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EFFECTS OF MANURE AND FERTILIZER ON GRAIN YIELD, SOIL CARBON AND PHOSPHORUS IN A 13-YEAR FIELD TRIAL IN SEMI-ARID KENYA

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SUMMARY

Long-term indicators of soil fertility were assessed by measuring grain yield, soil organic carbon (SOC) and soil Olsen phosphorous for a P-deficient soil. In one set of treatments, goat manure was applied annually for 13 years at 0, 5 and 10 t ha^{-1}, and intercrops of sorghum/cowpea, millet/green gram and maize/pigeonpea were grown. Yield depended on rainfall and trends with time were not identifiable. Manure caused an upward trend in SOC, but 10 t ha^{-1} manure did not give significantly more SOC than 5 t ha^{-1}. Only 10 t ha^{-1} manure increased Olsen P. Measurements of both SOC and Olsen P are recommended. In another set of treatments, manure was applied for four years; the residual effect lasted another seven to eight years when assessed by yield, SOC and Olsen P. Treatment with mineral fertilizers provided the same rates of N and P as 5 t ha^{-1} manure and yields from manure and fertilizer were similar. Fertilizer increased Olsen P but not SOC. Management systems with occasional manure application and intermediate fertilizer applications should be assessed. Inputs and offtakes of C, N and P were measured for three years. Approximately 16, 25 and 11% of C, N and P respectively were stabilized into soil organic matter from 5 t ha^{-1} a^{-1} manure. The majority of organic P was fixed as soil inorganic P.

INTRODUCTION

Sustainable agriculture is concerned with the capacity of agricultural systems to remain productive in the long run (Herdt and Steiner, 1995), but the quantitative assessment of sustainability is difficult. Long-term experiments provide data that can be obtained in no other way. Long-term implies that the primary objectives, treatments and management are not changed during the period under consideration, often at least ten years. Unfortunately, there is a paucity of long-term experiments in the semi-arid tropics (Laryea *et al.*, 1995), and normal change, such as new crop varieties, pests and diseases, means that completely unchanged treatments are unrealistic. However, long-term information on soil fertility can be obtained by measuring trends in the soil nutrient concentrations even though the crops may change. Although there is no universally agreed definition of sustainability, it is certain that adequate soil fertility is an essential component, and the monitoring of nutrient concentrations in soil is a practical approach to the assessment of sustainability.

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In sub-Saharan Africa, there is evidence that declining soil fertility is becoming a major worry to farmers. In the semi-arid Mbeere District (Lower Embu, Kenya), farmers regard low soil fertility as a medium-to-high constraint on land use and a priority for research (Micheni *et al.*, 1999). Rapid population growth and changes in land use occurred from 1985 to 1995 in Mbeere District, just north of the Machang'a trial site, which is described here. There was a 75% increase in cultivated land, leaving only 27% uncultivated in 1995 (Imbernon, 1999). A diagnostic survey of farming found that the economic importance of farm activities was in the order arable > livestock > agroforestry and that the most important crops were maize, sorghum, millet, beans, cowpea and green gram, frequently grown as intercrops (Sutherland *et al.*, 1994). Fallowing had almost ceased and livestock-keeping was declining. Around Machang'a village, the typical farm size was 1.6 ha and about 70% of farmers used manures, but only 8% used mineral fertilizers (J. W. Irungu, personal communication).

The Machang'a manure experiment started as 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 manure and fertilizer. Crop yield and biomass, soil organic C (SOC) and extractable soil P (Olsen P method) were measured until 2002 and the data used to validate APSIM (Agricultural Production SIMulator), a simulation model devised with special consideration for tropical crops and long-term effects. APSIM predicted well the general trends and differences between treatments with and without manure, but for SOC in particular, the difference between 5 and 10 t ha^{-1} manure rates was not well represented (Micheni *et al.*, 2004). Because models contain many adjustable parameters, outputs can be tuned to fit the data, but this does not prove that a model is accurate. Independent and empirical assessment of the significant and non-significant changes and treatment effects is helpful for model validation and essential for the drawing of inferences about soil processes. This is the aim of this paper.

The general objective was to improve the assessment of changes in SOC and available P in a typical semi-arid climate on a P-deficient soil. The data were collected during a medium-to-long term period of 13 years under typical cereal/legume intercropping systems. Specific objectives were (i) to identify significant trends and differences in soil C and P status, (ii) to assess the residual value of manure, (iii) to assess the relative effects of manure and fertilizer at the same rates of N and P addition, and (iv) to identify the relative importance of manure and crop residues in maintaining soil organic matter.

MATERIALS AND METHODS

Field site

The experimental site was at Machang'a, Mbeere District (0°47′S, 37°40′E; 1050 m asl) on a concave slope averaging 5 %. 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,

Table 1. Soil fertility treatments applied at the Machang'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.

	Treatment period	
Treatment code	1989–1992	1993–2002
A1	5 t ha^{-1} a^{-1} manure	5 t ha^{-1} a^{-1} manure
A2	10 t ha^{-1} a^{-1} manure	10 t ha^{1} a^{-1}manure
B1	5 t ha^{-1} a^{-1} manure	None
B2	10 t ha^{-1} a^{-1} manure	None
C	None	None
F	None	NPK fertilizer

personal communication). Meteorological data were collected at the site. The biannual cropping seasons are identified by the month of peak rainfall, and the rainfall for each season was assessed by summation of the total rainfall for October–January and March–June for the November and April seasons respectively.

Agronomy, crop sampling and analysis

The site was previously uncultivated and cleared from native bush at the end of 1988. Existing biomass was removed from the site. All tillage then and subsequently was by hand to approximately 0.15 m depth with a 'jembe' (mattock). Cropping started in March 1989 and the manure treatments commenced in September 1989. 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. Plot size was 5 m^2. The crop rotations compared intercropping and two sole crop rotations. The fertility treatments for all crop rotations were annual additions of goat manure at 0, 5 and 10 t ha^{-1}. The results for the period 1989 to 1993 were published by Gibberd (1995). In February 1993, soil was sampled from all plots, and it was found that the different crop rotations had created no significant differences in SOC, total N, Olsen P or exchangeable cations (Warren *et al.*, 1997). The intercropped rotation was continued, amended as described below or without alteration to the manure treatments. 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 of cereals in October and legumes in March continued to 1996 and then became sole cereals. These results are not reported in detail because the treatment was no longer part of the main experimental comparison.

The soil fertility treatments are summarized in Table 1. Treatments C, A1 and A2 were maintained from 1989 to 2002. The goat manure was obtained from the Ministry of Agriculture's Marimanti experiment station, Tharaka-Nithi District, in September each year, broadcast and immediately incorporated by hand tillage. 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 analysed for 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 A1. 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} and 23.7 kg P ha^{-1} from 1993 to 1996.

The crops were (i) sorghum (*Sorghum bicolor*, cv. 954066), intercropped with cowpea (*Vigna unguiculata*, cv. M66); (ii) pearl millet (*Pennesitum typhoides*, cv. KPM1), intercropped with green gram (*Vigna radiata*, cv. N26); and (iii) maize (*Zea mays*, cv. Katumani) intercropped with long duration pigeonpea (*Canjunus cajun*, cv. Kimbeere), the latter being a local variety. Cereals were planted in rows 0.7 m apart at a spacing of 0.25 m within rows, and the associated legume was planted at the same density in extra rows midway between the cereal rows. In the initial season (April 1989), sorghum/cowpea was grown, and then the pattern of crops was as follows:

November 1989 to April 1993: millet/green gram for two seasons, alternately with sorghum/cowpea for two seasons.
November 1993 to April 1999: sorghum/cowpea each November season; millet/green gram each April season.
November 1999 to April 2002: maize/pigeonpea every season.

The first pigeonpea crop was sown in October 1999, grain harvested in May–August 2000 and the plots then cleared. The second pigeonpea crop was sown in October 2000 and the seed harvested in May–August 2001 and 2002 from the same plants. The intercropped maize was sown every October and March. The change made in 1993 was to bring the experiment into line with local farmers' practice. The change made in 1999 was because cowpeas failed every season from 1995. This was caused by disease, so a change of rotation was essential. The plots that were converted to soil treatments B1, 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, A1 and A2.

