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Long term effects of continuous cereal cropping on soil fertility parameters in farmers fields in Southern Tanzania

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Introduction

Soil organic matter (SOM) levels are known to strongly influence soil productivity. This effect is partially direct, through the mineralization of plant nutrients and provision of cation exchange capacity and partially indirect, mediated through the effects of SOM on soil pH, and a number of soil physical and chemical properties. Some studies have failed to establish any link between changes in SOM levels and soil productivity. A greater number, however, have shown convincingly that soils with high SOM levels are likely to be more productive than soils with low SOM levels and that declines in SOM are usually linked to declines in productivity. SOM levels have been shown to be particularly important in cultivated tropical soils where the high temperatures lead to rapid SOM breakdown, organic matter reserves are often low and the use of other inputs rare. Thus there is much current emphasis on trying to measure and predict changes in SOM levels in cultivated soils and interest in management options that maintain or increase these levels, particularly in low-input tropical production systems.

Where long-term data are available (i.e. over five or more years) it is possible to directly measure changes in SOM levels. However, such data sets are rare in the tropics and frequently come from on station experiments that may not reflect environmental or management conditions on farmers fields. A number of models have been developed to simulate long term organic matter dynamics and these can be useful and relatively successful in their simulations but the data sets do not exist for their validation across the full range of tropical environments. In particular the effect of specific SOM management practices e.g. those involving crop residues, are difficult to model reliably due largely to the paucity of data available for validation.

A third possible method for looking at long-term SOM changes is the spatial analogue method. A useful tool for looking at long term effects of global climate change (e.g. Tate, 1992) this method has also been used to look for long term changes in soil productivity parameters (e.g. Tiffen, 1994). Conceptually simple, it involves comparing soil samples taken from cultivated fields with samples from nearby uncultivated 'virgin' areas or areas which have been under a long-term fallow. Differences between these pairs of samples are attributed to the land-use history of the cultivated field. A number of methodological challenges have to be overcome and assumptions have to be made in order to use this method. One of the methodological difficulties is identifying sites that have not been cultivated through history. In this research aerial photography and satellite imagery have been used to do this. The biggest assumption in using these techniques is that the soils from the cultivated and virgin areas were the same before the former was cultivated. Careful choice of sample sites and meticulous recording of their history reduces the likelihood that this and other assumptions are invalid.

Many of the key land husbandry questions relating to tropical arable and mixed production systems are linked to management of crop residues. The research described here was carried out in semi-arid central Tanzania but the SOM decline and management issues are similar across much of sub-Saharan Africa. Fallow cropping systems have been replaced by continuous cultivation with residues commonly burnt unless needed for livestock grazing. Maize and sorghum are the dominant crops, planted across 90% or more of the area and yields are low averaging at less than 1 tonne/ha. The incorporation of cereal residues is rare, even if they are not required by livestock, as the labour demands, the risks of harbouring pests and the short term nutrient supply benefits which come from burning make incorporation unattractive to farmers. Crop residues remain, however, the largest source of organic matter available in these systems for consideration as a soil amendment.

Thus the indigenous residue management system consists of a combination of grazing and burning depending on household livestock ownership and the location of the livestock relative to the cultivated fields. Clearly, however, a proportion of the cereal residues, above and below ground, remain in the soil and, in theory, can potentially help maintain or at least reduce the decline in long-term SOM levels. The extent to which this is happening is not known. Much work has shown that the decomposition of tropical crop residues is normally quite rapid which would suggest the potential they have to contribute to long-term SOM is limited. Yet, the logic of incorporating or otherwise retaining cereal residues in the fields in these systems depends significantly on their contribution to SOM over the medium to long-term.

Maize and sorghum are C4 plant species and their organic matter has a characteristic ^{13}C signature. The vast majority of the species in the natural vegetation communities are C3 with a different distinctive ^{13}C signature. When working well ^{13}C analysis techniques allow estimates to be made of the amount and rate of incorporation of cereal-derived organic matter in the SOM.

This research addresses a number of questions:

i. Can the spatial analogue method be used to reveal long-term changes in soil organic matter?

ii. What effect does current farmer practice have on SOM levels?

iii. Is there a decline in SOM and to what extent do the surviving cereal residues (above and below ground) contribute to maintaining soil organic matter?

The implications of the findings for residue management 'best practice' in these systems is discussed. The spatial analogue method in combination with delta 13C analysis has been used across a number of sites in Central Tanzania to answer these questions.

