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Effect of selected organic materials and inorganic fertilizer on the soil fertility of a Humic Nitisol in the central highlands of Kenya

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Abstract

The effect on soil fertility of applying particular organic resources to a humic Nitisol in the central highlands of Kenya was studied. The organic resources (*Calliandra calothyrsus*, *Leucaena trichandra*, *Tithonia diversifolia*, *Mucuna pruriens*, *Crotalaria ochroleuca* and cattle manure) were either applied solely or along with inorganic fertilizer in a cropping trial using maize as the experimental crop. After 4 years of continuous cultivation and manuring, soil fertility effects varied among treatments. Cattle manure proved to be the most effective and improved soil fertility by increasing pH, cations (Ca, K and Mg), and C. *Calliandra, Leucaena, Tithonia* and herbaceous legumes generally reduced soil pH, C and N but increased Ca, K and Mg. Cattle manure is therefore an important resource for maintaining soil organic matter (SOM) in the area and in other similar areas with arable-livestock systems. Reduction of soil C and N by the high quality organic materials suggests that their role in maintaining SOM in the long-term is limited in this area. A sound nutrient management system should strive to make a balance between maximizing crop production and sustaining soil quality.

Keywords: Herbaceous legumes, *Calliandra calothyrsus*, cattle manure, *Leucaena trichandra, Tithonia diversifolia*

Introduction

Decline in soil fertility is one of the primary constraints to agricultural production in sub-Saharan Africa (Sanchez & Jama, 2002). In Kenya, farmers typically apply insufficient soil inputs, usually below the recommended rates (Cheruiyot *et al*., 2001). This along with poor agricultural practices has led to soil nutrient depletion estimated at 30 kg N/ha annually at district scales (Smaling *et al*., 1993). Farmyard manure is the main way to manage soil fertility in central Kenya, but is insufficient in quantity and poor in quality (Kihanda, 2003).

Many long-term studies have shown that combinations of both organic and inorganic nutrient sources lead to enhanced nutrient availability and synchronization of nutrient release and uptake by crops (Bekunda *et al*., 1997; Mugendi *et al*., 1999) and positive effects on soil properties (Wallace, 1996). However, the effects of applied materials vary with cropping systems, soil types, organic material management and environmental factors (Kang, 1993; Schroth *et al*., 1995). Since the 1990s, tropical agricultural research has focused on alternative organic materials (OMs) such as derived from agroforestry and legume cover crops for potential soil fertility replenishment (Palm *et al*., 1995; Abayomi *et al*., 2001); the result has been the development of an Organic Resource Database (ORD) (http://www.ciat.cgiar.org/downloads/pdf/ord_manual.pdf) that mainly uses the quality of OMs to guide the use of organic resources on farms (Palm *et al*., 2001). However, the effect of OMs on soil is also dependent on other factors such as soil type, management and climate and information on these interactions is scarce.

We designed an experiment to investigate the effects of selected OMs on soil fertility of a Humic Nitisol in the central highlands of Kenya. Six OMs were tested and the hypothesis was that single applications of OMs (60 kg N/ha) would contribute more to increases in soil nutrients than

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treatments having lower applications of 30 kg N/ha when combined with fertilizer.

Materials and methods

Study site

This study was in Chuka Division, Kenya at an elevation of 1500 m on the eastern slopes of Mt. Kenya. The locality has an annual mean temperature of 20 °C and a bimodal rainfall pattern totalling 1200–1400 mm. Long rains (LR) and short rains (SR) last from March to June, and October to December, respectively. In the East African Highlands, the long rains occur during the first cropping season. Usually, most of the annual rainfall and crop growth in the study area are in this period (Jaetzold *et al*., 2006). The soils are Humic Nitisols (Jaetzold *et al*., 2006) which are well weathered with high inherent fertility but this has declined over time with poor management.

Experimental design and management

This experiment was established in March 2000 and continued to March 2004 (4 years). It was laid out as a randomized complete block design with three replications and 14 treatments in which six OMs were applied either singly or combined with inorganic fertilizer; a single inorganic fertilizer and a control were also included (Table 1). Treatments were selected to represent 'best bet' soil fertility management practices for the area. Nutrient inputs were applied at the beginning of each of the four seasons to give equivalent applications of 60 kg N/ha as the recommended N rate with Maize (*Zea mays* L, var. H513) as the test crop. Plot dimensions were 6 × 4.5 m with maize planted at an inter-row spacing of 0.75 m and an intra-row spacing of 0.5 m.

