received none. By 2002, FMR was not significantly different from 1.0 (Fig. 7). These results are tentative evidence that fertilizer had increased the soil organic matter.

Discussion

Effects of continuous manure

Short duration sorghum in the tropics generally requires between 500 and 600 mm of well-distributed rainfall to give optimum yield in conditions of good soil fertility (Chantereau and Nicou 1994). Grain yield results at Machang'a agreed perfectly with this observation, because the best yields were obtained at around 500 mm of rainfall and when this was exceeded, yield was reduced (Fig. 3).

Interactions occur between water and the availability of nutrients because water increases the rate of release of nutrients from organic or insoluble forms and enables transport to roots and losses from soil to occur. For all crops, the grain yield results demonstrate a strong interaction between soil fertility and water supply: the higher the manure rate, the better the response to water (Fig. 3). This was particularly clear for sorghum. For sorghum, when rainfall was more than about 250 mm, fertility was more limiting than water because additional rainfall in the unmanured soil never gave as high a yield as manure with 250 mm rainfall (Fig. 3). Nutrients supplied in less soluble forms are less prone to loss, and more suitable than mineral fertilizers when rainfall tends to be irregular and then heavy.

Without manure or fertilizer, SOC declined slowly, as would be expected. The degradation of soil organic matter by continuous cultivation has long been known and a comparison of cultivated and forest soils in Nigerian soils showed that cultivated soils contained about half of the SOC in forest soils (Jones 1973). Loss of SOC was lower in soils with higher clay content. Machang'a soil has a clay content of 30.8% and the loss of SOC at Machang' a was slow, the trend being a loss rate of 0.5% and 1.5% per year in 1993–1997 and 1997–2002, respectively, estimated from the regression equations. In contrast, Jones and Wild (1975) concluded that more sandy West African soils lost C at 5–10% per year until reaching a SOC content of 25–45% of the value under natural vegetation.

Significant increases in SOC with manure application are widely reported in the tropics. After 13 applications, manure had increased SOC at Machang'a by 52% and 85% in treatments Al and A2 respectively, compared with treatment C. This increase is comparable to the 40% increase caused by an annual 4.9 t ha^{-1} manure over 15 years in Nigeria (Bache and Heathcote 1969). De Ridder and van Keulen (1990) concluded that 5 t ha^{-1} manure was needed to maintain SOC in West Africa. In some agreement, this application rate at Machang'a resulted in a steady increase of SOC for about seven years to 1997, after which, a new dynamic equilibrium appeared to be reached (Fig. 5). At Machang'a, extra manure, up to 10 t ha^{-1} did not create significantly more SOC than 5 t ha^{-1}, at any time. Clay is the most important soil component that stabilizes SOC, and it was not low (30%) at Machang'a.

However, X-ray diffraction analysis of separated clay showed that it contained approximately 60% kaolinite, a clay mineral of low surface area, charge and chemical activity, which may be unable to stabilize much SOC. It is suggested that the SOC concentration reached by 1997 is about the highest amount can be sustained in this soil and that additional C input in manure was lost as CO_2.

Olsen-P is a widely accepted test for plant-available P, and in the semi-arid tropics, a value of 5 mg kg^{-1} is a commonly accepted critical value, above which P is unlikely to be limiting. By 1994, Olsen-P was near or above 5 mg kg^{-1} in treatment A2, while Olsen-P in treatment A1 remained below this critical value up to 2002 (Fig. 4), suggesting that P availability was a fertility constraint at 5 t ha^{-1} manure treatment throughout the experiment. The increase in Olsen P caused by treatment Al was never quite large enough to be significant, either in an individual season or when assessed by trends. This suggested that the P applied in manure at 5 t ha^{-1} was little more than that required for crop P uptake and immobilization in soil, since P is not subject to gaseous loss and leaching losses are normally small. From 1993 to 1997, manure at 10 t ha^{-1} (A2) clearly resulted in surplus P, which increased the labile P pool in the soil, assessed by Olsen P (Fig. 4). From 1997 to 2002, there was no further rise in Olsen P, suggesting that a new dynamic equilibrium had been reached between P inputs, offtakes, immobilization and mineralization, This interpretation is supported by a partial nutrient budget. Uptakes of P by crops in the year October 1994 to September 1995 were 2.0, 14.8 and 24.0 kg P ha^{-1} in treatments C, A1 and A2, respectively, compared to inputs in manure of 0, 23.5 and 46.9 kg P ha^{-1}. These data show a surplus of P that was 2.7 times greater for A2 (22.9 kg P ha^{-1}) than for A1 (8.6 kg P ha^{-1}). This is approximately in line with the finding that, in February 1995, Olsen P was 3.2 times higher in treatment A2 than for A1. Detailed nutrient budgets to elucidate the dynamics of individual nutrients will be published separately.

Residual value

The assessment of residual value in the field is always difficult because of the expense and commitment needed to maintain work over several years and season-to-season variations in crop growth. The procedure used here, of calculating RV relative to no-manure and continuous manure enabled trends to be observed and results calculated with grain yield, SOC and Olsen P agreed rather well.

Manure applied for four consecutive years increased grain yield up to nine years later, which is a longer period than has been commonly reported elsewhere in semi-arid dryland agriculture, such as three years for maize at Katumani, Kenya (Ikombo 1984), two to three seasons in India (Singh and Desai 1991) and three seasons in Botswana (Carter et al. 1992). Williams et al.