In the remaining sole-cropped treatment, cowpea was planted in April 1989 and then the sequence was millet, green gram, sorghum, cowpea until April 1996. Then the crops were: maize (November 1996); followed by millet in April and sorghum in November to April 1999. From November 1999 to April 2002, sole maize was grown.

Crop management was at locally achievable standards, with hand cultivation and weeding, and locally purchased crop protection materials, but the manure and fertilizer were brought in to ensure a constant quality of these inputs. 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. Crop residues were returned to the plots and incorporated at the start of the following season, with the exception of pigeonpea stalks, which were removed. From 1993 to 1996, crop and manure samples for analysis were further dried to constant weight at 60 °C, and their N and P concentrations measured by dissolution in $H_2SO_4/H_2O_2/Li_2SO_4/Se$ solution at

360 °C and colorimetric analysis (Anderson and Ingram, 1993). The surpluses of N and P over crop requirement were calculated from the differences between inputs in manure and fertilizer and offtakes in grains. Recoveries of added nutrients in treatments A1, A2 and F were calculated from the differences between offtakes in grains from these treatments and those from treatment C, expressed as a percentage of added nutrients.

Soil sampling and analysis

Sampling of soil from the 0–0.20 m horizon commenced in February 1993 and was carried out at intervals of approximately six or twelve months, as described by Warren *et al.* (1997). Pits (0.30 × 0.30 × 0.20 m) were dug within steel frames driven into the soil, the soil weighed, mixed, sieved (10 mm mesh) to remove stones, sampled (1 kg) and soil returned to the pit. The sample was air-dried and ground by hand to pass through a 2-mm aperture sieve. 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 pit was dug on the other occasions. From weighing at each stage of sampling and preparation, the mean soil mass (oven-dry, 105 °C) of 2152 t ha^{-1} was found and used to present soil analysis results on an area basis when appropriate. Soil mass ha^{-1} was not significantly affected by time or treatments. 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. Soil organic carbon 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 $(NH_4)_2.Fe(SO_4)_2$ (Anderson and Ingram, 1993).

Statistical methods

Great variability is inevitable for field trials in semi-arid climates, making it difficult to discern meaningful effects. Where possible, different statistical approaches were tried on a data set, to see if the conclusions agreed. An analysis of variance was always calculated for each season individually. Then, linear or multiple regressions were fitted over sequences of seasons to search for trends. Statistical calculations were performed with INSTAT (Stern *et al.*, 1990). The letters *a*, *b*, and *c* are used to denote fitted parameters in model equations. To avoid a proliferation of symbols, they are re-used afresh in each equation, but this does not imply that a letter has a similar meaning in the different equations.

Relationships between grain yield and rainfall under continuous manure

For the continuous treatments (C, A1 and A2), the relationships between grain yield (Y) and seasonal rainfall (X) were described by multiple regression with X and X^2 as explanatory variables. Data for the first season were excluded because the manure treatments had not yet started.

Trends over time in SOC and Olsen P under continuous manure

For treatments C, A1 and A2, the trends were described by linear regression, with soil sampling time (T) in years as the explanatory variable. A value of T = 0 was set at

1 January 1989. Soil organic carbon and Olsen P were assumed to be the same in all plots within each block before manure was first applied in 1989, and a set of three joint regression lines was fitted, diverging from a common origin at 1989. Each equation was of the following form, one for each treatment, with parameter a common to all treatments:

$$\text{SOC or Olsen P} = a + b\,\text{T} \tag{1}$$

To do this, the data were pooled and multiple regression used to fit the model equation:

$$\text{SOC or Olsen P} = a + b_{\text{C}}\,\text{T}_{\text{C}} + b_{\text{A1}}\text{T}_{\text{A1}} + b_{\text{A2}}\text{T}_{\text{A2}} \tag{2}$$

where the subscript denotes the associated treatment. For example, a value for Olsen P in treatment A1 was associated with its sampling time T_{A1}, and T_{C} and T_{A2} were set to zero.

Trends over time in SOC and Olsen P with fertilizer.

For the fertilizer treatment (F), the explanatory variable T (in years) was set to zero at 16 February 1993, the soil sampling date in 1993 before fertilizer was first applied. Olsen P showed a clear curvilinear trend that suggested an asymptote, so these data were fitted to the following empirical exponential equation:

$$\text{Olsen P} = a + b \times c^{\text{T}} \tag{3}$$

For comparison, the same equation was also fitted to data for treatment A1, with the same rate of P addition. The explanatory variable T (years) was set to zero at 1 January 1989.

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:

$$\text{RV}i = \frac{\text{Yield (B}i\text{)} - \text{Yield (C)}}{\text{Yield (A}i\text{)} - \text{Yield (C)}} \tag{4}$$

where Ai denotes continuous manure at rate i, Bi residual manure at rate i and C the treatment without manure. 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 SOC and Olsen P, calculated by equation 4, with the substitution of yield by SOC or Olsen P values.

The trends in yield, SOC and Olsen P were assessed by linear regression with time (T) in years as the explanatory variable.

$$\text{RV} = a + b\,\text{T} \tag{5}$$

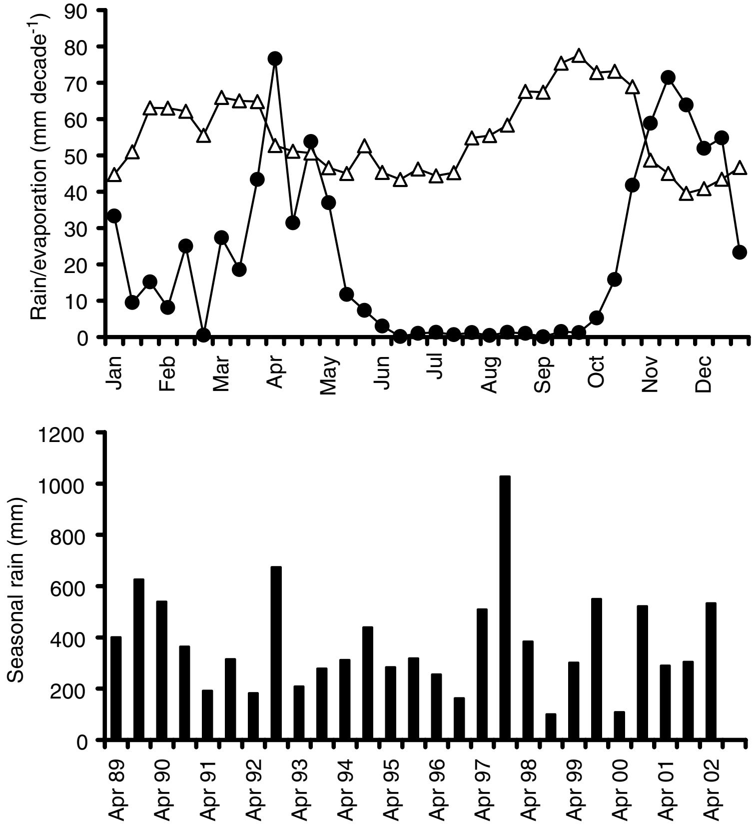

Figure 1. Mean rainfall (●) and USDA class 'A' pan evaporation (△) in 'decades' (10-day periods), averaged over the period 1990–2002, and rainfall during each cropping season, assessed by summation of the rainfall from 1 October to the following 31 January for each November season and from 1 March to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

The value T = 0 was set to 1 January 1993 since the new treatments commenced during 1993.

