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Effect of Land Use Management Patterns on Mineralization Kinetics of Soil Organic Carbon in Mount Bambouto Caldera Area of Cameroon

Formeluh Abraham Toh[1*], Lawrence Monah Ndam[2], Tsi Evaristus Angwafo[3], Ngosong Christopher[2]

[1]Dschang School of Agriculture and Environmental Sciences, University of Dschang, Dschang, Cameroon
[2]Faculty of Agriculture and Veterinary Medicine, University of Buea, South West Region, Buea, Cameroon
[3]Department of Fundamental Science, HTTTC, Bambili, University of Bamenda, Bamenda, Cameroon
Email: *formeluhat@gmail.com

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Abstract

Soil organic carbon (SOC) mineralization was carried out on soil samples collected from two depths: 0 - 20 cm and 20 - 40 cm for all land use (LU) types (grasslands, croplands, natural forest/fallow lands, cocoa/palm plantations, and settlement/agro-forests). Microbiological analyses were carried out by measuring microbial activity in 40 g of dried soil samples wetted to 60% water holding capacity and incubated at 27˚C. Carbon dioxide (CO_2) emission was measured for 10 weeks using a CO_2 trap. Descriptive and graphical analyses of CO_2 respiration were done using CO_2 emission data. Models were developed to describe CO_2 respiration and the first order kinetic model provided best fit to C-mineralization. Potentially mineralizable carbon (C_o) and C-mineralization rate were higher in grasslands than other LU types, indicating a higher rate of microbial activity and carbon cycling. Metabolic quotient was higher in forest/fallow lands and reflects greater stress of the microbial community and a high requirement of maintenance energy. Grasslands enhanced more SOC accumulation and decomposition, suggesting a better carbon sink than other land use and management systems (LUMS). Microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) varied across LU patterns with maximum values in grasslands and minimum values in natural forest/fallow lands insinuating better soil quality for grasslands. MBC and SOC positively correlated with C_o and C-mineralization, which intimates that C-mineralization is influenced by availability of MBC and SOC. Metabolic quotient (qCO_2) negatively correlated with microbial quotient (MBC:SOC), depicting that higher values of qCO_2 signify difficulties in using organic substrates during microbial activity as a result of low MBC:SOC. Changes in

LUMS affected the mineralization kinetics of SOC in the study area.

Keywords

Land Use, Carbon Mineralization, Kinetic Models, Mount Bambouto Caldera

1. Introduction

Land use and management patterns are inherently associated with changes in soil nutrients and soil quality parameters, which affect the immediate biophysical environment and agricultural productivity. From a microbiological perspective, soil organic carbon (SOC) mineralization is an indicator of soil health [1] [2] and is related to long term soil fertility. Steady population growth increasingly triggers the conversion of natural vegetation to different land use types and management patterns [3] [4] with significant changes in soil properties and associated soil health implications. The effects of land use changes on soil carbon pools and atmospheric CO_2 concentrations have various environmental implications [3] [5] [6] since soils serve as C sinks and are large sources of atmospheric carbon supply. Due to increasing large carbon losses from land use changes over the years [3] [7], efforts to understand the manifestation of biological activities of soils in different land use types and management are being intensified. There is need to be abreast with variations that occur in the organic carbon pool due to land use changes since they have implications on the sustainable management of ecosystems [8] [9].

Soil respiration is undoubtedly one of the fundamental processes in the carbon cycle that represents the pathway by which carbon is returned to the atmosphere [5]. Several studies have used measurements of microbial respiration to estimate carbon mineralization rates [10]. The process involves the emission of CO_2 during organic matter decomposition, which is carried out by metabolic activity of plant roots and soil microorganisms [11]. This implies that even small changes in soil respiration can affect atmospheric carbon concentrations [12]. In recent times, studies on soil respiration have received considerable attention because of the release of significant quantities of CO_2 from the soil to the atmosphere [5]. Hence, assessing the impact of land use changes on soil respiration is of significant importance to provide insight into the relationship between soil metabolism and carbon budgets [13].

Description of the dynamics of C-mineralization in incubation studies by fitting experimental data to kinetic models is important to foster prediction of the ability of soils to supply potentially mineralizable organic carbon [14]. Laboratory incubation under standardized conditions is an effective method to examine C-mineralization [15]. Although a study [16] found a zero-order equation adequately describing C-mineralization, the first order equation has been frequently used to describe the C-mineralization process of SOC [17] [18]. Besides the sim-

ple first-order model, a two-part parabolic equation is applied [19] that assumes SOC to be divided into a labile fraction and a more recalcitrant one, each decaying exponentially at rates characterized by its own constants (k and h, respectively). Numerous field and laboratory incubation studies have been carried out [13] [20] [21], with most of the studies on the effects of land use changes on soil respiration focused on temperate environments [3] [14] [22]. Soil microbial organisms and activities are greatly affected by site characteristics including soil type, texture, temperature, moisture and pH. Such activities vary with vegetation cover changes and management practices, environmental conditions and land use types [23].