Tithonia, Calliandra and *Leucaena* were harvested from nearby plots while cattle manure was obtained from a local farm. These OMs (*Tithonia, Calliandra, Leucaena* and cattle manure) were incorporated into the soil to a depth of 15 cm during land preparation. Before application, organic inputs were sampled and analysed for N following Anderson & Ingram (1993). Cattle manure had the lowest N content (1.3%) while the other OMs had > 3% N in most seasons (Table 2). Amounts of OMs to be applied, equivalent to 30 or 60 kg N/ha, were determined from N contents (an equivalent of 60 and 30 kg N/ha was applied to single and integrated treatments, respectively). These were applied at the start of every season. For treatment 5–13, the rates were constant across the season. For treatments 1–4, the rates varied depending on the amount that was produced during the growing season (Table 3).

N fertilizer (calcium ammonium nitrate (CAN)) was split applied, with 33.3% top-dressed four weeks after planting (WAP) and the rest (66.6%) eight WAP while basal P was applied to all plots at the recommended rate (60 kg P/ha) as triple super-phosphate (TSP). Inorganic fertilizers (CAN and TSP) and pesticides were purchased from local dealers. During the cropping season, recommended agronomic procedures for maize (e.g. weeding and application of pesticides) were followed.

Herbaceous legumes (*Mucuna* and *Crotalaria*) were intercropped between two maize rows 1 week after planting. After

Table 1 Treatments showing organic materials, amount of inorganic N applied and the cropping system in the experiment at Chuka, Meru South district, Kenya

Treatment number	Treatment	N supplied (kg/ha)		Cropping system
		Organic	Inorganic	
1	*Mucuna pruriens* (velvet bean)	[a]	0	Intercropping
2	*Mucuna* + 30 kg N/ha	[a]	30	Intercropping
3	*Crotalaria ochroleuca* (slender leaf rattlebox)	[a]	0	Intercropping
4	*Crotalaria* + 30 kg N/ha	[a]	30	Intercropping
5	Cattle manure (sole)	60	0	Monocrop
6	Cattle manure + 30 kg N/ha	30	30	Monocrop
7	*Tithonia diversifolia* (Mexican sunflower)	60	0	Monocrop (biomass transfer)
8	*Tithonia* + 30 kg N/ha	30	30	Monocrop (biomass transfer)
9	*Calliandra calothrysus* (Calliandra)	60	0	Monocrop (biomass transfer)
10	*Calliandra* + 30 kg N/ha	30	30	Monocrop (biomass transfer)
11	*Leucaena trichandra* (Leucaena)	60	0	Monocrop (biomass transfer)
12	*Leucaena* + 30 kg N/ha	30	30	Monocrop (biomass transfer)
13	Recommended rate of fertilizer	0	60	Monocrop
14	Control (no inputs)	0	0	Monocrop

[a] Total N applied varied among seasons and depended on amount of biomass produced during the previous season. Mean applied per season ranged from 34 to 40 kg N/ha for *Mucuna pruriens* and 36–43 kg N/ha for *Crotalaria ochroleuca*.

Table 2 Average nutrient composition (%) of organic materials applied to the soil during the study period

Treatment	N	P	Ca	Mg	K	Ash
Cattle manure	1.3	0.2	1.0	0.4	1.8	45.9
Tithonia	3.2	0.2	2.1	0.6	3.0	13.0
Calliandra	3.3	0.2	1.0	0.4	1.2	5.9
Leucaena	3.6	0.2	1.4	0.4	1.8	8.5
SED	0.4	0.004	0.04	0.01	0.05	0.27

the maize harvest, legumes were left to grow until land was prepared for subsequent seasons when they were harvested, weighed, chopped and incorporated into the soil to a depth of 15 cm. Weights of herbaceous legumes applied during the experiment varied across the seasons. The amount of N contributed to the soil via incorporated biomass was calculated by multiplying biomass production (kg) with biomass N concentration (%) (Table 3). Generally, the biomass yields increased in 2002, but declined sharply in 2003, especially in *Mucuna,* partly because of rainfall decline. The 2002–2003 rainfall declined by 41% (Table 3) which is substantial (Malhi *et al*., 2008). Maize grain and stover were harvested at physiological maturity (data for maize grain yield are reported elsewhere (Mugwe, 2007; Mugwe *et al*., 2009)).