RESULTS

Weather

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

Continuous manure

Grain yields. For the unmanured plots (treatment C), the first season gave the highest yields of cereals and legumes (Figure 2), and, from then on, yields remained low every

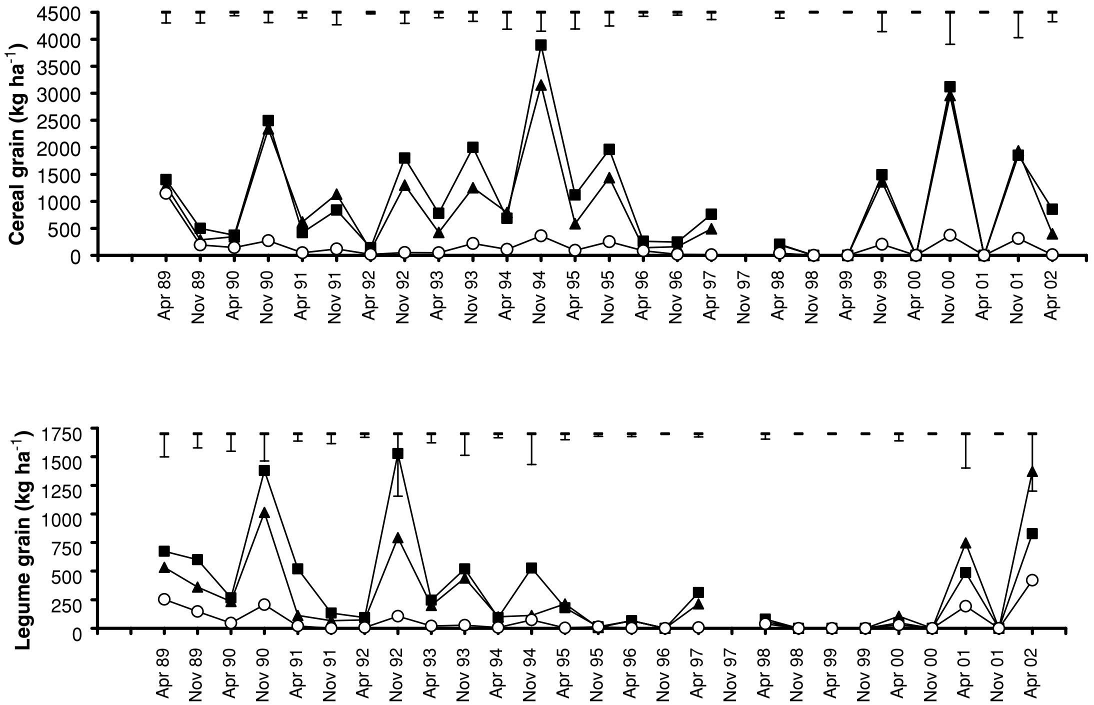

Figure 2. Grain yields of cereals and legumes in each season with intercropping and soil fertility treatments C (●), A1 (▲) and A2 (■), in which 0, 5 and 10 t ha^{-1} a^{-1} manure respectively were applied. Vertical bars represent *s.e.d.* for each season.

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. However, 10 t ha^{-1} manure never gave significantly more grain than 5 t ha^{-1} manure (Figure 2). In the period 1996–1998, all yields were low. For the cereals, this was attributed mainly to adverse weather conditions, e.g. the November seasons of 1996, 1997 and 1998 had the highest and the two lowest rainfall totals on record for that season (Figure 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 (Figure 2); this was caused by an increasing incidence of disease, principally root rot in the cowpeas. After conversion to the maize/pigeonpea system, grain yields were generally better (Figure 2), but this coincided with more favourable rainfall patterns, so the two effects cannot be separated.

The relationships between grain yield and seasonal rainfall were plotted for each rate of manure (Figure 3). For sorghum, the fitted curves suggested that yield with manure increased with rainfall up to a maximum at about 480 mm of seasonal rain and then declined. The regression coefficients of rainfall (X) for manured treatments (A1 and A2) were significantly greater than that for the unmanured (C) treatment, indicating that the yield response to water was increased by manure. There were no significant differences between treatments A1 and A2 for the fitted parameters for rainfall, showing that extra manure gave no benefit in yield. For millet, the results appeared to show a similar pattern, with a maximum yield at around 410 mm rainfall (Figure 3). However, the data were more scattered than for sorghum, so significant relationships were not found. For cowpea and green gram, the fitted response curves were almost linear, and the regression coefficients for X^2 were not significantly different from zero. Simple linear regressions were therefore fitted. Coefficients for X increased in the order $C < A1 < A2$ and many of the differences were significant showing that the higher the manure application, the greater the response to rainfall. This was significant in all three soil fertility treatments. Maize and pigeonpea yields were obtained for only four and three seasons respectively, and these data were not enough to obtain relationships between yield and rainfall.

SOC and Olsen P in 1989. Soil organic C and Olsen P contents should have been the same in all treatments in 1989 and it is unfortunate that no soil analysis was made then. In 2002, samples were taken from an adjacent area that was cleared in 1989, but had reverted to grass and was maintained as a grass pathway. The SOC was 6.4 g kg^{-1} and Olsen P was 1.07 mg kg^{-1}. The common joint origins fitted were 6.84 g kg^{-1} for SOC and 1.65 mg kg^{-1} for Olsen P. The best-fit simulation model with APSIM (Micheni *et al.*, 2004) used SOC = 5.9 g kg^{-1} and Olsen P = 1.0 mg kg^{-1}. We consider that these data are in reasonable agreement and suggest that the common joint origin values found by data fitting were acceptable representations of the original C and P status of the soil.

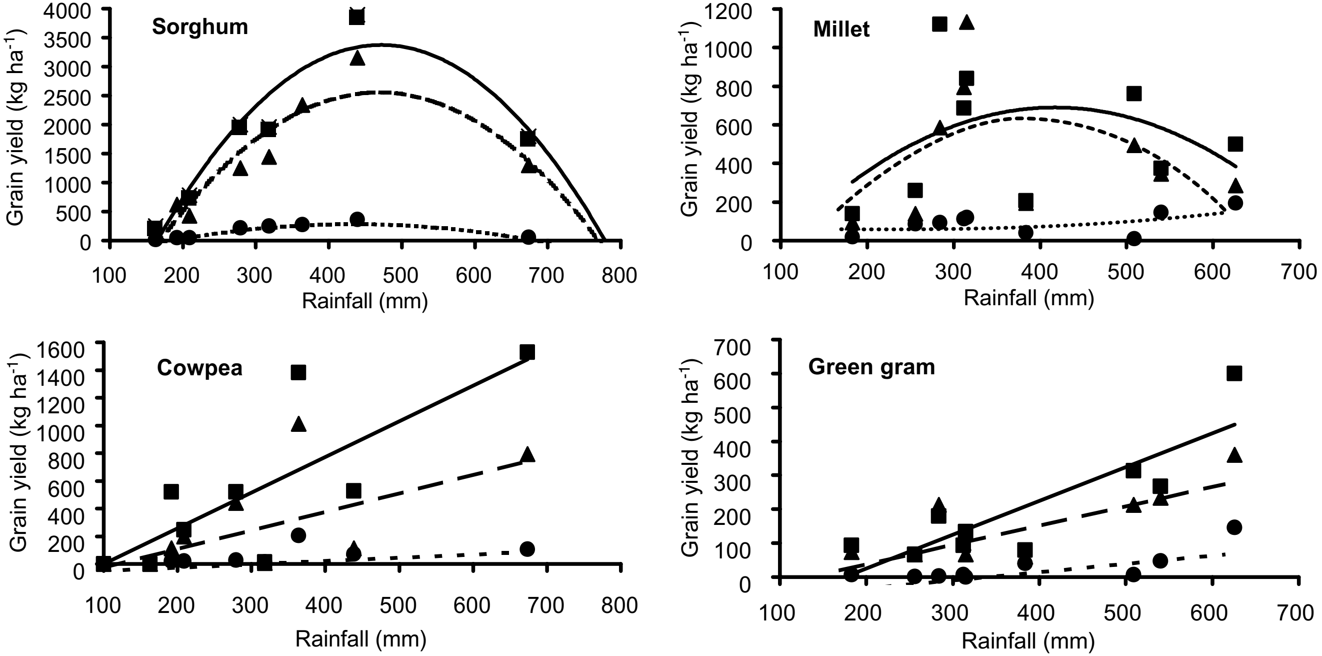

Figure 3. Relationships between grain yield (Y) of sorghum, cowpea, millet and green gram, and seasonal rainfall (X, mm), for soil fertility treatments C (●), A1 (▲) and A2 (■), in which 0, 5 and 10 t ha^{-1} a^{-1} manure respectively were applied. Fitted regression lines (*s.e.* of parameter; *d.f.* = 24) were as follows; it should be noted that no significant correlation was found for millet. Sorghum: Treatment C (······), Y = −348(*90*) + 2.98(*0.54*)X−0.00349(*0.00068*)X^2; Treatment A1(-----), Y = −2352(*398*) + 19.85(*2.39*)X − 0.02092(*0.00301*)X^2; Treatment A2 (——), Y = −2834(*494*) + 24.13(*2.97*)X − 0.02508(*0.00374*)X^2. Millet: Treatment C (······), Y = 112(*114*) −0.331(*0.607*)X + 0.00065(*0.00073*)X^2; Treatment A1 (-----), Y = −913(*722*) + 7.74(*3.86*)X − 0.00963(*0.00466*)X^2; Treatment A2 (——), Y = −533(*820*) + 5.86(*4.38*)X−0.00702(*0.00529*)X^2. Cowpea: Treatment C (······), Y = −19.7(*25.3*) + 0.235(*0.073*)X; Treatment A1 (-----), Y = −112(*139*) + 1.346(*0.402*)X; Treatment A2(——), Y = −256(*238*) + 2.569(*0.688*)X. Green Gram: Treatment C (······), Y = −63.7(*26.0*) + 0.244(*0.065*)X; Treatment A1 (------), Y = −64.3(*73.7*) + 0.577(*0.183*)X; Treatment A2 (——), Y = −174.3(*77.1*) + 0.996(*0.191*)X.

