

Organic Inputs and Chemical Fertilizer on Carbon Mineralization From Two Ultisols

Daniel M. Kalala¹, Victor Shitumbanuma¹, Noah Adamtey² & Benson H. Chishala¹

¹ University of Zambia, Great East Road Campus, Lusaka, Zambia

² Research Institute of Organic Agriculture (FiBL), Frick, Switzerland

Correspondence: Daniel M. Kalala, School of Agricultural Sciences, Soil Science Department, University of Zambia, Great East Road Campus, P.O. Box 32379, Lusaka, Zambia. Tel: 260-977-749-368. E-mail: danielkalala2@gmail.com

Received: July 13, 2020

Accepted: September 23, 2020

Online Published: October 15, 2020

doi:10.5539/jas.v12n11p223

URL: <https://doi.org/10.5539/jas.v12n11p223>

Abstract

There are challenges that limit the use of organic inputs for soil fertility management. Amongst them is the limited knowledge of factors that affect rates of decomposition and nutrient release from different organic inputs. A study was conducted on surface soil samples of two Ultisols to determine factors affecting carbon (C) mineralization from selected organic inputs. A loamy sand (LS) from a Kandistult and a sandy clay loam (SCL) from a Paleustult were used. Fine earth fractions of the soils mixed with organic inputs with and without chemical fertilizer were incubated for 13 weeks and the CO₂ evolved was measured. Organic inputs used were biomasses of *Cajanus cajan*, *Tephrosia vogelii*, *Crotalaria juncea*, *Mucuna pruriens*, a mixture of native grasses and shrubs and composted cattle manure. The latter two inputs are traditionally used by farmers, while the leguminous plants were recommended by scientists. Treatments with chemical fertilizer only, representing the conventional farming practice, and a control with soil alone were included. Addition of organic inputs with or without fertilizer increased total CO₂ emissions by 81 to 129% on the LS and by 18 to 34% on the SCL. Adding chemical fertilizer significantly ($p < 0.05$) increased C mineralization rate constant (k) by 116% on the LS and 48% on the SCL. The mean residence time of organic carbon from treatments grouped by input type followed the order: Control > Traditional > Legumes > Conventional on both soils. In general, the k on the LS was double that on the SCL. The type of organic input, soil texture and application of chemical fertilizer significantly affected C mineralization rates from the soils.

Keywords: carbon mineralization, chemical fertilizer, soil texture, mineralization rate constant (k), mean residence time (MRT)

1. Introduction

Low soil fertility is one of the major constraints to achieving high crop yields, food security, and alleviating poverty in Sub-Saharan Africa (Ajayi, Akinnifesi, Sileshi, & Chakeredza, 2007; Bindraban, Batjes, Leenars, & Bai, 2010; Place, Barrett, Freeman, Ramisch, & Vanlauwe, 2003; Rusinamhodzi, Corbeels, Zingore, Nyamangara, & Giller, 2013). Although conventional farming systems that rely heavily on the use of chemical fertilizers have been proposed as a solution to the low soil fertility (Matson, Parton, Power, & Swift, 1997), there are a number of concerns on the suitability of such systems. This is in view of the challenge of balancing the requirement for increased food production with preserving the natural resource base, and coping with threats of climate change (Diacono & Montemuro, 2010; Tilman, Cassman, Matson, Naylor, & Polasky, 2002). The conventional farming systems have further been deemed to be unsuitable for most low-income small-scale farmers in Africa because of the high cost and sometimes unavailability of chemical inputs (Bationo et al., 2012; Lal, 1987).

The use of organic inputs with or without chemical fertilizer has been proposed as an alternative way of managing problems of low soil fertility in sub-Saharan Africa (Ajayi et al., 2007; Nalivata et al., 2017; Roobroeck, Van Asten, Jama, Harawa, & Vanlauwe, 2015; Samuel & Ebenezer, 2014). Although there is abundant literature citing benefits of using organic inputs alone or in combination with chemical fertilizer on soil fertility (Bouajila & Sanaa, 2011; Diacono & Montemuro, 2010; Muyayabantu, Kadiata, & Nkongolo, 2013; Nyamangara, Piha, & Giller, 2003; Waswa, Mugendi, Vanlauwe, Nandwa, & Kung'u, 2003), there are still

challenges with the use of organic inputs. They include how to determine correct application rates and when to apply the inputs to ensure that nutrient release coincides with crop nutrient demand. The challenges are largely due to differences in the nutrient mineralization rates of organic inputs (Nyamangara, Mtambanengwe, & Musvoto, 2009) which are influenced by soil microbial activity, which in turn depends on the soil temperature, moisture content, pH, and the quality of organic matter (E. Ambrosano, Trivelin, Cantarella, G. Ambrosano, & Muraoka, 2003; Rustad et al., 2000).

As opposed to the readily release of nutrients to crops when chemical fertilizers are applied alone, the rate and pattern of nutrient release when fertilizer is applied with organic inputs varies widely (Khalafalla & Hamed, 2015), depending on the C/N ratio, lignin, and polyphenol contents of the organic inputs (Hossain et al., 2017; Khalafalla & Hamed, 2015). Harmonizing nutrient release from organic inputs with crop nutrient requirements is critical to increasing crop yields and improving soil fertility in systems dependent on organic inputs for maintaining soil fertility. The objective of this study was to assess the effects of organic inputs, soil texture and application of chemical fertilizer on carbon mineralization. The hypothesis was that the rate of carbon mineralization in soils is significantly influenced by soil texture, type of organic inputs and addition of chemical fertilizer.