Methods

Sites and sampling

Three sites were sampled:

i) Vitono: Maize systems predominantly with some sorghum. Relatively intensive cultivation in the majority of the area since the 1960s
ii) Ikuwala hill area: Again mostly maize based systems but more recently opened up to cultivation. Some shifting cultivation and long fallow systems
iii) Mkulula: Sorghum/maize systems. As with Vitono, relatively recently opened up to cultivation.

Where available (Vitono) a time series of remote sensed data was used to identify suitable sites for sampling. Aerial photos from the years 1955/56 (1:30,000) and 1977 (1:50,000) were used to identify apparently "virgin" areas adjacent to cultivated fields. The photos were scanned into a digital format (300 dpi). Rectification of the 1977 images was done individually to UTM co-ordinates by identification of corresponding features on maps. The 1955/56 images were subsequently rectified to the corrected 1977-photo based on identifiable fix-points. Finally the photos from each year were assembled by the mosaic function in the CHIPS-programme.1. Sites identified from the aerial photography analysis were then visited with the owner and detailed information on the land-use history and farmer-perceived fertility was collected. Remote sensed data were not available for the Ikuwala Hill area or Mkulula thus the farmer/owner was relied upon for site information.

Organic matter extraction

Three composite samples representing the top 20 cm were collected from each of the sites using an auger. Samples were sun dried and sieved (4mm) to remove most of the very recently added organic material. The large particulate organic matter fraction (LPOM) was decanted from this fraction and the mineral remnants on the sieve (> 4mm) discarded. This LPOM was considered to be representative of the more recent organic matter input. Part of the soil was ground using a ball mill and analysed for total c and N using IRMS spectroscopy. The milled whole soil and LPOM fractions were

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1 CHIPS is an image processing software developed by the CHIPS-group at the Institute of Geography, University of Copenhagen.

weighed into tin capsules and analysed subsequently, using a Europa Scientific 20-20 Isotope Ratio Mass Spectrometer, for the determination of total C and N, as well as $^{13}C/^{12}C$ ratios.

Calculations

Gross comparisons were made between cultivated and "virgin" soils for % C , % N, C:N ratio, and $\delta^{13}C$ ‰. Calculations of the proportion of C4 (maize, sorghum) derived material in the SOM of the cultivated soils were made in two ways:

1. Using the theoretical expected difference between the measured $\delta^{13}C$ ‰ value and that expected from uncultivated soil under vegetation dominated by C3 plants (-27 $\delta^{13}C$ ‰) i.e. fraction of C4 derived material in cultivated soil sample

$$= 1 \quad - \frac{\delta^{13}C\ \mathbf{m} - \delta^{13}C\ \mathbf{b}}{\delta^{13}C\ \mathbf{a} - \delta^{13}C\ \mathbf{b}}$$

where:

$\delta^{13}C$ **a** = theoretical signature from wholly C3 plant community = - 27 $\delta^{13}C$ ‰
$\delta^{13}C$ **b** = theoretical signature from wholly C4 plant community = - 12 $\delta^{13}C$ ‰
$\delta^{13}C$ **m** = signature measured in sample

2. Calculating the % C4 relative to the $\delta^{13}C$ ‰ signature of the adjacent "virgin" sample assuming that the signature of SOM wholly derived from C3 plants would be -12 $\delta^{13}C$ ‰. This method was probably more accurate as it accounts for variation in $\delta^{13}C$ ‰ signatures from "virgin" areas due, for example, to the presence of some C4 species in the natural vegetation. The fraction of C4 derived material in the cultivated soil sample

$$= 1 \quad - \frac{\delta^{13}C\ \mathbf{m} - \delta^{13}C\ \mathbf{b}}{\delta^{13}C\ \mathbf{v} - \delta^{13}C\ \mathbf{b}}$$

where:

$\delta^{13}C$ **v** = signature measured in "virgin" area closed to cultivated field.

Calculations were also made to express nitrogen and carbon concentrations in the cultivated soils relative to the concentrations in the adjacent virgin areas.

Data analysis

T-tests were used to test for significance between virgin and cultivated soil parameters were appropriate and linear regression analysis was used to identify relationships between soil parameter changes and the number of years under continuous cereal cultivation.

Results

Site selection and data quality control

Where remote sensing was used to identify adjacent "virgin" and cultivated sample sites (Vitono) the locations corresponded well with information from farmers. The aerial photography interpretation proved a very useful tool for initial identification, particularly in the absence of the farmer/land-owner.