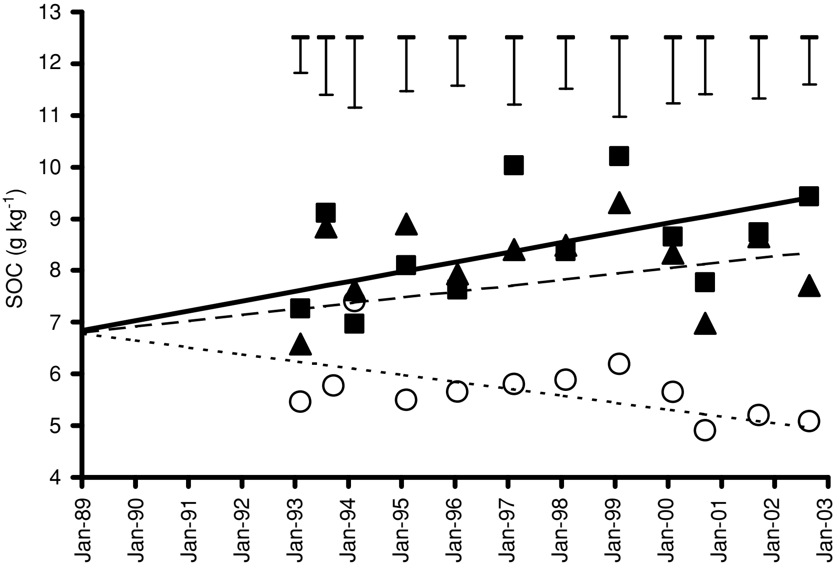

Figure 4. Soil organic C (g kg^{-1}) for treatments C (○), A1 (▲) and A2 (■), in which 0, 5 and 10 t ha^{-1} a^{-1} manure respectively were applied. Vertical bars represent *s.e.d.* for each season. The fitted joint regression lines (*s.e.* of parameter, *d.f.* =139, $F_{(3,139)}$=34.6) describing the relationships between Olsen P and time (T, years, starting 1 January 1989) were: Treatment C (······): P = 6.84(*0.33*) – 0.134(*0.040*) T; Treatment A1 (----): P = 6.84(*0.33*) + 0.113(*0.040*) T; Treatment A2 (—): P = 6.84 (*0.33*) + 0.188(*0.040*) T.

Soil organic C. Compared to the control, treatments A1 and A2 caused significant increases in SOC at almost every sampling (Figure 4), but the difference between treatments A1 and A2 was never significant. For treatment C, the regression coefficient for the trends in SOC with time showed a significant downward trend. From the regression coefficient, the estimated mean rate of loss of SOC in the 0–0.20 m horizon from 1989 to 2002 was 288 kg C $ha^{-1}a^{-1}$, approximately 2 % per year. For treatments A1 and A2, SOC showed significant upward trends, and the mean rates of SOC increase were 243 and 405 kg C ha^{-1} a^{-1} respectively, approximately 1.7 and 2.7 % per year respectively. However, there was no significant difference between treatments A1 and A2 in the rates of increase.

Olsen P. Significant increases in Olsen P were caused by the high rate of manure application. Compared to the control, treatment A2 resulted in significant increases in Olsen P at almost every sampling (Figure 5), 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 A1 for 9 out of 13 sampling occasions. In 1993, continuous manure application had created significant differences between treatments C, A1 and A2, the Olsen P values being 1.0, 2.1 and 3.3 mg kg^{-1} respectively. By 2002, the differences between treatments had widened with the Olsen P values of 1.0, 2.6, and 8.9 mg kg^{-1} respectively (Figure 5).

The trend in Olsen P with time (T) found by the fitted regression coefficient in the joint linear regression was small for treatment C and not significantly different

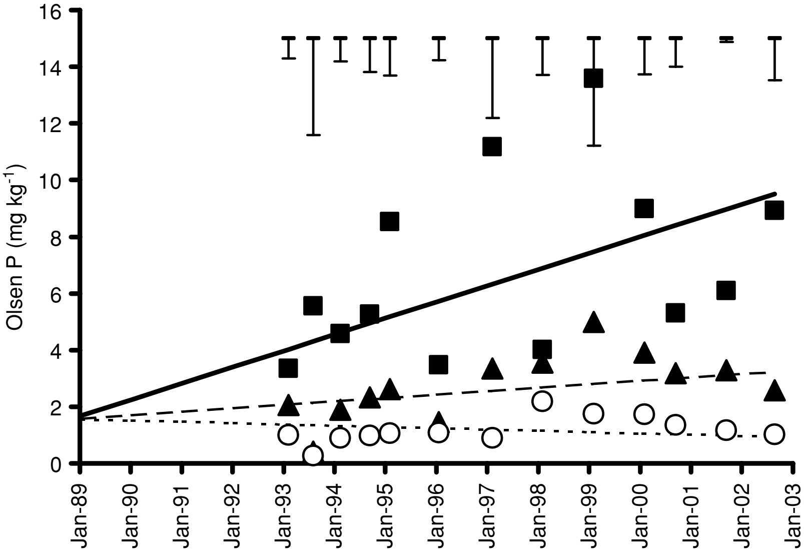

Figure 5. Soil Olsen P (mg kg^{-1}) for treatments C (○), A1 (▲) and A2 (■), in which 0, 5 and 10 t ha^{-1} a^{-1} manure respectively were applied. Vertical bars represent *s.e.d.* for each season. The fitted joint regression lines (*s.e.* of parameter, *d.f.* =148, $F_{(3,148)}$=45.7) describing the relationships between Olsen P and time (T, years, starting 1 January 1989) were: Treatment C (······): P = 1.65(*0.55*) − 0.045(*0.069*) T; Treatment A1 (- - - -): P = 1.65(*0.55*) + 0.122(*0.069*) T; Treatment A2 (——): P = 1.65(*0.55*) + 0.574(*0.069*) T.

Table 2. Inputs of carbon to soil (kg ha^{-1}) and surpluses of N and P (kg ha^{-1}) under intercropping with sorghum/cowpea and millet/green gram between 1 September 1993 and 1 September 1996. Residue C inputs were from above-ground crop residues. Nutrient surpluses were calculated as the differences between nutrient applied and nutrient offtake in grain.

Treatment code	Carbon inputs		N surplus	P surplus
	Manure	Residues		
C	0	2002	−24	−2.2
A1	4593	7100	146	54.6
A2	9184	8397	382	118.6
B1	0	5259	−130	−11.5
B2	0	5669	−127	−13.3
F	0	7136	133	58.4
s.e.d. (*d.f.* = 10)	–	677.1	24.6	2.34

from zero (Figure 5), but it represented a mean annual loss of 0.10 kg P ha^{-1}. For treatment A1, Olsen P increased slightly, at a rate of 0.26 kg P ha^{-1} a^{-1}, but this was not significantly greater than zero. For treatment A2, there was a significant upward trend in Olsen P at a mean rate of 1.24 kg P ha^{-1} a^{-1}.