2. Materials and Methods

2.1 Description of Sites From Which Soil Samples Used in the Study Were Obtained

Surface soil samples from 0 to 20cm depth were collected from field crop trial plots at Misamfu (10°10'09.36"S; 31°14'24.92"E) and Msekera (13°38'43.17"S; 32°33'38.93"E) Agricultural Research Stations (ARSs) in Zambia where the Organic Resource Management to Build Soil Fertility Project (<http://www.r4d.ch/modules/food-security/building-soil-fertility>) was implemented. The locations of Misamfu and Msekera ARS are presented in Figure 1. Misamfu ARS is at an average elevation of 1536 m above sea level, while Msekera ARS is 1030 m above sea level. The average air temperature during the growing season ranges from 23 °C to 25 °C and from 16 °C to 24 °C at Msekera ARS and Misamfu ARS respectively. The soil at Msekera was a Paleustult (Veldkamp, 1987) with a sandy clay loam surface horizon while the soil Misamfu was a Kandiuustult (Magai, 1985) with a loamy sand surface horizon. These two soils are representative of extensively cultivated agricultural soils in the Eastern and Northern Regions of Zambia. Zambia has a tropical continental climate with three distinct seasons namely (i) a cool dry season from April to August (ii) a hot dry season from September to November and (iii) a warm wet season from November to March (Muchinda & Spaargaren, 1985). Msekera and Misamfu ARSs are in agro-ecological regions II and III of Zambia respectively. Region II has a mean annual rainfall of between 800 to 1000 mm while region III receives more than 1000 mm rainfall.

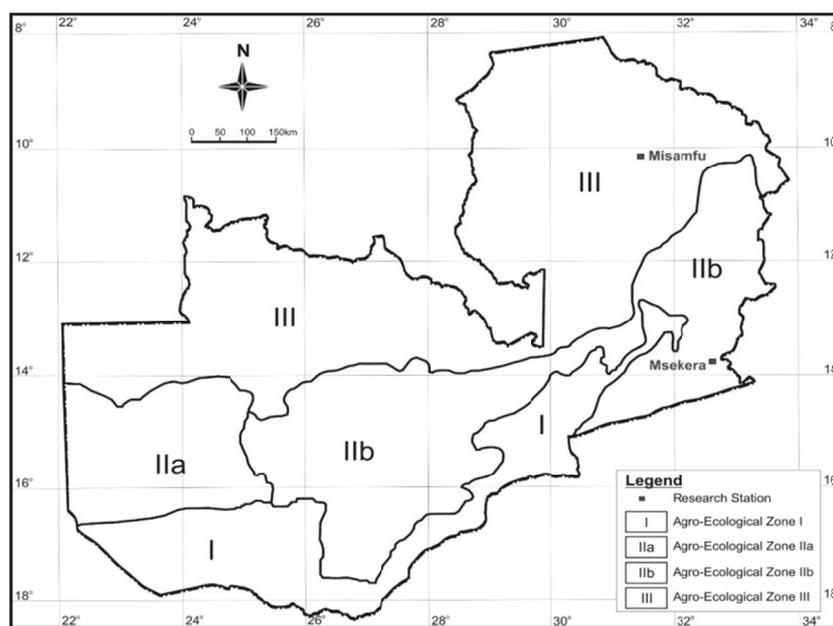


Figure 1. Map of Zambia showing the agro-ecological regions and locations of Misamfu and Msekera ARS

The field experiment at both sites was laid out in a randomized complete block design (RCBD) in 10×10 m plots with four replicates at Misamfu ARS and five replicates at Msekera ARS. There were eight treatments at Misamfu ARS and nine treatments at Msekera ARS.

2.2 Description of Treatments Used in the Study

The organic inputs used in the incubation study were part of the treatments used in field experiments by the ORM4Soil Project at Misamfu and Msekera ARSs. Inputs used in the field experiments at each location had been selected following recommendations from local farmers through a participatory rural appraisal to identify traditional and researcher-recommended soil fertility management practices with the potential of improving soil fertility on small-scale farmers' fields. The treatments recommended by researchers at both ARSs were interplants of maize with *Cajanus cajan* (pigeon peas) and with *Tephrosia vogelii* (tephrosia). Besides these two interplants, a further interplant of maize with *Crotalaria juncea* (black sunnhemp) was included at Msekera ARS. All the interplant systems included the use of chemical fertilizers consisting of Compound D fertilizer (10% N; 20% P₂O₅; 10% K₂O) used as a basal dressing fertilizer and urea (46% N) used as a top-dressing fertilizer. The chemical fertilizers were applied at full (200 kg/ha) and half (100 kg/ha) of the recommended rate for small-scale farmers in Zambia.

The traditional soil fertility management practices used was the *Fundikila* system at Misamfu ARS and composted cattle manure at Msekera ARS. The *Fundikila* system involves burying native grasses and shrubs under large soil ridges towards the end of the growing season at the end of March to early April. The organic inputs decompose under the ridges, until the ridges are opened-up and flattened before the onset of the rainy season in early December and the crop is then planted. A modification of the traditional *Fundikila* system which consisted of burying biomass of velvet beans (*Mucuna pruriens*) grown from December to April instead of the native grasses and shrubs was included at Misamfu ARS. The traditional *Fundikila* was tested in combination with the full rates of Compound D and urea fertilizers as practiced by farmers, while the modified *Fundikila* was assessed with full and half rates of the chemical fertilizers. The composted cattle manure was used singly or in combination with half of the recommended rate of Compound D fertilizer. A conventional treatment consisting of a maize monocrop with full rates of Compound D and urea was included in both sites as a control treatment. For the laboratory study all treatments except the control received an equivalent of 4,877 kg maize stover biomass /ha. Table 1 gives a summary of the treatments used on the two soils and the associated treatment codes.

Table 1. Codes and description of field treatments used in the study

Treatment Code	Amount (kg/ha) and type of organic inputs applied	Amount (kg/ha) and type of fertilizer applied	Soil Used
PpSF	6121 pigeon pea + 4,877 maize stover	200 D + 200 Urea	LS and SCL
PpSF _{1/2}	6121 pigeon pea + 4,877 maize stover	100 D + 100 Urea	LS and SCL
TepSF	8014 tephrosia + 4,877 maize stover	200 D + 200 Urea	LS and SCL
TepSF _{1/2}	8014 tephrosia + 4,877 maize stover	100 D + 100 Urea	LS and SCL
SunnSF	7,812 sunnhemp + 4,877 maize stover	200 D + 200 Urea	SCL
SunnSF _{1/2}	7,812 sunnhemp + 4,877 maize stover	100 D + 100 Urea	SCL
VvSF _{1/2}	10,328 velvet bean + 4,877 maize stover	100 D + 100 Urea	LS
VvS	10,328 velvet bean + 4,877 maize stover	0 D + 0 Urea	LS
IndSF	20,480 native grasses and shrubs + 4,877 maize stover	200 D + 200 Urea	LS
ManSF _{1/2}	20,000 composted cattle manure + 4,877 maize stover	100 D + 0 Urea	SCL
ManS	20,000 composted cattle manure + 4,877 maize stover	0 D + 0 Urea	SCL
SF	4,877 maize stover	200 D + 200 Urea	LS and SCL
Cont	-None-	0 D + 0 Urea	LS and SCL