Soil sampling and analysis

Soil samples were collected from 0 to 15 cm depth at the beginning of the experiment in March 2000 and again after 4 years in March 2004, i.e. at the end of the short rains in 2003 (42 plots) by random bulking from six sampling points within plots to constitute composite samples. Afterwards, they were air dried, sieved (2 mm mesh) and analysed for pH, organic C, total N and exchangeable bases following Anderson & Ingram (1993).

pH was determined in a 1:2.5 ratio of soil to water. Total organic C was determined by colorimetric measurement of chromic ions (Cr^{3+}) produced after digesting soil at 130 °C for 30 min in acidified dichromate. Total N was determined using the Kjeldahl digestion method. Exchangeable bases (Ca and Mg) were extracted in 1 M KCl followed by colorimetric and titrimetric determination, respectively. For available P, extraction with 0.5 M $NaHCO_3$ + 0.001 M EDTA, pH 8.5 solution was used followed by colorimetric determination (Molybdenum blue method). Dried plant samples were also analysed for N, P, K, Ca and Mg following Anderson & Ingram (1993).

Statistical analysis

Data on soil parameters were subjected to ANOVA using Genstat (2008). Treatment means were separated by LSD at $P \le 0.05$. Log-transformed data (SPSS, 2002) were subjected to factor analysis by varimax rotation so as to compare the main soil processes that may have influenced soil fertility before and after the experiment (Brejda *et al*., 2000). Varimax rotation with Kaiser normalisation was used because it results in a factor pattern that highly loads into one factor which can then provide the basis for interpretation (Brejda *et al*., 2000).

Results

At the start of the experiment, the values of soil properties were uniformly distributed across the treatments. However, they changed after 4 years of continuous cropping and applied applications (Table 4).

Soil pH significantly increased only with the single manure treatment (5.2–5.8) ($P = 0.03$). All the other treatments recorded either a decrease in pH or remained constant. The decrease in soil pH was highest in the single fertilizer

Table 3 Amount of biomass produced by herbaceous legumes and their N contribution into the soil during 2002 LR to 2003 SR at Chuka, Meru South District, Kenya

	2002 LR	2002 SR	2003 LR	2003 SR	Average
Treatment	Biomass in t/ha/season and nutrients in kg/ha				
Mucuna	1.7 (42.5)	2.8 (72.8)	0.8 (17.6)	0.2 (4.8)	1.38 (34.4)
Mucuna + 30 kg N/ha	1.9 (45.6)	3.2 (80)	0.9 (23.4)	0.3 (8.4)	1.60 (39.3)
Crotalaria	2.3 (59.8)	2.3 (55.2)	0.6 (16.2)	0.2 (5.0)	1.36 (34.1)
Crotalaria + 30 kg N/ha	2.8 (78.4)	2.5 (65)	0.8 (22.4)	0.3 (6.0)	1.59 (42.9)
Mean monthly rain (mm)	136		81		
Cumulative annual rain (mm)	1636		969		41[a]

Values in parenthesis are amounts of N contributed by the biomass; calculated as biomass in t/ha* amount of N in the biomass which ranged from 2.2 to 2.8%. For the treatments with additional N from inorganic fertilizer, total N added includes the amount in parenthesis + 30 kg N. LR, long rains; SR, short rains. [a]Percentage rainfall decline in 2002–2003.

Table 4 Exchangeable magnesium, organic carbon and total nitrogen during the start of experiment (March 2000) and after 4 years of cropping (March 2004) at Chuka, Meru South District, Kenya