As discussed, the spatial analogue method relies on the validity of the assumption that the soils in the cultivated and the uncultivated areas were the same or very similar before cultivation began. In some cases this was likely to be a valid assumption, e.g. where farmers had kept virgin plots adjacent to cultivated fields or land had been left uncultivated because it had some spiritual significance. In other cases the only available 'virgin' land had been left uncultivated because it was important for access to a particular amenity or for livestock grazing. For these latter cases, though there had been no cultivation and C3 species dominated, there had clearly been some soil erosion, perhaps due to browsing livestock. Where informant information supported the visual observations of soil degradation a decision was made to exclude these samples from any statistical analyses comparing total carbon and nitrogen concentrations between cultivated and uncultivated soils. Processes such as run-off and erosion would be expected to decrease topsoil N, C and SOM concentrations in these 'virgin' areas and comparisons involving these parameters would therefore be invalid. There is no reason to expect that the SOM composition (i.e. relative proportions or C3 and C4 derived material) in these soils would have been affected by these processes, however, and therefore data from these samples were included in the statistical analysis of SOM composition.

Data was first aggregated for analysis and then data from each of three sites was examined separately.

Table 1. Raw sample data with calculations

Sample	village	virgin/ cult	years cult	closest virgin sample	notes on history	% N SOM	% C SOM	δ[13]C ‰ SOM	% N SOIL	% C SOIL	δ[13]C ‰ SOIL	% C4 (1)	% C4 (2)	% soil C change	% soil N change	C:N ratio
8401	Mkulula	cult	14	8408/8409	first cult 1972. Has had 10 yr fallow				0.040	0.34	-25.2	0.12	0.08	0.35	0.40	8.3
8402	Mkulula	cult	10	8408/8409	first cult 1972. Fallowed several times				0.061	0.48	-25.4	0.11	0.07	0.50	0.61	7.9
8403	Mkulula	cult	4	8408/8409	Not sure when first cult, maybe 1970s	0.83	35.05	-16.8	0.082	0.65	-24.2	0.18	0.14	0.68	0.82	7.9
8404	Mkulula	cult	10	8408/8409	Not sure when first cult, maybe 1970s	1.36	24.58	-27.7	0.054	0.41	-25.4	0.11	0.06	0.43	0.54	7.7
8408	Mkulula	virgin	0		rather stony				0.100	0.96	-25.2	0.12	0.08	1.00	1.00	9.6
8409	Mkulula	virgin	0		rather stony, sampled under trees	0.58	38.85	-25.0	0.083	0.76	-27.4	-0.03	-0.08	0.79	0.83	9.2
8405	Mkulula	cult	10	8418	first cult 1970s. Fallowed several times				0.034	0.24	-26.0	0.06	0.13	0.22	0.26	7.0
8406	Mkulula	cult	10	8418	first cult 1960s. Fallowed several times	0.88	31.90	-27.2	0.050	0.36	-26.1	0.06	0.13	0.33	0.38	7.1
8407	Mkulula	cult	8	8418	Not sure when first cult, maybe 1970s	1.23	30.44	-25.2	0.103	0.97	-22.8	0.28	0.33	0.91	0.79	9.4
8410	Mkulula	cult	12	8418	Not sure when first cult, maybe 1970s	0.75	38.89	-18.0	0.106	0.90	-25.6	0.09	0.16	0.84	0.81	8.5
8411	Mkulula	cult	22	8418	Not sure when first cult, maybe 1970s	0.45	42.40	-15.3	0.081	0.69	-25.3	0.11	0.17	0.64	0.62	8.5