2.3 Characterization of Soils and Organic Inputs Used in the Study

Air dried soil samples that had passed through a 2 mm mesh size were tested for their pH in 0.01 M CaCl₂ at a soil to solution ratio of 1:2.5 (McLean, 1973). Soil organic carbon was determined by the potassium dichromate wet oxidation method (Nelson & Sommers, 1982); total nitrogen (N) by the Kjeldahl distillation method (Jones, 2001) following digestion with concentrated H₂SO₄; available phosphorus (P) by the Bray 1 method (Jones, 2001); and exchangeable potassium (K) using the 1 M ammonium acetate method (Chapman, 1965). The particle size distribution was determined using the hydrometer method (Jones, 2001) while the bulk density was determined using the core ring method (Casanova, Tapia, Seguel & Salazar, 2016).

The plant biomasses and composted cow manure were air-dried under a shed for a week and then oven-dried at 65°C for 48 hours (Campbell & Plank, 1998; Dalal, Sahrawat, & Meyers, 1984). The organic materials were then milled using a Thomas-Wiley Laboratory mill (Model 4) and sieved using a 2 mm mesh size sieve. Total nitrogen contents of organic materials were determined using the salicylic-thiosulphate method described by Amin and Flowers (2004). The total K and P were extracted by dry-ashing and digested in 1M nitric acid (Jones, 2001). Concentrations of K in the extracts were determined on a Perkin Elmer Analyst 400 Atomic Absorption Spectrophotometer while concentrations of P were determined using a JENWAY 6305 UV/Visible spectrophotometer at a wavelength of 882 nm. The organic carbon content of the plant materials was determined by the Walkley and Black method (Okalebo, Gathua, & Woomer, 2002; Schumacher, 2002). The characteristics of the organic inputs are as shown in Table 3.

2.4 Set-Up of Incubation Study

The incubation experiment was conducted over 13 weeks to reflect the average growth period of early maturing maize varieties, which according to Oluwaranti, Fakorede and Badu-Apraku (2008) ranges from 80 to 95 days. The 13-week period also corresponds to observed recent duration of the rainy season, when microbial activity is not limited by the availability of water in the field in the agro-ecological region II of Zambia which is the major maize-growing region, in Zambia.

A 100 g of air-dried soil mixed with organic inputs with or without chemical fertilizer was moistened to 60% of total porosity of the soil (Samuel & Ebenezer 2014) and placed in a 1 L plastic jar with a screwable lid. The control treatment consisted of soil alone. A 100 cm³ beaker containing 5 mL of 0.2M KOH was placed inside the 1 L jar, which was closed air tightly and kept at room temperature. The average room temperature was 22 °C during the incubation period. The amount of mineralized carbon was determined by titrating the alkali solution that absorbed CO₂ with 0.1 M HCl (Kirita, 1971). After every measurement of CO₂ emissions, the soils were moistened to maintain a moisture content corresponding to 60% of the total porosity of the soil. This was done by weighing each jar and adding the required amount of water with a pipette. The experiment was laid out in a Completely Randomized Design (CRD) with four replicates. Carbon dioxide emissions were measured and recorded weekly during the first nine weeks, and fortnightly thereafter.

2.5 Determination of Mineralized Carbon

The emission of carbon as a percentage of the total carbon present in the soil was determined using Equation 1 below:

$$\%CO_2-C \text{ loss} = [C_{emit} / (C_{appl} + C_{soil})] \times 100 \quad (1)$$

Where,

C_{emit} is the total amount of carbon emitted during the 13 weeks in mg kg soil⁻¹; C_{appl} is the amount of carbon applied as input in mg kg soil⁻¹; C_{soil} is the initial soil organic carbon in mg kg soil⁻¹.

The % CO₂-C emission based on C applied to the soil is given by Equation 2.

$$\%C \text{ emission} = [(C_{treat} - C_{cont}) / C_{appl}] \times 100 \quad (2)$$

Where,

C_{treat} is the cumulative C emitted from the treatment in mg kg soil⁻¹; C_{cont} is the cumulative C emitted from the control treatment in mg kg soil⁻¹; C_{appl} is the amount of carbon applied as input in mg kg soil⁻¹.

The carbon mineralization rate constant was determined from the first-order kinetics equation as described in Equation 3 (Stanford & Smith, 1972; Moretti, Bertocini, & Abreu-Junior, 2017).

$$CO_2-C_{cum} = C_{io}(1 - e^{-kt}) \quad (3)$$

Where,

CO_2-C_{cum} is the amount of carbon mineralized during the incubation experiment; C_{io} is the potential mineralizable carbon in the sample; k is the carbon mineralization rate constant.

The mean residence time (MRT) of organic carbon, which is defined as the average time that a particular element resides in a given pool at a steady-state (Six & Jastrow 2002) was determined using Equation 4.

$$MRT = 1/k \quad (4)$$

Where, k is the mineralization rate constant.

2.6 Statistical Analyses

To determine whether there were significant differences among treatment means an Analysis of Variance (ANOVA) was carried out, and Duncan's Multiple Range Test was used to separate the treatment means when results of the ANOVA indicated the presence of significant differences among treatment means. The analyses were conducted using the SAS software version 9.0 for windows.

3. Results

3.1 Properties of the Soil and Organic Inputs

The properties of the two soils used for the study are presented in Table 2. The soils were very strongly acid and had moderate levels of organic matter. The levels of total N were low on the loamy sand (LS) soil from Misamfu and very low on the sandy clay loam (SCL) soil from Msekera. The soils had higher levels of K than the critical value of 0.2 cmol kg⁻¹, while the available P was very low on the SCL and very high on the LS according to the interpretation by Hazelton and Murphy (2007).