SOC dynamics in different land uses and its contribution to CO_2 fluxes continue to pull the attention of researchers as they seek to fill the knowledge dearth between CO_2 emissions from soils and LUMS [6]. Quantifying soil microbial activity parameters commonly affected by land use would enhance the evaluation of changes in soil microbial functions that are driven by changes in land use [24]. Hence, this work aimed at: 1) assessing the C-mineralization potentials of soils from different LUMS (grasslands, croplands, natural forest/fallow lands, cocoa/palm plantations, settlement/agro-forests) by laboratory scale incubation experiments; 2) comparing the suitability of different decay models for describing rates and amounts of C-mineralization; 3) evaluating soil microbial activity parameters vis-à-vis the C-mineralization parameters derived from the best fit model.

2. Materials and Methods

2.1. Study Site

This work was done in Mount Bambouto Caldera Area (Wabane Subdivision) in the South West Region of Cameroon. Situated between latitudes 5˚44'N and 5˚36'N and longitudes 9˚55'E and 10˚07'E, and extending from 200 m to 2700 m a.s.l., the topography of the area is highly diverse (**Figure 1**). Annual rainfall ranges between 2000 - 3000 mm and mean monthly maximum and minimum temperatures are 32˚C and 17˚C, respectively [25] [26]. The area has a moist agro-climate with two seasons: rainy season that spans from March to October, and dry season from November to February. It is characterized by a multi-agricultural production system within the caldera and its environs that is water-fed by springs and streams flowing from the caldera top to form rivers in the middle and low lying zones.

The soils in this area are of volcanic origin [27] and range from rich loose alluvial and silty-loam soils, rarely interspersed with outcrops of chalk and clay in the upper belt through sandy-loam to reddish alluvial soils in the middle and lower belts [28]. The undulating mountainous topography at the top is characterized by organic matter-rich andosols between 2000 and 2740 m altitude [29] [30]. Different soils also found in this upper area are ferralitic red soil on granite, ancient basalt and trachyte, grey and black andosolic soil on recent volcanic

rocks (basalt, trachyte and pyroclastic) with thicknesses varying between 0.01 m to 0.60 m [31].

2.2. Dominant Land Use and Management Systems

A survey of the LUMS carried out in 2018 identified five types: grassland, cropland, natural forest/fallow lands, cocoa/palm plantations, and settlements/agro-forests (Table 1). The identification and classification of the five land use and management systems was achieved through interpretation of satellite images and