Nutrient balances. Between September 1993 and September 1996, there were significant surpluses of N and P in treatments A1 and A2 (Table 2). These surpluses were about twice as large for treatment A2 than for treatment A1, in proportion to

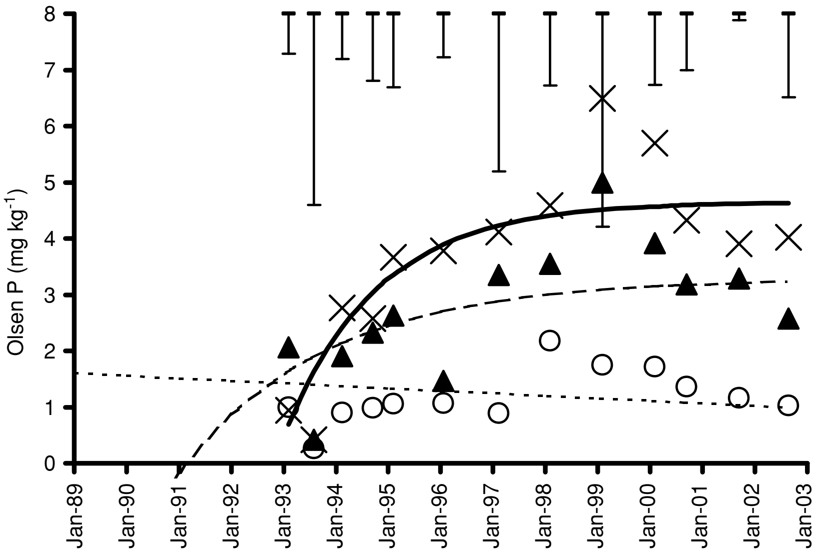

Figure 6. Soil Olsen P (mg kg^{-1}) for treatments C (○), A1 (▲) and F (×), which received no manure or fertilizer, 5 t ha^{-1} a^{-1} manure and NPK fertilizer respectively. Vertical bars represent *s.e.d.* for each season. Data for treatments A1 and F were fitted to exponential equations $P = a + b \times c^{T}$ (*s.e.* of parameter, *d.f.* = 48) where T is time (years), starting 1 January 1989 for treatment A1, and 16 February 1993 for treatment F. The fitted line for treatment C is the joint linear regression line described above (Figure 4). Treatment C (· · · · · ·): $P = 1.65(\mathit{0.55}) - 0.045(\mathit{0.069})T$; Treatment A1 (- - - - -): $P = 3.30(\mathit{0.419}) - 7.21(\mathit{8.06}) \times 0.702(\mathit{0.208})^{T}$; Treatment F (——): $P = 4.65(\mathit{0.283}) - 3.96(\mathit{0.438}) \times 0.571(\mathit{0.101})^{T}$.

the inputs in manure. Over these three years, the nutrient recoveries for treatments A1 and A2 respectively were 52.9 and 38.3 % for N, and 23.3 and 18.4 % for P.

Comparison of fertilizer and manure treatments

Grain yields. Separate comparisons were made for the first three years of fertilizer use, to coincide with the nutrient balance data, and for the subsequent six years. For both cereals and legumes, no significant differences were found between treatments A1 and F in the first period. In the second period, the mean yields per season in treatments F and A1 respectively were 515 and 682 kg ha^{-1} for cereals and 122 and 222 kg ha^{-1} for legumes. Although yields were consistently lower with fertilizer, the differences were never significant even if the data were averaged over the entire period.

Olsen P. Fertilizer immediately increased Olsen P. After one fertilizer application in 1993, Olsen P in February 1994 was significantly higher for treatment F than treatment C and also at several sampling dates thereafter (Figure 6). In any one season, there were no significant differences between treatments F and A1, but from February 1995, this difference appeared relatively constant (Figure 6). The results for the years 1995 to 2002 were pooled and an ANOVA calculated with sampling date and treatments C, A1 and F as factors. Olsen P was significantly higher under fertilizer by a difference of 1.19 mg kg^{-1} ($F_{2,60} = 65.33$) and the difference did not vary between soil sampling dates.

Trends in Olsen P with time were assessed by linear and exponential equations. For treatment A1, the exponential equation did not account for significantly more of the variance than a linear equation, so linear equations were used for comparisons between manure treatments as described above. But an exponential equation was fitted to treatment A1 for a comparison with treatment F, where the trend was clearly curvilinear. The value of the asymptote (parameter a) was significantly higher for treatment F than for A1 (Figure 5).

Soil organic C. Fertilizer appeared to create a small increase in SOC, which in 2002 was 5.08 and 6.29 g kg^{-1} in treatments C and F respectively, but the difference was not significant at any time.

Nutrient balances. Between September 1993 and August 1996, there were no significant differences between treatments F and A1 in the surpluses of N and P, or the returns of C in crop residues (Table 2). Over these three years, the nutrient recoveries for treatments A1 and F respectively were 52.9 and 46.8 % for N, and 23.3 and 18.5 % for P.

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 variability. 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 (Figure 7). Nevertheless, the linear regression between RV and time showed a significant downward trend. The confidence limits ($p < 0.05$) for the fitted mean regression line were also plotted and projected back to April 1993 (Figure 7). They indicated that (i) from April 1993 to December 2001, RV was significantly less than 1 but more than 0, (ii) at April 1993, RV was not significantly different from 1 (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 0. These data suggest that the effects of manure lasted approximately eight years, from the first residual effect season (November 1993) until December 2001.

Olsen P. Residual Value data were rather scattered, but the linear regression of RV with time showed a significant downward trend (Figure 7). The confidence limits ($p <$ 0.05) for the fitted mean regression line were wider than for the grain yield data 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 RV data showed a clear and significant downward trend (Figure 7). 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 0. These data suggest that the residual effects of manure on SOC lasted approximately eight years, until nine years after the final manure application.

Nutrient balances. Between September 1993 and August 1996, there were significantly negative balances for soil N and P (Table 2). However, there were no differences

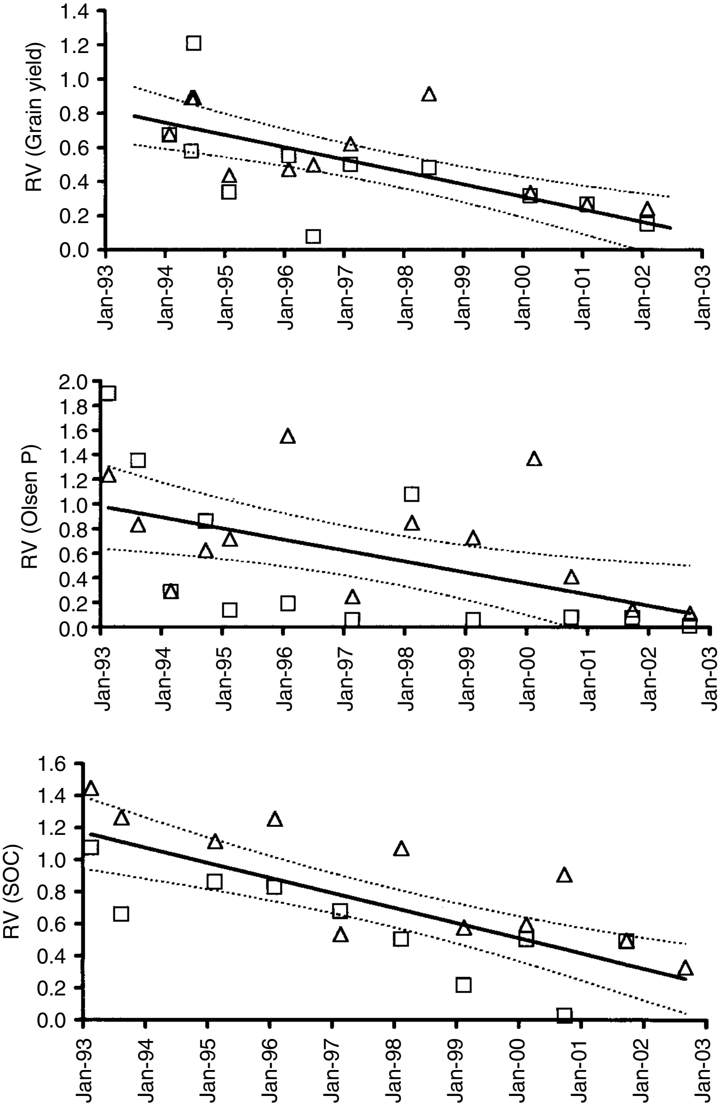

Figure 7. Residual value (RV) of manure, calculated as response to residual manure (treatment B) divided by the response to continuous manure (treatment A), at 5 t ha^{-1} manure (△) and 10 t ha^{-1} manure (□) for cereal grain yield, Olsen P and SOC. Solid lines show the fitted linear regression of RV with time (T years, starting 1 January 1993). The fitted lines (*s.e.* of parameters, *d.f.* = 22) were: RV (Grain Yield) = 0.820(*0.087*) − 0.0727(*0.0157*)T; RV (Olsen P) = 0.980 (*0.165*) − 0.0897(*0.0305*)T; RV (SOC) = 1.169(*0.107*) − 0.0941(*0.0183*)T. Dotted lines denote the 95 % confidence intervals of the fitted lines.

between treatments B1 and B2. This suggests that the extra N and P provided between 1989 and 1992 by treatment B2 compared with B1 did not increase the residual available N and P.