Table 2. Mean values with standard errors of selected properties of soils used in the study

Soil Property	Study Site	
	Msekera	Misamfu
USDA Textural class	Sandy clay loam	Loamy Sand
pH (0.01M CaCl ₂)	4.39 ± 0.04	4.33 ± 0.04
Organic matter (%)	2.42 ± 0.12	2.53 ± 0.15
Bray1-phosphorus (mg kg ⁻¹ soil)	5.38 ± 0.43	25.15 ± 0.17
Exchangeable potassium (cmol.kg soil ⁻¹)	0.69 ± 0.02	0.44 ± 0.06
Total nitrogen (%)	0.03 ± 0.01	0.09 ± 0.01
Bulk Density (Mg m ⁻³)	1.48 ± 0.03	1.38 ± 0.00
Sand (%)	58.8 ± 1.31	82.8 ± 0.40
Silt (%)	14.0 ± 1.34	6.4 ± 0.40
Clay (%)	27.2 ± 1.04	10.8 ± 0.00

Selected properties of the organic inputs are shown in Table 3. Maize stover and pigeon pea biomass had the highest C content of about 57%, followed by Tephrosia, sunnhemp and velvet beans with about 54% C, while the traditional inputs—cattle manure and indigenous biomass, had the lowest C contents of less than 50%. The velvet bean biomass had the highest contents of total N, P and K while the maize stover had the lowest N, P and K. The legume biomasses had higher N content than the indigenous biomass and maize stover. The C:N ratios of the organic inputs were in the order: velvet beans < sunnhemp < tephrosia < composted manure < pigeon peas < indigenous biomass < maize stover.

Table 3. Mean values with standard errors of selected properties of organic inputs used

Organic input	% N	% K	% P	% C	C/N ratio
Composted cattle manure	1.87±0.04	2.00±0.05	0.36±0.02	35.16±0.23	18.80
Indigenous biomass	1.11±0.06	2.03±0.02	0.16±0.01	49.20±0.68	44.30
Pigeon peas	2.23±0.03	1.72±0.07	0.22±0.01	56.48±0.15	25.30
Tephrosia	2.84±0.07	0.99±0.04	0.21±0.02	54.48±0.20	18.10
Sunnhemp	3.18±0.12	1.47±0.06	0.33±0.02	54.48±0.27	17.10
velvet beans	3.56±0.19	2.30±0.06	0.38±0.01	53.36±0.37	15.00
Maize stover	0.48±0.05	1.42±0.04	0.19±0.01	56.56±0.55	118.00

3.2 CO₂-C Emissions

The CO₂-C losses from different treatments on the two soils are shown in Table 4. The total CO₂-C evolved from the control treatments was significantly lower ($p < 0.05$) than those from treatments with organic inputs with or without chemical fertilizer in both soils. No statistically significant differences ($p < 0.05$) in the total CO₂-C emissions were observed among the other treatments on the SCL. On the LS, the pigeon pea with full rate of chemical fertilizer (PpSF) had significantly higher total CO₂-C emissions than the control and the conventional treatments (SF). There were no statistically significant differences in the total CO₂-C emissions among the other

treatments on the LS. The effects of the treatments on CO₂ emissions were evident on the LS where significant differences ($p < 0.05$) in total CO₂-C emissions and percentage C lost from the inputs were observed.

Table 4. Total CO₂-C emissions, and fractional seasonal C losses of the total organic C and applied organic C for different treatments in the two soils

Loamy Sand				Sandy Clay Loam			
Treat.*	Total CO ₂ -C lost (mg/kg)	Percentage of total C lost (%)	Percentage of applied C lost (%)	Treat.*	Total CO ₂ -C lost (mg/kg)	Percentage of total C lost (%)	Percentage of applied C lost (%)
PpSF	486.6a	3.27a	12.18b	PpSF	432.0a	3.04a	10.48bc
PpSF½	462.8ba	2.96ba	11.15b	PpSF½	452.7a	3.19a	11.45b
TepSF	447.6ba	2.96ba	9.45bc	TepSF	447.3a	3.10a	10.13bcd
TepSF½	410.1ba	2.71b	7.95bc	TepSF½	453.6a	3.15a	10.38bc
VvSF½	462.9ba	3.11ba	8.35cb	SunnSF	460.2a	3.18a	10.48bc
VvS	456.6ba	2.92ba	8.15bc	SunnSF½	468.3a	3.24a	10.83bc
IndSF	449.7ba	2.64b	5.38c	ManSF½	479.1a	3.11a	8.08cd
SF	384.3b	2.82ba	17.23a	ManS	450.6a	2.92a	7.23d
Cont	212.1c	1.68c	NA	SF	422.1a	3.24a	22.53a
				Cont	358.2b	2.96a	NA

Note. *Treatment means within a column followed by the same subscripts are not significantly different at 0.05 level of significance using Duncan's Multiple Range Test. *All treatment codes are as described in Table 1.

3.3 Mineralization Rate Constants (k) and Mean Residence Times (MRT) of the Organic Carbon

The k and MRTs of organic carbon for the different treatments on the two soils are shown in Table 5. The MRT of soil organic carbon ranged from about 5 to 59 seasons on the LS and from 13 to 32 seasons on the SCL. The control treatments had the lowest k on both soils and consequently had the highest MRTs. In contrast, the conventional treatments on both soils had the highest k and the lowest corresponding MRTs.

Table 5. Carbon mineralization constants (k) and Mean Residence times (MRT) of organic carbon in different treatments on the two soils

Loamy sand soil			Sandy clay loam soil		
Treatment*	k (wk ⁻¹)	MRT (13wk seasons)	Treatment	k (week ⁻¹)	MRT (13wk seasons)
PpSF	0.0108	7.1	PpSF	0.0032	24.0
PpSF½	0.0101	7.6	PpSF½	0.0040	19.2
TepSF	0.0082	9.4	TepSF	0.0037	20.8
TepSF½	0.0068	11.3	TepSF½	0.0037	20.8
VvSF½	0.0073	10.5	SunnSF	0.0037	20.8
VvS	0.0073	10.5	SunnSF½	0.0045	17.1
IndSF1	0.0049	15.7	ManSF½	0.0034	22.6
SF	0.0170	4.5	ManS	0.0029	26.5
Cont	0.0013	59.2	SF	0.0058	13.3
			Cont	0.0024	32.1

Note. *All treatment codes are as described in Table 1.