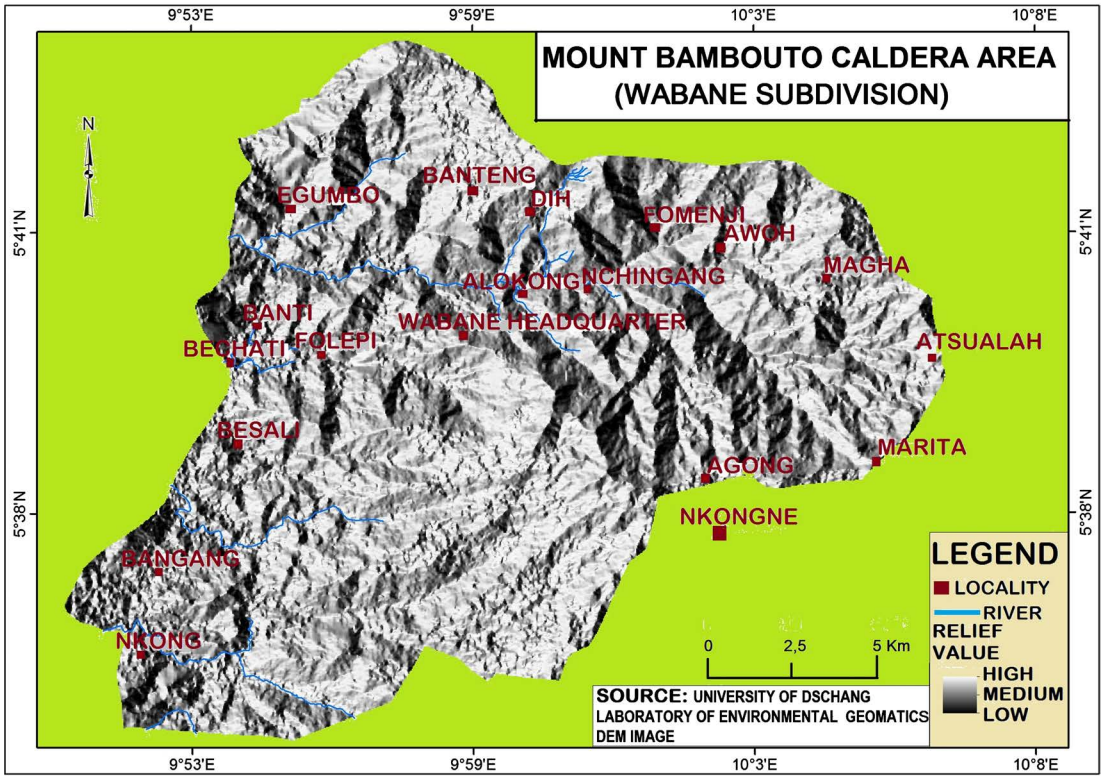

Figure 1. Location of the study site.

Table 1. Land use and management systems (LUMS) in Mount Bambouto Caldera Area of Cameroon.

Land use and management system	Description
Savannah/Grassland	Extensive open grazing areas dominated by natural tropical grasses
Cropland	Areas or patches of land dominated by monocultures and/or mixed cropping for cash and subsistence needs
Natural Forest/Fallow lands	Primary forest stands or patches of fallow lands that have not been cropped for at least 24 months
Cocoa/Palm Plantations	Separate cocoa and palm plantations or mixed cocoa/palm plantations interspersed with fruit trees and sometimes food crops
Settlement/Agro-forests	Eucalyptus, cypress, pine and/or fruit trees grown around homes and/or in farms

Source: (Toh *et al.*, 2018).

numerous survey trips in the study area [4]. Information about management practices was obtained from land owners, focus groups, key informants and government development agents.

2.3. Soil Sampling, Preparation and Properties

Sixteen sites were sampled within each land use system at two depths: 0 - 20 cm and 20 - 40 cm using a stainless steel soil auger. The sixteen sampled sites were replications while the LUMS were treatments. One hundred and sixty soil samples were collected from the five LU systems at two depths (16 samples per LUMS per depth for 5 LUMS) in a complete randomized block design. The samples were air dried, crushed and sieved through a 2 mm mesh before laboratory analysis and experiments.

Soil texture analysis was performed using hydrometric methods [32]. Soil pH was determined by potentiometric methods at a 1:2.5 soil to water ratio suspension while soil organic carbon (SOC) was measured by Walkley and Black method [33]. Total nitrogen (TN) was analysed by wet oxidation procedure of the Kjeldhal digestion, distillation and titration method [34]. Available phosphorus (avP) was determined using Olsen's extraction method [35] while exchangeable bases (Na^+, K^+, Ca^{2+}, and Mg^{2+}) were measured by atomic absorption spectrophotometry after extraction by ammonium acetate [36]. The cation exchange capacity (CEC) was determined by extraction with ammonium acetate [37]. Exchangeable-titratable acidity was determined in 1 M KCL extracts titrated with 0.01 M NaOH.

2.4. Microbiological Analyses

Microbiological analyses were carried out in each LU system by measuring microbial activity in the associated soil samples. In the experiments, 40 g of dried soil sample replicates from each LUMS were wetted to 60% of water holding capacity and incubated in 0.5 l air-tight jars at 27˚C. Carbon dioxide emission was measured by a standard method [38] every 10 days for 10 weeks using a CO_2 trap. The trap was prepared using 20 ml of 1.0 M NaOH and 25 ml of distilled water in a vial for trapping the CO_2 evolved. The trap solution in a beaker was placed in the air-tight jar. The control experiment consisted of 0.5 l air-tight jars without soil but containing the same alkali as in the other experiments. To determine the quantity of alkali that had not reacted with CO_2 at the end of each 10-day period, the trap solution was removed and titrated with 0.1 M HCl solution using phenolphthalein indicator and $BaCl_2$ solutions. Excess $BaCl_2$ was added to the NaOH solution to precipitate the carbonate as insoluble $BaCO_3$. The volume of acid needed for the titration was noted and the acid added slowly to avoid contact and dissolution of precipitated $BaCO_3$. The amount of CO_2 evolved from the soil during exposure to the alkali was calculated using the formula:

$$\text{mg } CO_2 = \left(V_{ac} - V_{as}\right) NE, \tag{1}$$

where

V_{ac} = Volume (ml) of acid used to titrate NaOH in jars from the control experiment,

V_{as} = Volume (ml) of acid used to titrate the NaOH in beakers exposed to soil,

N = Normality of the acid,

E = Equivalent weight for CO_2 = 22, and CO_2 emission was expressed as mg CO_2 kg^{-1} soil.