8412	Mkulula	cult	15	8418	Not sure when first cult, maybe 1970s				0.071	0.63	-24.8	0.14	0.20	0.58	0.54	8.8
8413	Mkulula	cult	5	8418	Not sure when first cult, maybe 1970s	0.54	39.32	-29.5	0.077	0.63	-24.2	0.19	0.25	0.59	0.59	8.2
8414	Mkulula	cult	7	8418	Not sure when first cult, maybe 1970s	0.35	24.53	-26.7	0.077	0.66	-24.6	0.16	0.22	0.61	0.59	8.5
8415	Mkulula	cult	7	8418	Not sure when first cult, maybe 1970s	0.68	37.52	-29.1	0.112	1.12	-23.0	0.26	0.32	1.04	0.86	9.9
8416	Mkulula	cult	10	8418	first cult 1976, alternate year fallow	0.46	29.23	-22.9	0.079	0.80	-21.0	0.40	0.44	0.75	0.61	10.1
8417	Mkulula	cult	15	8418	first cult 1967, alternate year fallow	0.45	40.58	-25.0	0.097	0.87	-22.3	0.31	0.36	0.81	0.74	8.9
8418	Mkulula	virgin	0			1.13	35.45	-28.7	0.131	1.07	-28.1	-0.08	0.00	1.00	1.00	8.2
plot4	Vitono	virgin	0		not partic fertile (farmer)	1.93	31.57	-28.1	0.106	1.03	-27.1	-0.01	0.00	1.00	1.00	9.8
plot5	Vitono	cult	5	plot4	next to plot4, not clear if cultivated	0.71	21.46	-28.8	0.121	1.18	-27.8	-0.05	-0.05	1.14	1.15	9.7
plot6	Vitono	cult	45	plot4	near to plot 4	1.04	19.69	-24.7	0.073	0.69	-24.3	0.18	0.19	0.67	0.70	9.5
plot7	Vitono	virgin	0		clearly poor soil - not good virgin area	0.87	36.05	-26.9	0.055	0.47	-25.4	0.11	0.00	1.00	1.00	8.6
plot9	Vitono	cult	20	plot7	near plot 7	0.79	19.07	-23.0	0.051	0.44	-23.9	0.21	0.11	0.94	0.93	8.7
101	Vitono	virgin	0		rather poor	0.84	33.79	-31.2	0.055	0.64	-27.0	0.00	0.00	1.00	1.00	11.8
102	Vitono	cult	1	101		0.77	39.03	-29.5	0.039	0.46	-25.8	0.08	0.08	0.72	0.72	11.7
103	Vitono	cult	10	101		0.84	28.77	-21.5	0.040	0.50	-25.4	0.11	0.11	0.78	0.74	12.4
104	Vitono	virgin				1.02	33.35	-26.9	0.048	0.51	-27.7	-0.05	0.00	1.00	1.00	10.8
105	Vitono	cult		104	cont. maize for many years	0.84	26.23	-20.8	0.040	0.51	-24.1	0.19	0.23	1.00	0.84	12.8
106	Vitono	cult		104	boma sample from field 105	0.94	15.33	-25.1	0.239	2.37	-21.0	0.40	0.43	4.61	5.03	9.9
107	Iku hills	cult	20	110	lower slope	0.48	17.51	-25.0	0.064	0.81	-23.9	0.21	0.23	0.32	0.32	12.7
108	Iku hills	cult	20	110	middle slope	0.89	38.11	-23.9	0.083	1.06	-25.1	0.13	0.15	0.42	0.41	12.8
109	Iku hills	cult	20	110	upper slope	0.61	23.05	-28.9	0.055	0.75	-24.9	0.14	0.16	0.30	0.28	13.6
110	Iku hills	virgin	0		difficult to find grass free area - taked under shrub	0.92	34.13	-27.1	0.200	2.54	-27.4	-0.03	0.00	1.00	1.00	12.7
111	Iku hills	cult	16	110		0.83	30.38	-27.7	0.103	1.27	-24.2	0.19	0.21	0.50	0.51	12.4
112	Iku hills	cult	4	114	lower field, seemed more fertile.	0.75	44.80	-29.0	0.091	1.16	-25.4	0.10	0.18	0.63	0.54	12.7
113	Iku hills	cult	4	114	upper field, seemed less fertile.	0.74	32.75	-25.6	0.100	1.06	-23.2	0.26	0.32	0.58	0.59	10.6
114	Iku hills	virgin	0			1.08	33.93	-29.0	0.168	1.83	-28.4	-0.09	0.00	1.00	1.00	10.9

Comparing all cultivated with all virgin areas

Total soil

Of the 9 "virgin" areas sampled farmers volunteered that 4 areas were very poor or very degraded and this was why they were not cultivated. These samples were therefore not included in the calculations.

Table 2. Mean soil characteristics for virgin and cultivated samples.