The k and MRTs of organic carbon for groups of treatments are shown in Table 6. In both soils, the stability of soil organic carbon in the different treatments was in the order of Control > Traditional > Legumes > Conventional. Treatments with lower k emitted less carbon and had correspondingly longer MRTs.

Table 6. Means of C mineralization rate constants (k) and Mean Residence Times (MRT) of grouped treatments in the two soils

Grouped Treatments	Loamy Sand		Sandy Clay Loam	
	k (wk ⁻¹)	MRT (13 wk seasons)	k (wk ⁻¹)	MRT (13 wk seasons)
Control	0.0013c	59.0a	0.0024c	32.0a
Traditional	0.0049bc	16.0b	0.0032bc	25.0b
Legumes	0.0084b	9.5c	0.0038b	20.5b
Conventional	0.0170a	5.0c	0.0058a	13.0c
Average	0.0079	9.74	0.0038	20.24

Note. Treatment means within a column followed by the same subscripts are not significantly different at 0.05 level of significance using Duncan's Multiple Range Test.

* Traditional on LS = IndSF; traditional on SCL = ManS and ManSF^{1/2}; legumes on LS = VvS, VvSF^{1/2}, TepSF^{1/2}, TepSF, PpSF^{1/2}, PpSF; legumes on SCL = SunnSF^{1/2}, SunnSF, PpSF^{1/2}, PpSF, TepSF^{1/2} and TepSF.

Table 7 shows the k and MRTs of C on aggregated treatments on the two soils with and without application of chemical fertilizer. Applying chemical fertilizers to the soil significantly ($p < 0.05$) increased the rate of C mineralization and significantly ($p < 0.05$) reduced the MRT of the organic carbon on both soils.

Table 7. Means of C mineralization rate constants (k) and Mean Residence Times of aggregated treatments with and without chemical fertilizer on the two soils

Treatments *	Loamy Sand			Sandy Clay Loam		
	n	k	MRT	n	k	MRT
Without chemical fertilizer	2	0.0043b	35.0a	2	0.0027b	29.5a
With chemical fertilizer	7	0.0093a	9.6b	8	0.0040a	19.9b

Note. Treatment means within a column followed by the same subscripts are not significantly different at 0.05 level of significance using Duncan's Multiple Range Test.

* Without chemical fertilizer on LS = VvS and Cont; with chemical fertilizer on LS = VvSF^{1/2}, TepSF^{1/2}, TepSF, PpSF^{1/2}, PpSF, IndSF, SF; without fertilizer on SCL = Cont and ManS; with chemical fertilizer on SCL = PpSF, PpSF^{1/2}, TepSF, TepSF^{1/2}, SunnSF, SunnSF^{1/2}, ManSF^{1/2}, SF; without chemical fertilizer on SCL = Cont and ManS.

4. Discussion

4.1 Effects of Organic Inputs on Carbon Mineralization

The addition of organic inputs with and without chemical fertilizer significantly ($p < 0.05$) increased CO₂-C emissions compared to the control on both soils. The increases in C emissions compared to the control ranged from 81 to 129% on the loamy sand, and 18 to 34% on the sandy clay loam. This was as expected as the addition of fresh organic matter normally stimulates microbial activity resulting in increased C mineralization. These results corroborate the assertion of Hossain et al. (2017) that the nature and quantity of organic inputs applied to soils have an influence on the rate of soil carbon emissions. There were significant differences in the proportion of applied C lost from different treatments on both soils. The conventional farming (SF) treatment with maize stover biomass as the main organic input and a full rate of chemical fertilizer had the highest C losses of 17.2% on the LS and 22.5% on the SCL.

Composted cow manure, the traditional organic input used by farmers in the Eastern Province of Zambia had the lowest rate of C lost from organic inputs on the sandy clay loam soil. This could be attributed to the composting process which removed significant amounts of labile carbon from the manure leaving it with more stable carbon compared to the other organic inputs used the study. According to Coleman (1989), besides the C: N ratio, carbon mineralization from organic inputs is also influenced by their lignin and polyphenolic contents. On the loamy sand soil, the treatment with indigenous biomass (IndSF) traditionally used by farmers in the Northern Province of Zambia had the lowest rate of C loss per C applied of 5.4%. These results indicate that on both soils from the two agro-ecological regions, treatments representing traditional farming practices had lower losses of C from the soil, compared to treatments with legumes suggested by researchers as means of shortening fallow periods, and to the conventional farming practices that rely on the use chemical fertilizers.

As discussed above, among the treatments that received organic inputs, the treatments representing traditional farming practices on both soils had the longest MRTs of 16 seasons on the LS and 25 seasons on the SCL, while the shortest MRTs on both soils were those of treatments representing the conventional farming practices (SF) with mean values of 5 seasons on the LS and 13 seasons on the SCL. The longer MRT of organic C in traditional farming practices compared to conventional farming practices and to treatments with leguminous plant biomass is worth noting when considering sustainable management of soil organic matter and carbon sequestration in the soils. The observed shorter MRT of organic C in soils under the conventional farming treatments in this study corroborates the argument of Chirinda et al. (2009) that conventional cropping systems, that rely on chemical fertilizers and focus on short-term management of soil fertility may not be appropriate for improving soil organic matter and sequestering carbon. As indicated by Palm Gachengo, Delve, Cadisch and Giller (2000), a balance between the long-term maintenance of soil organic matter and soil carbon sequestration with the short-term crop nutrient is required for sustainable soil fertility management. The use of leguminous organic inputs with intermediate MRTs could help achieve the goal of balancing short-term soil fertility requirements with the long-term goal of maintaining soil organic matter.