Table 3. Estimated cumulative inputs of carbon to soil between 1989 to August 2002 from manure, applied at 0, 5 and 10 t ha^{-1}, and crop residues, under intercropped and sole-cropped systems, with SOC and Olsen P measured at August 2002. Crop residue inputs were from above-ground crop residues. Soil C inputs were estimated using measurements of C concentrations made in 1993 to 1997. The mean difference between sole crops and intercrops treatments was significant ($F_{(1,10)} = 5.95$) for crop residues C, but not significant for SOC and Olsen P.

	Treatment		
	Control	A1	A2
Manure C (kg ha^{-1})	0	20374	40749
Sole crops residues C (kg ha^{-1})	3422	14341	18010
Intercrops residues C (kg ha^{-1})	5799	17900	20277
$s.e.d.(d.f. = 10)$		1941	
Sole crops SOC (g kg^{-1})	5.61	7.31	9.47
Intercrops SOC (g kg^{-1})	5.08	7.71	9.60
$s.e.d.$ $(d.f. = 10)$		0.089	
Sole crops Olsen P (mg kg^{-1})	0.93	3.10	10.17
Intercrops Olsen P (mg kg^{-1})	1.02	2.57	8.94
$s.e.d.$ $(d.f. = 34)$		1.83	

Sole crop treatments.

Throughout the experiment, the same continuous manure treatments C, A1 and A2 were applied to both intercropped and sole-crop and treatments. Table 3 presents results for these treatments only, arranged in a two-way ANOVA. By 2002, intercropping had produced the same grain yield but significantly more residues (Table 3) suggesting that offtakes of N and P and inputs to soil of C in residues were higher for the intercropped system. However, there were no significant differences between intercrop and sole-crop systems in SOC and Olsen-P (Table 3).

DISCUSSION

Grain yields and indicators of soil fertility under continuous manure

According to Chantereau and Nicou (1994), 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. Sorghum grain yield results at Machang'a agreed well with this observation, because the best yields were obtained at around 480 mm of rainfall and when this was exceeded, yields dropped (Figure 3). Millet yields appeared to peak at about 400 mm rainfall, but the data are not precise enough for this assertion to be justified by statistical results. For all crops, it was clear that manure application improved the response to water (up to a peak for cereals). Improvement of soil fertility in a semi-arid climate is an investment that enables a farm to benefit from potential high productivity in favourable years. Without a run of ten years' data, it would be impossible to quantify statistically the relationship between yield and the most important yield-determining factor. To assess these effects, it is essential to undertake well-characterized medium-to-long term experiments, not single-season trials, and to detail the interactions rather than averaging the responses over different seasons and environments, as stated by Tandon and Kanwar (1984).

In some long-term experiments in semi-arid climates, it has proved possible to identify yield trends or changes over 15 to 20 years, such as in data summarized by Pieri (1995) for groundnut in Senegal, and Nambiar (1995) for a soyabean/wheat/maize rotation in India. For the Machang'a experiment, it was impossible to draw a trend line with time though the yield data shown in Figure 2. The grain yields varied widely in response to rainfall (Figure 3). A seasonal pattern with better yields in the November than the April seasons, regardless of crop combination and rainfall appears to exist (Figure 2). Local experience is that the November season rainfall is more reliable in distribution and starting date, hence many farmers' typical choice of November for sorghum and maize, and April for millet. However, the observation of this effect did not help to identify trends with time. For SOC and Olsen P, trend lines identified significant changes averaged over the 13 years of the experiment and significant differences between treatments (Figures 4 and 5). Therefore, for this time scale of one or two decades, soil measurements are a better indicator of the sustainability of a cropping system. 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.

Residual value of manure

The assessment of residual value in the field is always difficult because of the commitment needed to maintain work over several years and season-to-season variations in crop growth. The method used here, of calculating RV relative to no-manure and continuous manure enabled trends to be observed. 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 for yield was supported by residual effects lasting seven years for Olsen-P and eight years for SOC. Long residual effects for manure of nine years for millet and thirteen 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 (Figure 7), enabling calculation of a combined trend for both manure treatments. This was because the higher manure rate did not create significantly more SOC (Figure 4) in the years 1989 to 1992. This was confirmed by data for the depletion of soil N and P by crops in the three years immediately following cessation of manure application (Table 2), where there were no differences between treatments B1 and B2.

Comparison of fertilizer and manure

Fertilizer increases biomass production and therefore the C input to soil from roots and crop residues, so it should increase SOC. 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). An increase in SOC caused by mineral fertilizers was predicted for Machang'a soil by simulation modelling (Micheni *et al*. 2004), and although a small increase in SOC for treatment F was noted it was not significant.

From September 1993 to August 1996, the effects of manure and fertilizer on grain yields, residues C and surpluses of N and P were almost equal (Table 2). This shows that for the first three years, organic and inorganic sources of P were equally effective for crop production. From the fourth to the ninth years, grain yields were slightly but not significantly lower for fertilizer and this might be the beginning of a decline in the effectiveness of mineral fertilizer, such as has been found in some other semi-arid experiments, as reported by Pieri (1995).

SOC dynamics

In comparison with manure, crop residues were ineffective at increasing SOC. From 1993 to 1996, C input from residues in the fertilizer treatment was 3.6 times that from the control treatment and the same as from manure at the same rate of N and P (Table 2), but only manure increased SOC. From 1989 to 2002, C input from residues in the fertilized treatment was 3.2 times that in the control, but this created no extra SOC after almost 10 years. The intercropped treatments provided more residues than the sole-crop treatment, but failed to create more SOC (Table 3). Reasons for the ineffectiveness of crop residues may include the timing of incorporation in the soil and their decay pattern. In keeping with local farming practice, crop residues were incorporated during tillage before planting rather than immediately after harvest. Especially during the dry July–September period, significant losses of C may have occurred. Potential mechanisms are decay on the surface, termite activity and wind.

Without manure, SOC declined, 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 the SOC of forest soils (Jones, 1973). Loss of SOC was lower in soils with a 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 2 % per year in treatment C, estimated from the regression equations. In comparison, Jones and Wild (1975) concluded that more sandy West African soils lost C at 5 to 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 A1 and A2 respectively, compared with treatment C. This increase is comparable to the 40 % increase caused by an annual application of 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 partial agreement, this application rate at Machang'a resulted in a modest increase of SOC at about 1.7 % per year. From 1993 to 1996, the mean annual increase in SOC accounted for 16 and 13 % of the applied manure C in treatments A1 and A2 respectively, similar to the stabilization value (13 %) found by Jones (1971) in the savanna climate at Samaru, Nigeria. At Machang'a, 10 t ha^{-1} manure did not create significantly more SOC than 5 t ha^{-1}. 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. The additional C input in manure was lost as CO_2.