Treatment	pH		Calcium (cmol$_c$/kg soil)		K (cmol$_c$/kg soil)		Mg (cmol$_c$/kg soil)		Organic C (%)		Total N (%)		Number of parameters increased
	2000	2004	2000	2004	2000	2004	2000	2004	2000	2004	2000	2004	
Mucuna pruriens	5.6	5.6	5.6	6.0	0.31	0.18	1.57	1.47	1.83	1.71	0.25	0.22	1
Mucuna + 30 kg N/ha	5.1	5.1	2.7	3.0	0.30	0.31	1.07	1.33	1.74	1.69	0.24	0.24	3
Crotalaria ochroleuca	5.1	4.9	3.2	3.5	0.30	0.17	1.10	1.10	1.89	1.78	0.24	0.24	1
Crotalaria + 30 kg N/ha	5.1	5.2	3.7	4.3	0.26	0.23	1.03	1.57*	1.87	1.79	0.25	0.23	3
Cattle manure	5.2	5.8*	3.9	6.1*	0.33	1.08*	1.07	2.27*	1.68	1.82*	0.24	0.25	***6***
Cattle manure + 30 kg N/ha	5.4	5.1	4.0	5.1*	0.34	0.63*	1.47	1.93*	1.65	1.64	0.23	0.25	***4***
Tithonia diversifolia	5.2	5.1	3.1	3.7	0.22	0.57*	1.37	1.63*	1.89	1.79	0.25	0.24	3
Tithonia + 30 kg N/ha	5.8	5.5	5.6	5.2	0.38	0.44	1.53	1.53	1.71	1.57	0.24	0.21	1
Calliandra calothrysus	5.1	5.1	2.8	3.0	0.26	0.33	0.93	1.30*	1.79	1.69	0.25	0.25	3
Calliandra + 30 kg N/ha	5.0	4.8	2.6	2.2	0.31	0.42	1.03	0.83	1.92	1.90	0.25	0.27	2
Leucaena trichandra	5.6	5.4	5.1	5.0	0.48	0.60	1.57	1.23	1.82	1.65	0.24	0.24	1
Leucaena + 30 kg N/ha	5.2	4.9	3.4	3.0	0.29	0.31	1.43	1.17	1.67	1.54	0.23	0.23	1
Fertilizer (60 kg N/ha)	5.3	4.9	3.4	3.2	0.35	0.19	1.30	1.10	1.87	1.60	0.25	0.20	***0***
Control (no inputs)	5.2	5.0	2.8	2.7	0.377	0.253	0.377	0.253	1.66	1.50	0.22	0.20	***0***
Mean across treatments	5.2	5.3	3.5	4.2	0.32	0.40	1.23	1.38	1.78	1.70	0.24	0.24	
P-value (across treatments)	0.3	0.03	1.1	< 0.001	0.10	< 0.001	0.10	< 0.001	0.873	< 0.001	0.987	0.024	
LSD$_{(0.05)}$ (across treatments)	0.53	0.47	2.02	1.81	0.195	0.202	0.195	0.202	0.397	0.225	0.042	0.029	
P-value (treatment × year interaction)	ns		ns		< 0.001		< 0.05		ns		ns		

*Significant at the 0.05 level. Only significant differences within treatments have been indicated at the end of 2004. Other treatments did not show significant changes. ns, not significant.

treatment (7.5%), followed by manure + 30 kg N/ha (6%), *Leucaena* + 30 kg N/ha (5.8%), *Tithonia* + 30 kg N/ha (5.1%), then the single treatments of *Crotalaria* (4%), *Leucaena* (3.6%), *Crotalaria* + 30 kg N/ha (2.0%), and single *Tithonia*. The general pattern in those treatments that decreased pH was that most of the treatments with fertilizers tended to record higher pH declines followed by those with predominantly single organic treatments.

Exchangeable Ca, K and Mg increased in most of the treatments but with varying magnitudes. Ca increased significantly in the manure treatment (56%) and manure + 30 kg N/ha (26%) but increased slightly in *Tithonia* (16%), *Crotalaria* + 30 kg N/ha (11%), *Mucuna* + 30 kg N/ha (11%), single *Crotalaria* (9%), *Calliandra* (7.7%) and *Mucuna* (7%) treatments (Table 4). The highest declines in calcium were recorded in *Calliandra* + 30 kg N/ha (15%) followed by *Leucaena* + 30 kg N/ha (12%), *Tithonia* + 30 kg N/ha (7%), fertilizer (6%), control; (4%) and *Leucaena* (2%). Overall Ca increased significantly (*t*-test, $P = 0.055$) from an overall mean of 3.5 cmol$_c$/kg soil in 2000 to 4.2 cmol$_c$/kg soil in 2004.