4.2 Effect of Applying Chemical Fertilizer on Carbon Mineralization

The aggregated effect of chemical fertilizer application across treatments on C mineralization on the two soils shows that applying chemical fertilizer significantly increased carbon mineralization rates. The increases in CO₂ emissions due to fertilizer application were about 116% on the LS, and 48% on the SCL. There were corresponding significant ($p < 0.05$) reductions in the MRT of the organic carbon by 73% on the loamy sand soil, and by 33% on the sandy clay loam soil as a result of application of chemical fertilizer. The reductions in the MRT on sandy loam were from 35 seasons without fertilizer to about 10 seasons with chemical fertilizer and from 30 seasons without chemical to about 20 years with chemical fertilizer on the sandy clay loam.

No significant differences in C emissions were observed between the two rates of chemical fertilizers used in the study on the SCL loam. However, some general trends were observed on the two soils regarding treatments with the same type of organic inputs. On the loamy sand higher CO₂-C emissions were associated with higher rates of chemical fertilizer, while on the SCL soil, higher CO₂-C emissions generally occurred on treatments with lower rates of chemical fertilizer. The trend observed on the SCL is similar to the findings of Nyamangara, Mtambanengwe and Musvoto (2009) in Zimbabwe, where a reduction in C mineralization rates was observed upon addition of nitrogenous chemical fertilizer. According to Manzoni, Jackson, Trofymow and Porporato (2008) this could be due to the enhanced carbon-utilization efficiency of soil microbes associated with N fertilizer application which results in reduced CO₂ emissions.

4.3 Effect of Soil Texture on Carbon Mineralization

Although there were only two soil textural classes evaluated in this study, results in Table 6 show that the carbon mineralization rate was generally higher on the LS than on the SCL. The overall mean carbon mineralization rate constant k on the sandy loam of 0.0079 wk⁻¹ was about twice that on the sandy clay loam of 0.0038 wk⁻¹, with corresponding MRTs of about 10 seasons for the loamy sand and about 20 seasons for the sandy clay loam. Longer MRTs of carbon on the SCL compared to the LS could be attributed to the higher clay content of the SCL of about 27% compared to 10% of the LS. Clay is reported to have a protective effect on soil organic matter which enhances the storage of carbon in soils, a phenomenon Rakhsh, Golchin, Agha and Alandari (2017) refer to as the “carbon storage effect of clay”.

5. Conclusion

Based on the results and foregoing discussion it was concluded that the factors that significantly influenced carbon mineralization in the surface samples of the two Ultisols were the type of organic inputs, the addition of chemical fertilizer and the texture of the soil.

Acknowledgements

The authors gratefully acknowledge the financial support received from the Swiss Programmed for Research on Global Issues for Development and the Swiss National Science Foundation through the Research Institute of Organic Agriculture (FiBL) for this study. The authors acknowledge the useful comments and support from Dr. Andreas Fliessbach, Dr. Alice M. Mweetwa, and the help from laboratory staff of the Department of Soil Science at the University of Zambia.

References

- Ajayi, O. C., Akinnifesi, F. K., Sileshi, G., & Chakeredza, S. (2007). Adoption of Renewable Soil Fertility Replenishment Technologies in the Southern African Region: Lessons Learnt and the Way Forward. *Nat Resour Forum*, *31*, 306-317.
- Ambrosano, E. J., Trivelin, P. C. O., Cantarella, H., Ambrosano, G. M. B., & Muraoka, T. (2003). Nitrogen Mineralization in Soils Amended with Sunnhemp, Velvet Bean and Common Bean Residues. *Sci Agric*, *60*(1), 133-137.
- Amin, M., & Flowers, T. H. (2004). Evaluation of the Kjeldhal Method. *J Res Sci*, *15*(2), 159-179.
- Bationo, A., Hartemink, A., Lungu, O., Naimi, M., Okoth, P., Smaling, E., ... Waswa, B. (2012). Knowing the African soils to improve fertilizer recommendations. In J. Kihara, D. Fatondji, J. W. Jones, G. Hoogenboom, R. Tabo, & A. Bationo (Eds.), *Improving soil fertility recommendations in Africa using the decision support system for agrotechnology transfer (DSSAT)*. https://doi.org/10.1007/978-94-007-2960-5_3
- Bhatia, A., Pathak, H., Jain, N., Singh, P. K., & Singh, A. K. (2005). Global Warming Potential of Manure Amended Soils under Rice-wheat System in the Indo-gangetic Plains. *J. Atmosenv.*, *39*, 6976-6984. <https://doi.org/10.1016/j.atmosenv.2005.07.052>
- Bindraban, P. S., Batjes, N. H., Leenars, J. G. B., & Bai, Z. (2010). *Relevance of Soil and terrain information in studies of major global issues*. 19th World Congress of Soil Science, Brisbane.
- Bouajila, K., & Sanaa, M. (2011). Effects of Organic Amendments on Soil Physico-chemical and Biological Properties. *J Mater Environ Sci*, *2*(1), 485-490.
- Campbel, C. R., & Plank, C. D. (1998). Preparation of plant tissue for laboratory analysis. In Y. P. Kalra (Ed.), *Handbook of reference methods for plant analysis*. London: CRC Press.
- Casanova, M., Tapia, E., Seguel, O., & Salazar, O. (2016). Direct Measurement and Prediction of Bulk Density on Alluvial Soils of Central Chile. *Chilean Journal of Agricultural Research*, *76*(1), 105-113. <https://doi.org/10.4067/S0718-58392016000100015>
- Castellanos-Navarrete, A., Tiftonell, P., Rufino, M. C., & Giller, K. E. (2015). Feeding, Crop Residue and Manure Management for Integrated Soil Fertility Management—A Case Study from Kenya. *Agricultural Systems*, *134*, 24-35. <https://doi.org/10.1016/j.agsy.2014.03.001>
- Chapman, H. D. (1965). Cation-exchange Capacity. In C. A. Black (Ed.), *Methods of Soil Analysis: Chemical and Microbiological Properties* (Vol. 9, pp. 891-901). Agronomy, Madison.
- Chirinda, N., Carter, M. S., Albert, K. R., Ambus, P., Olesen, J. E., Porter, J. R., & Petersen, S. O. (2010). Emissions of Nitrous Oxide from Arable Organic and Conventional Cropping Systems on two Soil Types. *Agric Ecosyst Environ*, *136*, 199-208. <https://doi.org/10.1016/j.agee.2009.11.012>
- Coleman, D. C., Oades, J. M., & Uehara, J. (1989). *Dynamics of soil organic matter in tropical ecosystems*. Honolulu: University of Hawaii Press. <https://doi.org/10.1017/S0021859600075304>
- Dalal, R. C., Sahrawat, K. L., & Meyers, R. J. K. (1984). Inclusion of Nitrate and Nitrite in the Kjeldhal Nitrogen Determination of Soils and Plant Materials using Sodium Thiosulphate. *Commun Soil Sci Plant Anal*, *15*(2), 1453-1461. <https://doi.org/10.1080/00103628409367572>
- Delgado-Baquerizo, M., García-Palacios, P., Milla, R., Gallardo, A., & Maestre, F. T. (2015). Soil Characteristics Determine Soil Carbon and Nitrogen Availability during Leaf Litter Decomposition Regardless of Litter Quality. *Soil Biol Biochem*, *81*, 134-142. <https://doi.org/10.1016/j.soilbio.2014.11.009>
- Diacono, M., & Montemurro, F. (2010). Long-term Effect of Organic Amendments on Soil Fertility—A Review. *Agron Sustain Dev.*, *30*, 401-422. <https://doi.org/10.1051/agro/2009040>
- Hazelton, P., & Murphy, B. (2007). *Interpreting soil test results-What do all the numbers mean?* Collingwood. CSIRO Publishing.
- Hossain, B., Rahman, M., Biswas, J. C., Miah, M. U., Akhter, S., Choudhury, A. K., ... Kalra, N. (2017). Carbon Mineralization and Carbon Dioxide Emission from Organic Matter added Soil under Different Temperature Regimes. *Int J Recycl Org Waste Agricult*, *6*, 311-319. <https://doi.org/10.1007/s40093-017-0179-1>
- Jones, J. B. (2001). *Laboratory guide for conducting soil tests and plant analysis*. Florida. CRS Press.
- Khalafalla, M. Y., & Hamed, M. H. (2015). Impact of Nitrogen Fertilization on Soil Organic Carbon Decomposition. *Alexandria Science Exchange Journal*, *36*(4), 381-389.