Soil organic matter is the major soil N pool, so measurements of SOC indicate the reserve of available N. For the 1993–1996 period, the N surplus was measured (Table 2) and part of this was retained by immobilization with SOC. The approximate accumulation of soil organic N was estimated using the regression coefficients for the fitted equations describing the change in SOC with time (Figure 4) divided by the mean C/N ratio of 9.50 for manured soil in 1993 (Warren *et al.*, 1997). From 1993 to 1996, organic N increased by 99.2 and 165.0 kg ha^{-1} in treatments A1 and A2 respectively, leaving 46.8 and 217 kg ha^{-1} to be lost by leaching and gaseous processes. For treatment F, SOC did not change between August 1993 and August 1996, so the surplus 133 kg N ha^{-1} was lost. Losses of N were actually somewhat higher, because additional inputs of N have been ignored. They were (i) atmospheric deposition, which may provide 5 kg ha^{-1} annually, but no local data are available, and (ii) fixation of N by the legumes. On nearby farms, cowpeas fixed 14 to 20 kg N ha^{-1} if P fertilizer was applied (Irungu *et al.*, 2002), but in 1993 to 1996, cowpea yield was poor (Figure 2) so N fixation was probably small. For the 5 t ha^{-1} manure treatment, 24 % of manure N at most, was retained in the soil and 22 % lost. For 10 t ha^{-1} manure, stabilization was lower (21 %) and loss higher (41 %). The retention was lower than at Samaru in semi-arid Nigeria, where about 30 % of manure N was accumulated in the soil (Jones, 1971).

Soil P dynamics

In the semi-arid tropics, 5 mg kg^{-1} is a commonly accepted critical value for Olsen-P, above which P is unlikely to be limiting (El-Swaify *et al.*, 1985). In treatment C, Olsen P was almost always less than 1 mg kg^{-1}, showing that the soil was severely deficient in P. By 1994, Olsen-P was near or above 5 mg kg^{-1} in treatment A2 and continued to increase thereafter (Figure 5), indicating that the supply of P was in excess of the requirement for this P-deficient soil. Olsen-P in treatment A1 remained below the critical value up to 2002 (Figure 5), suggesting that P availability was a fertility constraint at 5 t ha^{-1} manure throughout the experiment.

Despite the season-to-season variability of results, significant trend lines could be fitted. Very high amounts of Olsen P were found in February 1997 and February 1999. In both cases they were immediately after seasons with rainfall well below average (Figure 1) and little or no crop yield (Figure 2), so there would be little offtake of P, explaining the high values for extractable P. Subjectively, the differences between the continuous manure treatments become obvious from 1999 (Figure 4), 10 years after the start of the experiment. Similar results were observed by Nambiar (1995) for semi-arid sites in India, supplied with mineral fertilizers at recommended rates: in a vertisol and a lateritic soil, delays of ten and six years respectively occurred before concentrations of soil extractable P increased. Compared to treatment C, the increase in Olsen P caused by treatment A1 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 P fixation and immobilization in soil, since gaseous loss of P is impossible and leaching losses are normally small. In the early years of the Indian trials (Nambiar 1995) and at Machang'a, a large proportion of the applied P would be used to satisfy the P fixation capacity of this P-deficient soil.

At 18.4 to 23.3 %, the recoveries of P from manure and fertilizer were good, since values range from 5 to 25 % for arable crops (Wild, 1988). However, the majority of P, whether applied as organic or inorganic compounds, was apparently retained in soil inorganic constituents. From 1993 to 1996, Olsen P increased little, by 0.8 and 3.7 kg ha^{-1} in treatments A1 and A2 respectively (derived from mean trends), leaving 53.8 and 114.9 kg ha^{-1} to be fixed. For treatment F, Olsen P increased by approximately 7.6 kg ha^{-1} between August 1993 and August 1996 (Figure 6), leaving 50.8 kg ha^{-1} fixed, a little less than for treatment A1. Surplus fertilizer P must have been fixed as inorganic compounds because fertilizer did not significantly increase SOC. Surplus P from manure could be retained as either organic or inorganic compounds. The organic C/organic P ratio for manured treatments in 2002 was 90.4 (unpublished data), and assuming that it was constant during the experiment, the mean increase in SOC over three years would account for 8.1 and 13.4 kg P ha^{-1} immobilized for treatments A1 and A2 respectively. The remaining 45.7 and 101.5 kg P ha^{-1} were therefore fixed in inorganic compounds. Despite the addition of P as organic compounds, it appears that the majority of manure P, 62 or 69 %, was retained in inorganic compounds. Conversion of organic P to inorganic may also have occurred in treatment C. Over three years, the mean decline in Olsen P provided 0.3 kg ha^{-1}. At a C/P ratio of 90.4, the mean decline in SOC appeared to supply 9.6 kg P ha^{-1}, in excess of the requirement of 2.2 kg P ha^{-1} (Table 2), suggesting that some native organic P was mineralized and then fixed as inorganic compounds.

Data for mineralization and immobilization of organic P under field conditions are scarce. Mineralization of soil organic P can supply P in excess of crop requirements, thus a Nigerian soil provided 29 and 24 kg P ha^{-1} in the first and second years respectively after forest clearance (Mueller-Harvey *et al*., 1986). Machang'a results are in approximate agreement, considering that the Nigerian soil contained about 50 % more SOC and was in a wetter climate (1271 mm mean annual rainfall) so higher P mineralization rates are expected. Over three years at Machang'a, treatments B1 and B2 supplied 11.5 and 13.3 kg P ha^{-1} respectively to crops, associated with a decline in SOC (Figure 7), while up to 12.4 kg P ha^{-1}, may have been mineralized in treatment C. Immobilization into soil organic P of 8.1 and 13.4 kg P ha^{-1} for treatments A1 and A2 respectively occurred over three years, amounting to 10.9 and 9.1 % of the manure P input. As well as immobilization from organic inputs, immobilization from fertilizer P can occur in savanna climates (Ayodele, 1986). Beneficial effects of organic additions to soil, such as the supply of P, reduced P sorption and increased bioavailable fractions (Iyamureme and Dick, 1996) have been emphasized. P fixation from organic sources to inorganic components seems not to have been explicitly considered, but appears to be a major process affecting P availability.

Optimization of soil fertility management

Manure and mineral fertilizers can be complementary methods of soil fertility improvement. Manure is usually in short supply, bulky and heavy, and it can introduce weeds and pests. Even in the successful manure-based farming system of smallholder farmers around Kano, Nigeria, livestock manure does not provide all the nutrients required to sustain it (Harris and Yusuf, 2001). Labour may be saved by using mineral fertilizers, which are a more concentrated form of nutrients but they require cash for their purchase. 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.

Crop residues were not effective for improvement of SOC. Early incorporation into the soil might increase the proportion of C added to SOC, but would increase the farmer's labour requirement. After incorporation in the June/July harvest, further tillage would be needed to create a seedbed before planting in October. Alternative strategies for conserving this organic C resource could be recycling residues via composts or livestock fodder to produce manure. Practical advice for composting in Kenya shows that frequent water addition is usually essential (Njoroge, 1994), and a limitation in most semi-arid areas. Recycling of crop residues via livestock appears better since manure is highly effective for improvement of SOC. However, the keeping of livestock in Mbeere District is in decline (Sutherland *et al*., 1994) because of increasing veterinary costs and small land holdings, problems applicable elsewhere in tropical smallholder agriculture. A better strategy for recycling crop residues as fodder is required, encouraging farmers to maintain a mixed farming system. Processing crop residues via livestock obviously gives a much smaller amount of organic fertilizer, but the manure is far more effective.

There are very many possible combinations of organic and mineral fertilizers that could be applied over a period over 13 years or more. Formal field experiments over this time are limited in scope and expensive. The development of suitable combinations could be better investigated through simulation modelling, provided that the model is acceptably accurate. 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.

CONCLUSIONS

Sustainable 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. Sufficient time is required to assess significant trends, and the data sets used here, taken over 13 years and spanning 15 to 25 seasons were sufficient for SOC and Olsen P. Methods are required to assess the nutrient resource base. Significant trends in grain production were not detected, but SOC and Olsen P showed significant differences and trends with time. The dynamics of C and P were different and both should be measured. SOC and Olsen P are complementary indicators of soil fertility change.

The residual effect of manure could last at least seven years, a longer period than had been expected. For up to nine years, mineral fertilizers maintained yields but did not improve SOC, so in the longer term they could be unsatisfactory. Manure applications to maintain SOC could be made intermittently in conjunction with mineral fertilizers to boost available nutrients. Rotations lasting several years should be examined by modelling and farmer-participatory methods.

Crop residues were ineffective for maintaining SOC, although the quantity of residues-C could exceed the inputs of manure-C. An improved strategy for the use of crop residues as fodder should be sought, since manure is effective for improving soil organic matter.