K increased significantly in single manure, single *Tithonia* and manure + 30 kg N/ha treatments. Declines in K were recorded in the fertilizer treatment (46%), followed by *Crotalaria* (43%), *Mucuna* (42%), control (33%), and *Crotalaria* + 30 kg N/ha (12%). *Calliandra* + 30 kg N/ha and single *Calliandra* contributed 36 and 27% K increments after the experimental period. Other treatments showed modest increases ranging from 3 to 25%.

Manure had a profound effect on Mg with > 100% increase, while other treatments increased Mg by < 52% or declined otherwise. The highest decline was in the control treatment (33%) while slight increases resulted after treating soils with *Crotalaria* + 30 kg N/ha (52%), *Calliandra* (40%), manure + 30 kg N/ha (31%), *Mucuna* + 30 kg N/ha (24%), and *Tithonia* (19%). Other treatments showed slight declines ranging from 6 to 22%.

Soil C decreased in all the treatment plots except the manure ones ($P = 0.02$) (Table 4). Fertilizer had the highest decline (14%), followed by the control (10%) while other treatments declined slightly from 0.6% (for manure + 30 kg N/ha) to 9% (for *Leucaena*). Total N showed the highest declines in the fertilizer (20%), *Tithonia* (13%) and *Mucuna* (12%) treatments. Only cattle manure + 30 kg N/ha (9%), *Calliandra* + 30 kg N/ha (8%), and manure (4%) recorded positive changes in total N. Minor declines were also experienced in *Crotalaria* + 30 kg N/ha (8%) while other treatments remained invariable.

Table 5 Rotated component solution for a 2 factor model of soil fertility parameters in 2000 and in 2004 in central Kenya

2000				2004			
	Component				Component		
Parameters	1	2	Communalities	Parameters	1	2	Communalities
Total N	0.922		0.852	Magnesium	0.879		0.775
Carbon	0.918		0.847	Potassium	0.824		0.697
Calcium		0.937	0.878	Calcium	0.805		0.771
Magnesium		0.791	0.641	Carbon		0.881	0.788
pH		0.535	0.488	Total N		0.874	0.772
Potassium		–	0.194	pH		−0.628	0.477
Eigen values	**2.17**	**1.73**		Eigen values	**2.30**	**1.98**	
% Variance	**36.14**	**28.85**		% Variance	**38.27**	**33.06**	
Cumulative variance	**36.14**	**65.00**		Cumulative variance	**38.27**	**71.33**	

Extraction method: Varimax rotation with Kaiser Normalisation, $L = 0.5$ (the cut-off point for displaying loadings was set at 0.5).

Overall, manure increased soil properties for all six measured parameters while manure + 30 kg N/ha positively influenced four parameters (Table 4). Other treatments increased less than half of the parameters, while values for all soil properties from the control and single fertilizer treatments declined. Across treatments, C, total N and pH had average declines of 5, 3 and 2%, while K, Mg and Ca increased by 29, 12 and 8%, respectively. There were significant interactions between OM and time with respect to K and Mg.

Factor analysis of the soil properties before and after the experiment showed changes in the soil correlation matrix in 2004 (Table 5), a result which was expected.

In 2000, the first component (factor) had high loadings (correlation) with total N and C (Table 5) while the second factor had high loadings with Ca and Mg, and a weak pH loading. The first and second components explained 36 and 29% of the total soil variance, respectively. In 2004, components 1 and 2 explained 38 and 33% of the variance, respectively. The first component had high loadings with soil cations while the second component had high loadings with soil C, N, and a medium (−0.628) negative relationship with soil pH.

Discussion

The significant increase in C and pH in the single manure treatment suggests the importance of manure in improving soil organic matter (SOM) as also indicated by Kihanda *et al.* (2006) and Mucheru-Muna *et al.* (2007). Changes in exchangeable bases and pH are mainly influenced by SOM or clay type (Brady, 1984; Bationo & Buerkert, 2001). In this study, a change in soil C content probably explains the changes in soil bases and pH because the soil type was similar across treatments in the experimental site. Cations increase pH by contributing to hydroxyl ions and reduce exchangeable Al in acid soils (Hue & Amien, 1989). A decline in pH and macro-nutrients in all other treatments accords with the findings of Kang (1993) and Mugendi *et al.* (1999) who reported a general reduction in pH after application of fertilizer and legume biomass. This reduction can be explained by continuous cultivation and crop removal which leads to breakdown of soil aggregates, thus exposing the SOM to decomposition and greater soil acidity (Six *et al.*, 2000).