Sample	% N SOM	% C SOM	C:N SOM	$\delta^{13}C$ SOM	% N soil[1]	% C soil[1]	C:N soil	$\delta^{13}C$ soil	Fraction C4 (1)	Fraction % C4 (2)	Frac. soil C	Frac soil N rem.[2]
Virgin	1.05	34.64	37.16	-27.9	0.14	1.49	10.16	-27.1	-	-	-	-
Cultivated	0.76	31.51	46.23	-24.6	0.07	0.74	9.90	-24.5	0.17	0.19	0.61	0.58
Sig. level[3]	*	ns	ns	*	***	***	ns	***	-	-	-	-

[1] Virgin samples 8409, plot 4, plot 7, 101 excluded from these calculations as farmers reported soil to be degraded or inherently very poor
[2] Calculated relative to local virgin sample
[3] significance (p) levels: * = 0.05, ** = 0.01, *** = 0.001

Average nitrogen and carbon concentrations in the virgin samples were 0.14% and 1.49%, much higher than those in the soil from cultivated fields ($p < 0.001$, Table 2). Cultivated fields contained approximately 60% of the nitrogen and carbon present in the adjacent virgin area. Soil C:N ratios were normal for tropical soils at close to 10 in both virgin and cultivated fields. They were much higher in the extracted organic matter samples, at close to 40 which indicates low that C:N ratio organic material, perhaps associated with the soil mineral components, was not extracted using this method. Mean $\delta^{13}C$ ‰ values were -27.1, very close to the theoretical -27, which indicates the isotopic analysis was sufficiently accurate, though virgin soil sample signatures ranged from -25.2 - -28.4. The mean signature from the cultivated soils was significantly higher ($p < 0.001$) at -24.5 $\delta^{13}C$ ‰ which led to estimates of a mean of 19% C4 plant derived material in the cultivated soils.

Extracted SOM

Virgin/cultivated differences in the parameters % N, % C and $\delta^{13}C$ ‰ were similar in the extracted organic matter to the differences between the whole soils but the variability was greater and the differences sometimes not so large (Table 2). $\delta^{13}C$ ‰ signatures were significantly different between cultivated and virgin soils ($p < 0.05$) but % C differences were not significant. % N differences were significantly higher in the SOM from the virgin soil and can perhaps be explained either by addition of nitrogen rich plant litter (e.g. legume-derived) to the virgin soils under natural vegetation, or relatively more high C:N ratio, cereal-derived residues in the cultivated soil SOM.

Regression analysis

Perfect relationships between time of cultivation and changes in particular soil parameters are unexpected as the histories of the fields are so varied. It was clear during the farmer interviews that farmers could most easily recall what had happened in the last five to 10 years and that beyond this recollection was often difficult. Frequently farmers stated that a field had been cultivated for approximately 10 or 20 years and could be no more precise than this. Where fields had only be cultivated for up to 10 years farmers were better able to give the exact number of years of cultivation and it was easier to find significant relationships between this data and changes in soil parameters. Clearly also the most dramatic changes are most likely to occur in the first ten years after initial cultivation.

The following three parameters were regressed against time of cultivation:

1. % N and % C remaining in cultivated soil (based on current concentrations in the virgin soil)
2. Fraction of C4-derived material in the SOM, assuming this was derived from the two cereal crops: maize and sorghum (using method 2 above for calculations).
3. Soil C:N ratios

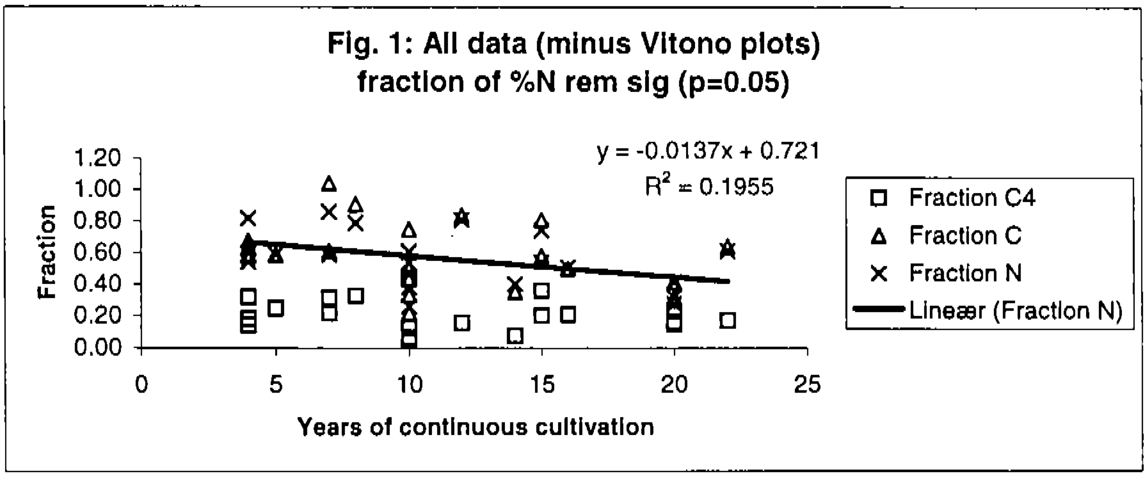
Data was aggregated and disaggregated in a number of ways during the regression analysis. Relationships were looked for between the length of cultivation period and:

(a) The whole data set
(b) Data from fields cultivated for less than 10 years
(c) Data separately for the three sampled areas: Vitono, Ikuwala Hills and Mkulula

C:N ratios overall

No significant differences or relationships were found with C:N ratios between different groups of samples in aggregated or individual data sets (i.e. Mkulula, Vitono or Ikuwala Hill samples) so C:N ratios are not discussed further in this section.

Looking at the aggregated data from cultivated fields the scatter plot suggests a trend towards decreasing %N and %C remaining with increasing time of cultivation but neither is significant, nor any relationship between length of cultivation and proportion of C4 derived material in the SOM. When, however, the Vitono plots linked to the poor or degraded virgin areas are excluded the relationship between % C and % N remaining and length of period of cultivation is stronger and significant in the case of N ($p = 0.05$, Fig 1) but not for C ($p = 0.10$). The relationship is still rather weak, however ($y = -0.0137x + 0.721$, $R^2 = 0.20$). From the scatter graph (Fig 1) it can be seen that the %C remaining data are just a little too dispersed for the relation to be significant. No significant trends were identified between soil % N or % C for aggregated or disaggregated data sets (this is why % N remaining, relative to local virgin soil, calculations were made).



Looking at data only from fields cultivated for less than 10 years (farmers gave more precise information for this period) there is quite a strong and significant relationship between %C4 derived material in the SOM and length of cultivated period (y = 0.0301x + 0.0797, R^2 = 0.57). No other relationship is significant looking only at fields cultivated for less than 10 years.

Mkulula only

No significant trends in the data were found when looking at Mkulula samples only. Visually there is a clear trend of increasing fraction C4 derived material with length of cultivated period if samples from fields cultivated for less than 10 years only are considered, but data are too few for significance.

Vitono only

A very strong relationship is apparent between the fraction of C4 derived material in SOM and time of cultivation (y = 0.0024x + 0.0788 R^2 = 0.97) including fields cultivated from 1 to 45 years.

Ikuwala hills only

With the samples taken from the fields in the hills behind Ikuwala (n=6) regressions linking time of cultivation to both %N remaining (y = -0.0137x + 0.6341, R^2 = 0.72) and % C remaining (y = -0.0157x + 0.6776 R^2 = 0.82) were significant (p = 0.05).

Interestingly the fraction N remaining and fraction C remaining / cultivation time equations are very similar whether based on the Ikuwala hill data alone (n=6) or the whole data set (Table 3, Fig. 2). This increases our confidence that the estimates of rate of N and C decline are reasonably accurate.

Fig. 2. Ikuwalla Hill data only. Fraction N and C remaining relative to virgin areas

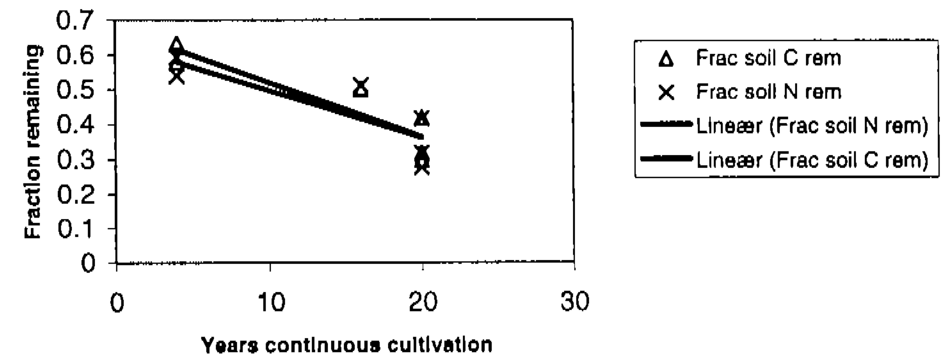
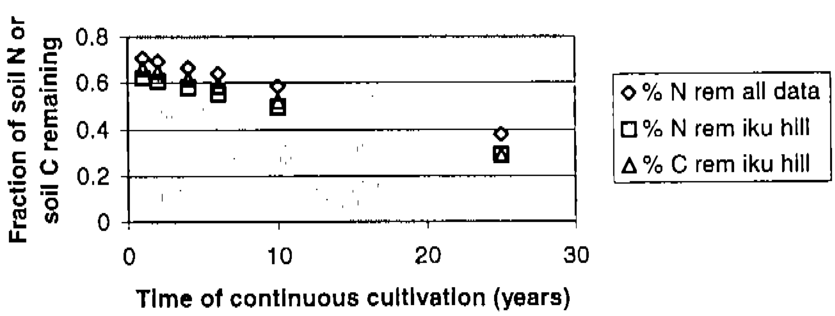