Organic materials of sub-Saharan Africa have been extensively assessed with regard to their potential to supply N when applied to soil, but data on their P dynamics are relatively scarce, and field assessments of P mobilization/immobilization in semi-arid conditions are almost non-existent. The recovery of applied P was similar for manure and fertilizer. Although manure added P in organic form, the build-up of P in soil organic matter was thought to be modest because this soil lacked the capacity to stabilize C in organo-mineral complexes, especially at the 10 t ha^{-1} manure application rate. A small part of the manure P not required by crops remained in the available Olsen fraction, but most was thought to be retained as inorganic P. Further research on the fate and availability of P added in organic forms is called for.

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REFERENCES

Anderson, J. M. and Ingram, J. S. I. (1993). *Tropical Soil Biology and Fertility. A Handbook of Methods*. Wallingford, UK: CABI Publishing.

Ayodele, O. J. (1986). Effect of continuous maize-cropping on yield, organic carbon mineralisation and phosphorus supply of savanna soils in western Nigeria. *Biology and Fertility of Soils* 2:151–155.

Bache, B. W. and Heathcote, R. G. (1969). Long term effects of fertilizers and manure on soil and leaves of cotton in Nigeria. *Experimental Agriculture* 5:241–247.

Carter, D. C., Harris, D., Youngquist, J. B. and Persaud, N. (1992). Soil properties, crop water use and cereal yields in Botswana after additions of mulch and manure. *Field Crops Research* 30:97–109.

Chantereau, J. and Nicou, R. (1994). *Sorghum*. London: Macmillan.

De Ridder, N. and van Keulen, H. (1990). Some aspects of the role of organic matter in sustainable intensified arable farming systems in the west African semi-arid tropics (SAT). *Fertilizer Research* 26:299–310.

El-Swaify, S. A., Pathak, P., Rego, T. J. and Singh, S. (1985). Soil management for optimized productivity under rainfed conditions in the semi-arid tropics. *Advances in Soil Science* 1:1–64.

Gibberd, V. (1995). Yield responses of food crops to animal manure in semi-arid Kenya. *Tropical Science* 35:418–426.

Greenland, D. J. (1994). Soil science and sustainable land management. In *Soil Science and Sustainable Land Management*, (Eds J. K. Syers and D. L. Rimmer). Wallingford, UK: CABI Publishing.

Harris, F. and Yusuf, M. A. (2001). Manure management by smallholder farmers in the Kano close-settled zone, Nigeria. *Experimental Agriculture* 37:319–332.

Herdt, R. W. and Steiner, R. A. (1995). Agricultural sustainability: concepts and conundrums. In *Agricultural Sustainability: Economic, Environmental and Statistical Considerations*, (Eds V. Barnett, R. Payne and R. Steiner). Chichester: Wiley.

Ikombo, B. M. (1984). Effects of farmyard manure and fertilizers on maize in semi-arid areas of Eastern Kenya. *East African Agricultural and Forestry Journal* 44:266–274.

Imbernon, J. (1999). Pattern and development of land-use changes in the Kenyan highlands since the 1950s. *Agriculture, Ecosystems and Environment* 76:67–73.

Irungu, J. W., Wood, M., Okalebo, J. R. and Warren, G. P. (2002). Enhancement of biological nitrogen fixation input in smallholder farms of semi-arid Kenya through application of phosphorus fertiliser. In *Challenges and Imperatives for Biological Nitrogen Fixation Research and Application in Africa for the 21st Century*, (Eds N. Karanja and J. H. P. Kahindi). Nairobi: African Association for Biological Nitrogen Fixation.

Iyamuremye, F. and Dick, R. P. (1996). Organic amendments and phosphorus sorption by soils. *Advances in Agronomy* 16:139–185.

Jones, M. J. (1971). The maintenance of soil organic matter under continuous cultivation at Samaru, Nigeria. *Journal of Agricultural Science*, Cambridge 77:473–482.

Jones, M. J. (1973). The organic matter content of soils of the savanna soils of west Africa. *Journal of Soil Science* 24:42–53.

Jones, M. J. and Wild, A. (1975). Soils of the West African Savanna. *Technical Communication No. 55. Harpenden: Commonwealth Bureau of Soils*.

Laryea, K. B., Andres, M. M. and Pathak, P. (1995). Long term experiments on alfisols and vertisols in the semi-arid tropics. In *Soil Management: Experimental Basis for Sustainability and Environmental Quality*, (Eds R. Lal and B. A. Stewart). Boca Raton: CRC Press.

Micheni, A., Rees, D. J., Kariuki, I. W., Materi, F. M., Manyara, F. R., Gathama, S. K., Kaburu, K., Ngungi, F. N. and Kang'ara, J. N. N. (1999). An overview of the farmer participatory regional research program of the RRC Embu mandate region. In: *Participatory Rural Appraisals of the Farming Systems of Eastern Kenya, 1998*, (Eds A. Micheni, I. Kariuki, M. Gethi and D. Rees). Kitale: Kenya Agricultural Research Institute.

Micheni, A. N., Kihanda, F. M., Warren, G. P. and Probert, M. E. (2004). Testing the APSIM model with experimental data from the long-term experiment at Machang'a (Embu), Kenya. In *Modelling Nutrient Management in Tropical Cropping Systems*, (Eds R. J. Delve and M. E. Probert). Canberra: Australian Centre for International Agricultural Research.

Mueller-Harvey, I., Juo, A. S. R. and Wild, A. (1985). Soil organic C, N, S and P after forest clearance in Nigeria: mineralisation rates and spatial variability. *Journal of Soil Science* 36:585–591.

Nambiar, K. K. M. (1995). Major cropping systems in India. In *Agricultural Sustainability: Economic, Environmental and Statistical Considerations* (Eds V. Barnett, R. Payne and R. Steiner). Chichester: Wiley.

Njoroge, J. W. (1994). *Field Notes on Organic Farming*. Nairobi: Kenya Institute of Organic Farming.

Peat, J. E. and Brown, K. J. (1962). The yield responses of rain-grown cotton, at Ukiriguru in the Lake Province of Tanzania. II. Land resting and other rotational treatments contrasted with the use of organic manure and inorganic fertilizers. *Empire Journal of Experimental Agriculture* 30:305–314.

Pieri, C. (1995). Long-term soil management experiments in semiarid Francophone Africa. In *Soil Management: Experimental Basis for Sustainability and Environmental Quality*, (Eds R. Lal and B. A. Stewart). Boca Raton: CRC Press.

Singh, R. P. and Desai, G. M. (1991). Farmers' fertilizer practices in the semi-arid tropics of India. *Progress Report 100, Economics Group, Resource Management Program, ICRISAT. Patacheru, Hyderabad: International Crops Research Institute for the Semi Arid Tropics*.

Stern, R. D., Knock, J. and Burn, R. W. (1990). INSTAT. Reading: Statistical Services Centre, The University of Reading.

Sutherland, A., Ouma, J. and Ndubi, J. (1994). Farming in Mbeere. *Report of an Informal Diagnostic Survey of the Farming Systems of Lower Embu, Kenya. Embu: Kenya Agricultural Research Institute*.

Tandon, H. L. S. and Kanwar, J. S. (1984). A review of fertilizer use research on sorghum in India. *ICRISAT Research Bulletin No. 8. Patancheru, Hyderabad: International Crops Research Institute for the Semi Arid Tropics*.

Warren, G. P., Muthamia, J. and Irungu, J. W. (1997). Soil fertility improvements under manuring in semi-arid Lower Embu and Tharaka-Nithi. In *Focus on Agricultural Research for Sustainable Development in a Changing Economic Environment. Proceedings of the 5th KARI Scientific Conference, 14 to 16 October 1996, Nairobi*, 151–163.

Wild, A. (1988). Plant nutrients in soil: phosphate. In *Russell's Soil Conditions and Plant Growth*. 11th edn. (Ed. A. Wild) Harlow: Longman.

Williams, T. O., Powell, J. M. and Fernandez-Rivera, S. (1995). Manure utilization, drought cycles and herd dynamics in the Sahel: implications for cropland productivity. In *Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of Sub-Saharan Africa. Vol II: Technical Papers. Proceedings of an International Conference held in Addis Ababa, Ethiopia, 22–26 November 1993*. Addis Ababa: International Livestock Centre for Africa.