The high K content in the applied biomass (Table 2) explains the significant increase in K (in manure and *Tithonia* treatments). This is in agreement with the findings of Gachengo *et al.* (1999) and Kihanda *et al.* (2006) who reported similar amounts of K in *Tithonia* and a significant increase in soil K following their application. Drastic declines in C and N in the control and inorganic fertilizer treatments in 2004 suggest that OM made a positive contribution to soil C and N in contrast to the non-OMs treatments. The decline in macro-nutrients (Mg and K) for some treatments by 2004 could have also been influenced by higher nutrient uptake in plots with higher inputs and leaching in plots with least C amendment.

While the high quality OMs (*Calliandra, Leucaena and Tithonia*) were associated with the highest maize yields (Mugwe, 2007; Mugwe *et al.*, 2009) (data not shown), the overall C reduction (except manure treatment) implies that the OMs did not improve the soil C status as expected. This can be attributed to faster SOM mineralization than its accumulation, mainly as a result of warm and moist conditions that favour decomposition. The contribution of OMs to increase in SOM reflects the balance between losses by decomposition and gains from addition of OMs (Zingore *et al.*, 2005). Continuous cultivation has been reported to lead to breakdown of soil aggregates, thus exposing SOM to increased microbial activity and mineralization (Teklay, 2005) and this may explain why continuous cultivation led to losses of SOM and N (Six *et al.*, 2000). The single manure treatment suggests that the net C addition which can be associated with low N and high ash manure content (Table 3), led to lower decomposition rates compared with other OMs that were of high quality (high N and low ash content). This study as well as other long-term cropping trials (10–18 years) have demonstrated a decline in OM with time even with OM addition followed by acidification (Kapkiyai *et al*., 1998; Ndung'u *et al*., 2003; Zingore *et al*., 2005). The soil type (Humic Nitisol) is typical of soils which are frequently deficient in N and P, and tends to acidify after continuous cultivation (Bekunda *et al*., 1997). The regular application of fertilizers failed to enhance soil fertility properties. Other workers have similarly noted that the use of fertilizers without inputs or corrective measures to maintain pH can lead to declines in soil C and crop productivity (Bekunda *et al*., 1997).

The results from factor analysis reveal which properties were most influenced by cropping, fertilization and OM management. In 2000, the first component was C and N content while the second factor was mainly dominated by cation exchange and soil acidity. Before the experiment, soil organic processes accounted more for spatial variability in soil fertility than cation exchange, a result found by Mairura *et al*. (2007). Soil C and total N were highly correlated in 2000, but both showed very low correlation with cations and soil pH. In 2004 when C declined in most treatments, pH had an overall decline. This was expected to influence the correlation matrix in 2004 when components one and two consisted of soil cations and soil organic components (C and N). Soil organic processes influenced soil fertility more than soil cation exchange in the experimental site in 2000 while in 2004 cation exchange was more influenced by treatment practices as indicated by the magnitude of eigenvalues and explained variance.

Conclusion

The effect of the OMs, applied singly or in combination with inorganic fertilizer, was variable over the 4 year period. *Crotalaria,* cattle manure, *Tithonia* and *Calliandra* treatments enhanced one or more of the soil properties (pH, soil cations and carbon) while no treatment had an effect on total N after four cropping years. However, cattle manure showed superiority in increasing soil fertility properties, especially pH, Ca, K, Mg and C compared with other OMs. It was the only OM that increased soil C. This suggests its importance as a resource that could be used to build up soil fertility over a long period. Due to its easy availability in the region and its multiple benefits, cattle manure is likely to remain one of the key resources for managing soil fertility in the central highlands of Kenya and in other livestock-arable farming systems in sub-Saharan Africa. There is therefore an urgent need to explore ways of increasing its availability and improving its use-efficiency to boost food production. The other organic resources tested in this study (*Tithonia diversifolia, Calliandra calothyrsus, Leucaena trichandra*) increased cations (Ca, K and Mg) but were limited in sustaining SOM. A sound nutrient management system should strive to make a balance between maximizing crop production and sustaining soil quality.

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