Table 3. Regression equations for rate of N and C decline in cultivated soils for aggregated and disaggregated data.

Data source for regression	Regression equation	R^2 (p= 0.05)
Ikuwala hill data alone (N remaining)	y = -0.0137x + 0.634	0.72
Ikuwala hill data alone (C remaining)	y = -0.0157x + 0.6776	0.82
All data [1] (N remaining)	y = -0.0137x + 0.721	0.20

[1] Excluding Vitono data linked to degraded virgin soil samples

Figure 3. Regression lines or decline in % soil N and C over time using total and Ikuwalla hill data sets

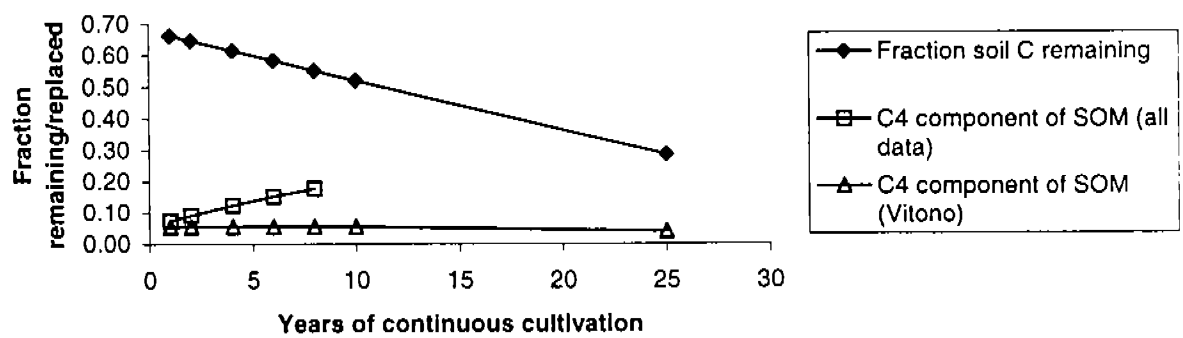


Discussion

In general the spatial analogue method worked well in this research. In particular where both remote sensed and farmer derived data on land-use history were available the sites and data analysis methods could be well chosen.

The aggregated data indicate a relatively steep decline in SOM concentrations is taking place in the cultivated soils with only a third of the original amounts remaining after 25 years of cultivation (Fig. 4). The total amount of carbon loss this involves depends on the concentration in the initial soil but, for an average cultivated soil with 0.74% C (Table 2) this is equivalent to the loss of 300-350 kg /ha/year during the main period of cultivation. The rate of loss may be much higher than this in the first few years

Fig. 4 Simulation of changes in SOM with increasing time of continuous cultivation (based on equations in table 3)



after clearing. This is likely to be one of the reasons for the poor productivity of these soils. With partial residue grazing and burning the dominant farmer residue management strategy it is not surprising that the soil is experiencing a moderately severe SOM decline. However, clearly the cereal residues remaining below and above ground after grazing and burning are contributing to the SOM fraction.

The regression line based on the samples from Vitono (R^2 = 0.97) indicates that the proportion of C4 derived material in the SOM is increasing but when the overall SOM decline is considered it is clear that the total *amount* of C4 derived material in the SOM is remaining remarkably constant. It can be roughly calculated as 5% of the mean cultivated soil C content (0.74%) or approximately 800 kg C/ha. This result indicates that most of the C4 derived organic matter is mineralizing within a few years (even one or two years) and relatively small quantities are contributing to long-term SOM pools. Thus, with current practice, cereal residues are not likely to significantly compensate for the loss of native soil organic matter. There is no reason to believe that larger quantities of cereal residues, if added to the soil, would take longer to decompose.