- Kirita, H. (1971). Re-examination of the Absorption Method for Measuring Soil Respiration under Field Conditions. Measuring Soil Respiration under Field Conditions-An Improved Absorption Method using a Disc of Plastic Sponge as Absorbent Holder. *Jpn. J. Ecol.*, 21, 119-127. https://doi.org/10.18960/seitai.21.3-4_119
- Lal, R. (1987). Managing the Soils of Sub-Saharan Africa. *Science*, 236(4805), 1069-1076. <https://doi.org/10.1126/science.236.4805.1069>
- Lekasi, J. C., Tanner, J. C., Kimani, S. K., & Harris, P. J. C. (2001). *Manure management in the Kenya highlands: Practices and potential* (2nd ed.). Kenilworth: HDRA Publications.
- Magai, R. N. (1985). Field tour guide. In P. R. Woode (Ed.), *Proceedings of the 11th International Forum on Soil Taxonomy and Agrotechnological Transfer, July 15 to August 1, 1985, Zambia*. IBSNAT, BADC, MAWD, NORAD, USAID, SMSS, UNZA.
- Maerere, A. P., Kimbi, G. G., & Nonga, D. L. M. (2001). Comparative Effectiveness of Animal Manures on Soil Chemical Properties, Yield and Root Growth of Amaranthus. *Afr J Sc Technol*, 1(4), 14-21. <https://doi.org/10.4314/ajst.v1i4.44623>
- Manzoni, S., Jackson, R. B., Trofymow, J. A., & Porporato, A. (2008). The Global Stoichiometry of Litter Nitrogen Mineralization. *Science*, 321, 684-686. <https://doi.org/10.1126/science.1159792>
- Matson, P. A., Parton, W. J., Power, A. G., & Swift, M. J. (1997). Agricultural Intensification and Ecosystem Properties. *Science*, 277(25), 504-509. <https://doi.org/10.1126/science.277.5325.504>
- Moretti, S. M. L., Bertoncini, E. I., & Abreu-Junior, C. H. (2017). Carbon Mineralization in Soils Irrigated with Treated Swine Wastewater. *J Agric Sci*, 9(3), 9-29. <https://doi.org/10.5539/jas.v9n3p19>
- Muchinda, M. R., & Spaargaren, O. (1985). The Agro climate of Zambia. In P. Woode (Ed.), *Proceedings of the IXth International Forum on Soil Taxonomy and Agro technological Transfer, July 15 to August 1, 1985, Zambia*. IBSNAT, BADC, MAWD, NORAD, USAID, SMSS, and UNZA.
- Mugwe, J., Mugendi, D., Odee, D., & Mairura, F. (2009). Effect of Selected Organic Materials and Inorganic Fertilizer on the Soil Fertility of a Humic Nitisol in the Central Highlands of Kenya. *Soil Use Manag*, 25, 434-440. <https://doi.org/10.1111/j.1475-2743.2009.00244.x>
- Mustafa-Msukwa, A. K., Mutimba, J., Masangano, C., & Edriss, A. K. (2011). An Assessment of the Adoption of Compost Manure by Smallholder Farmers in Balaka District, Malawi. *S. Afr. Jnl. Agric. Ext.*, 39(1), 17-25. Retrieved from <http://hdl.handle.net/2263/16406>
- Muyayabantu, G. M., Kadiata, B. D., & Nkongolo, K. K. (2013). Assessing the Effects of Integrated Soil Fertility Management on Biological Efficiency and Economic Advantages of Intercropped Maize (*Zea mays* L.) and Soybean (*Glycine max* L.) in DR Congo. *Am J Exp Agric*, 3(3), 520-541. <https://doi.org/10.9734/AJEA/2013/2628>
- Nalivata, P., Kibunja, C., Mutegi, J., Tetteh, F., Tarfa, B., Dicko, M. K., ... Wortmann, C. S. (2017). Integrated soil fertility management in Sub-Saharan Africa. In C. S. Wortmann, K. Sones (Eds.), *Fertilizer use optimization in Sub-Saharan* (pp. 25-39). Nairobi: CAB International.
- Nelson, D. W., & Sommers, L. E. (1982). Total carbon, organic carbon and organic matter. In A. L. Page, R. H. Miller, & D. R. Keeney (Eds.), *Methods of soil analysis, Part 2: Chemical and biological Properties* (2nd ed., pp. 199-224). Madison: Am Soc Agron. <https://doi.org/10.2134/agronmonogr9.2.2ed>
- Nyamangara, J., Mtambanengwe, F., & Musvoto, C. (2009). Carbon and Nitrogen Mineralization from Selected Organic Resources Available to Smallholder Farmers for Soil Fertility Improvement in Zimbabwe. *Afr J Agric Res*, 4(9), 870-877. <https://doi.org/10.5897/AJAR>
- Nyamangara, J., Piha, I. M., & Giller, K. E. (2003). Effect of Combined Cattle Manure and Mineral Nitrogen on Maize N-uptake and Grain Yield. *Afr Crop Sci J*, 11(4), 289-300. <https://doi.org/10.4314/acsj.v11i4.27579>
- Okalebo, J. R., Gathua, K. W., & Woome, P. L. (2002). *Laboratory methods for soil and plant analysis: A working manual* (2nd ed.). Nairobi: TSB-CIAT and SACRED Africa.
- Oluwaranti, A., Fakorede, M. A. B., & Badu-Apraku, B. (2008). Grain Yield of Maize Varieties of Different Maturity Groups under Marginal Rainfall Conditions. *J Agric Sci*, 53(3), 183-191. <https://doi.org/10.2298/JAS0803183O>