(1995) estimated that the annual breakdown of manure was in the ratio 50:40:10 over three years, in accordance with the commonest findings. At Machang'a, the long residual effect on yield was supported by the residual effects lasting seven years for Olsen-P and eight years for SOC. Long manure residual effects of nine years for millet and 13 years for cotton were also reported by Peat and Brown (1962) in Tanzania. RV for 10 t ha^{-1} manure was no better than for 5 t ha^{-1} manure (Fig. 6), enabling calculation of a combined regression for the trend. This was because the higher manure rate did not create significantly more SOC (Fig.5).

Fertilizer

The apparent increase of SOC in soil receiving only inorganic fertilizer was notable. An increase is to be expected because fertilizer increases biomass production and therefore the C input to soil from roots and crop residue. Similarly, applications of ammonium sulphate and single superphosphate over 15 years caused a small increase in soil C in the savanna zone of northern Nigeria (Bache and Heathcote 1969). The increase in SOC caused by mineral fertilizers is predicted for Machang'a soil by simulation modelling (Micheni et al. In press).

The rates of N and P application were almost the same in treatments A1 and F, but predominantly as organic forms in A1 and inorganic in F. The two treatments are not exactly comparable, since treatment A1 had been commenced in 1989 and reserves of soil organic matter and nutrients had been built up. This was expected to give an advantage to the manure treatment at the start. During the period of study, the effects of manure and fertilizer on grain yields were the same at the start of the comparison period, showing that initially, organic and inorganic sources of P were equally effective. Olsen P was maintained at a higher concentration by fertilizer, so the supply of P was not the cause of the difference between the treatments in grain yield. SOC tended to increase under fertilization, and by 2002 was not significantly different between the two treatments, so it is not clear that inadequate SOC was responsible for the relative decline in yield from fertilizer.

Optimization of soil fertility management

Manure and mineral fertilizers can be complementary methods of soil fertility improvement. Manure is usually in short supply, is bulky and heavy so there is substantial work in applying it, and farmers around Machang'a report that it can introduce weeds and pests. Even in the successful manure-based farming system around Kano, Nigeria, livestock manure does not provide all the nutrients required to sustain the farming system (Harris and Yusuf 2001). Labour may be saved by using mineral fertilizers, which are a more concentrated form of nutrients. However, they require cash for their purchase, so are difficult for smallholder farmers to acquire, and cannot maintain crop yields as well as manure. Based on the good residual value of manure, up to about eight years, manure can be applied intermittently and supplemented by mineral fertilizers in the intermediate years, to boost levels of immediately available nutrients.

There are very many possible, combinations of organic and mineral fertilizers that could be applied over a period up to about eight years, since organic and mineral N, P and K components can be applied separately. Field experiments over this time would be very expensive and inflexible. The development of suitable combinations could be better investigated through simulation modeling. Successful application of the principle of a long-interval manure rotation at the farm level requires farmer-participatory research, so that the many options could be reduced by the farm-specific biophysical and socioeconomic constraints.

Implications for simulation modeling

Simulation models of agro-ecosystems provide means of prediction beyond the bounds of experience or experimentation, and a credible model must handle long-term effects if it is to be useful in the assessment of sustainability. In the Machang'a experiment, most results for sorghum grain, the major product, were described well by correlations with data for only water and nutrient inputs, suggesting that mathematical description, and hence successful simulation modeling, should be achievable for this data set. The data excluded were those for the initial season, before fertility treatments were applied and for seasons when above-optimum rainfall occurred. This shows that a comprehensive simulation model to describe food output for all seasons must correctly describe system response to excess water. However, this could be difficult, because the grain yield losses, especially in the November 1997 season, were caused by events, spoilage in the field, which are unconnected with soil conditions.

Conclusions

Long-term experiments provide information on the sustainability of agricultural systems that can be obtained in no other way. The Machang'a manure experiment described here is one of few extant field experiments in semi-arid Africa of >10 years' duration with constant soil fertility treatments. It is representative of the farming systems of this region because it has used the most important grain crops of the region, a typical crop rotation, has components with manure and fertilizer, and was conducted in a n‘‘near-farm‘‘ situation with local management.

Sustainability of arable cultivation is difficult to define precisely, but may be defined as adequate crop production over an extended period without degradation of the natural resource base. At Machang'a, trends in grain production were not identifiable over 13 years because of the season-to-season variations, caused by variation in rainfall. Because of the central role of soil organic matter in maintaining soil fertility, SOC has been proposed as an indicator of sustainability in a soil management system (Greenland 1994). This is justified by our results. In contrast to the grain yield. data, trends and stable differences between treatments could be identified with SOC and Olsen P.

Two distinct phases were observed in the changes of SOC and Olsen P, from 1993 to 1997, and 1997 to 2002. In the phase soil fertility increased, and in the second it remained approximately stable, appearing to reach a new dynamic equilibrium. C and P behaved differently. Manure at 5 t ha^{-1} increased SOC, but gave only a small increase in Olsen P, probably because P supply did not greatly exceed demand because this was a P deficient site. Manure at 10 t ha^{-1} gave no extra SOC over that generated by 5 t ha^{-1} manure, and the extra C applied must have been lost. On the other hand, the higher manure rate increased Olsen P substantially because supply exceeded demand. Most likely, the P was transformed into insoluble forms.

Results for the residual manure treatments showed that the residual effect of manure could last at least seven years, a longer period than had been expected. Manure applications can be made intermittently and P and some N are stored in the soil. Nutrient supply in intermediate years may be improved with mineral fertilizers although they cannot maintain fertility in the long run. There are very many possible possibilities for the combinations of rates and timing of application of these organic and inorganic inputs, and they should be assessed by simulation modeling and tested with site-specific farmer-participatory research.

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