Changes in residue management practice.

Much work with poor quality, high C:N ration cereal residues has demonstrated there is a danger of nitrogen immobilization as the microbial communities utilize the added carbon. In semi-arid systems this immobilization phase frequently coincides with early-mid season crop growth and competition between crops and the microbial biomass for plant nutrients is common. This is one reason for the general reluctance of farmers to incorporate cereal residues. When considered with the other potentially negative consequences of cereal residue incorporation (pest carry over, labour demands, no early season nutrient flush) a convincing case is easily constructed *against* routine incorporation of cereal residues in low input tropical systems.

1 tonne maize residues remaining after grazing = 400 kg C based on 40% carbon (unpublished data). Clearly most is completely decomposed within two years without significant contributions to long term SOM pools. If *all* residues were returned then perhaps 2-3 tonnes dry matter or 800-200 kg C could be added annually but the mineralization patterns would not be any different and again, most of this would decompose within two years. Thus, if residue management practices change and residues are routinely incorporated, at any one time, they could only contribute a *maximum* or 2.4 tonnes C/ha to the soil, equivalent to 0.01% of the soil mass or only one or two percent of the carbon amounts required in a productive soil. The conclusion must be, therefore, that incorporation of cereal crop residues should not be recommended as a strategy for improving or reducing the decline in SOM levels.

Another important reason for incorporating crop residues is their potential in supplying plant nutrients. Each tonne of cereal residues may contain small amounts of P, 15-20 kg N and as much or more K. Removal of this quantity of nutrients from the soil over the medium to long term will lead to substantial nutrient mining and, eventually, to deficiency problems. Thus, if possible, these nutrients should be conserved within the system. However, as already mentioned, under normal conditions cereal residues are likely to have a net N immobilization effect in the short term and this will prevent rational farmers from opting for direct incorporation.

An option much more attractive for the farmer and also from a technical perspective is cycling the nutrients through grazing livestock where possible and then burning the remaining material. Providing the manure can be returned to the land the following four benefits should accrue:

1. Avoidance of the problems of pest carry over, labour demands, N immobilization etc.
2. Land clearance and nutrient flush (P and K mainly) benefits from burning residues which help with land preparation and early crop growth.
3. Return of nutrients of the soil in the livestock manure (fresh or stored) in a form unlikely to lead to net N immobilization.
4. Return of a proportion of the organic C derived from the crop residues in the manure, in a form more likely to contribute to *long term* SOM reserves with the associated benefits.

Other crop residues

Management recommendations for high quality (low C:N ratio) residues would be different as their incorporation is likely to lead to short term increases in N supply and not net N immobilization. Indeed N rich residues (e.g. from legumes) are one of the very few ways of maintaining or increasing plant available N levels in these systems where external inputs are not possible (usually the case particularly with non-cash, cereal crops). Without such an N input the system will inevitable be seriously N limited as both burning and cycling through livestock expose N to a number of important loss pathways and it is poorly conserved. Mineral fertilizer application are particularly problematic in these systems because of cost, risk of their use in semi-arid environments with erratic rainfall and the understandable reluctance of farmers to apply purchased inputs to their non-cash crops such as the staple cereals.

Conclusions

The results from this work underline the importance of crop-livestock interactions in low-input tropical cereal-based farming systems. The mixed farming model is an old one but components of it still appear to offer the best hope for sustainable improvements in nutrient management and production. The best route for cereal residue carbon to the soil would appear to be through an animal. Moreover, the focus on crop residue management as a means of increasing SOM levels and, through this, productivity, may be misplaced. It may be more realistic to focus on the effects of residues and other organic matter sources on short term nutrient supply. These effects, positive and negative, are much more likely to affect yields in the short term and influence farmers' management decisions. In continuous tropical production systems crop residues are only able to have a small, short term impact on SOM levels.

There are a number of labour, management and availability issues linked to the use of livestock manures which are justifiably receiving attention. It is clear that there will always be a short and long term problem with nitrogen supply in tropical production systems where the soil are poor. Thus the increasing focus on production of more and, in particular, better quality plant residues and organic matter is well placed. Legumes have a uniquely important role to play here. Any management strategy that is able to increase the inputs of legume derived N into these systems is technically attractive and, if it fits within the constraints of the wider production system, should also be an attractive option to farmers.