- Onduru, D., Zake, J., Ebanyat, P., & Ergano, K. (2002). Participatory On-farm Comparative Assessment of Organic and Conventional Farmers Practices in Kenya. *Biol Agric Hort*, *19*, 295-314. <https://doi.org/10.1080/1448765.2002.9754935>
- Palm, C. A., Gachengo, C. N., Delve, R. J., Cadisch, G., & Giller, K. E. (2000). Organic Inputs for Soil Fertility Management in Tropical Agroecosystems: Application of an Organic resource database. *Agric Ecosyst Environ*, *83*, 27-42. [https://doi.org/10.1016/S0167-8809\(00\)00267-X](https://doi.org/10.1016/S0167-8809(00)00267-X)
- Place, F., Barrett, C. B., Freeman, H. A., Ramisch, J. J., & Vanlauwe, B. (2003). Prospects for Integrated Soil Fertility Management using Organic and Inorganic Inputs: Evidence from Smallholder African Agricultural Systems. *Food Policy*, *28*, 365-378. <https://doi.org/10.1016/j.foodpol.2003.08.009>
- Rakhsh, F., Golchin, A., Agha, A. B. A., & Alandari, P. (2007). Effects of Exchangeable Cations, Mineralogy and Clay Content on the Mineralization of Plant Residue Carbon. *Geoderma*, *307*, 150-158. <https://doi.org/10.1016/j.geoderma.2017.07.010>
- Roobroeck, D., Van Asten, P., Jama, B., Harawa, R., & Vanlauwe, B. (2015). Integrated soil fertility management: Contributions of framework and practices to climate-smart agriculture. *Global Alliance for Climate-Smart Agriculture*. <https://doi.org/10.13140/RG.2.1.1695.2400>
- Rusinamhodzi, L., Corbeels, M., Zingore, S., Nyamangara, J., & Giller, K. E. (2013). Pushing the Envelope? Maize Production Intensification and the Role of Cattle Manure in Recovery of Degraded Soils in Smallholder Farming Areas of Zimbabwe. *Field Crops Res*, *147*, 40-53. <https://doi.org/10.1016/j.fcr.2013.03.014>
- Rustad, L. E., Campbell, J. L., Marion, J. M., Norby, R. J., Mitchell, M. J., Hartley, A. E., ... Gurevitch, J. (2001). A Meta-analysis of the Response of Soil Respiration, Net Nitrogen Mineralization, and Above-ground Plant Growth to Experimental Ecosystem Warming. *Oecologia*, *126*, 543-562. <https://doi.org/10.1007/s004420000544>
- Samuel, A. L., & Ebenezer, A. O. (2014). Mineralization Rates of Soil Forms of Nitrogen, Phosphorus and Potassium as Affected by Organomineral Fertilizer in Sandy Loam. *Adv. Agric.*, *2014*, Article ID: 149209. <https://doi.org/10.1155/2014/149209>
- Schumacher, B. A. (2002). *Methods for the determination of total organic carbon (TOC) in soils and sediments*. US Environmental Protection Agency, Washington.
- Six, J., & Jastrow, J. D. (2002). Organic matter turnover. In R. Lal (Ed.), *Encyclopedia of soil science* (pp. 936-942). New York, Marcel Dekker. [https://doi.org/10.1016/s0016-7061\(03\)00067-3](https://doi.org/10.1016/s0016-7061(03)00067-3)
- Stanford, G., & Smith, S. J. (1972). Nitrogen Mineralization Potentials of Soils. *Soil Sci. Soc. Am.*, *36*, 465-472. <https://doi.org/10.2136/sssaj1972.03615995003600030029x>
- Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S. (2002). Agricultural Sustainability and Intensive Production Practices. *Nature*, *418*(8), 671-677. <https://doi.org/10.1038/nature01014>
- Veldkamp, W. J. (1987). Soils of Zambia. *Soil Bulletin No. 13* (2nd ed.). Lusaka: Soil Survey Unit-Research Branch, Department of Agriculture.
- Waswa, B. N., Mugendi, D. N., Vanlauwe, B., Nandwa, S., & Kung'u, J. (2003). Soil properties as influenced by different organic residue amendments in selected experiments in Kenya. *African Crop Science Conference Proceedings*, *6*, 448-453.

Copyrights

Copyright for this article is retained by the author(s), with first publication rights granted to the journal.

This is an open-access article distributed under the terms and conditions of the Creative Commons Attribution license (<http://creativecommons.org/licenses/by/4.0/>).