Soil microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) were determined by the chloroform fumigation extraction method, using 0.5 M K_2SO_4 as extractant [39]. Twenty-five grams of dry weight-equivalent soil samples was fumigated with $CHCl_3$ for 24 hours in a dark room in vacuum desiccators in two duplicates. After removal of chloroform by three repeated evacuations, the soil samples were extracted by 0.5 M K_2SO_4 (using a soil: extractant ratio of 1: 4). Similarly, the non-fumigated controls were also subjected to 0.5 M K_2SO_4 extraction. After shaking for 30 minutes in automatic shaker, the extract was filtered through whatman filter paper (No. 42). The filtrates were analysed for organic carbon and total nitrogen by using SKALAR TOC/TN automatic analyser. The difference in the carbon content of the extracts from fumigated and non-fumigated samples was converted to biomass carbon by dividing the value obtained by a factor (K_C) of 0.45 [39]. The results were expressed as $\mu g \cdot g^{-1}$ of oven dried soil. The difference in content of nitrogen of the extractants was also converted to biomass nitrogen by dividing the value obtained by a factor (K_N) of 0.54 [40]. Metabolic quotient, qCO_2 [$(CO_2\text{-C}) \cdot h^{-1} \cdot g^{-1}$ MBC], was calculated from respiratory data using the formula [41]:

$$qCO_2 = \left[(CO_2\text{-C}) \text{mineralized} / \text{MBC} \right] \quad (2)$$

Metabolic quotient was considered an index of microbial efficiency in utilizing the available resources, with low efficiency attributed to high values of qCO_2 and vice versa.

2.5. Models Used for Carbon Mineralization Studies

To detect anomalies, descriptive and graphical analyses of CO_2 respiration data were done for data obtained during the ten-week incubation period of soil samples from different LUMS and depths. Different models were used to describe the CO_2 respiration. The models were tested to determine the one that best suited the data. Then, the convergence, values of adjusted coefficient of determination ($R^2_{adj.}$), squared sum error (SSE) and mean square error (MSE) were employed to select the best-fit model for the data. The model fittings were done by applying MODEL procedures of the SAS/STAT® statistical programme [42]. Table 2 presents five kinetic models used to describe the soil carbon mineralization.

2.6. Relation between Biochemical Parameters and Organic Carbon

When the model was fitted, different parameters were determined to analyse the potentially mineralizable carbon (C_o), rate constant of carbon mineralization (k),

Table 2. Models employed in describing soil carbon mineralization kinetics in the Mount Bambouto Caldera Area.

No.	MODEL	EQUATION
1.	Zero order	$C_t = a + kt$ [16]
2.	Linearized power function	$C_t = kt^m$ [43]
3.	First order	$C_t = C_o\left(1-e^{-kt}\right)$ [44]
4.	Two simultaneous reactions	$C_t = C_1\left(1-e^{-kt}\right)+C_2\left(1-e^{-ht}\right)$ [19]
5.	Special model	$C_t = C_1\left(1-e^{-kt}\right)+ht$ [45]

Note: C_t, C_o, C_1 and C_2 = Cumulative carbon mineralized after time t, potentially mineralizable, easily mineralizabe, and slowly mineralizable carbon (mgC-CO_2/kg soil), respectively; a = intercept; k, m and h = rate constants (day^{-1}); t = time from the start of incubation.

initial potential rate of carbon mineralization ($C_o{}^*k$), and half-life of carbon ($t_{1/2}$). A mixed model was applied to detect significant differences in the measured variables as a function of LUMS at the two depths. The depth was regarded as a repeated measure factor while the statistical model was expressed thus:

$$Y_{ij;k} = \mu + \alpha_i + \beta_j + \gamma_k + \beta\gamma_{jk} + \varepsilon_{ij;k} \quad (3)$$

with $i = 1,\cdots,16$ for sites, $j = 1,\cdots,5$ for LUMS and k = 1, 2 for the two depths;

$Y_{ij;k}$ = observed value of the dependent variable for LUMS j at depth k in site i.

μ = general mean effect; α_i = mean effect of the site i; β_j = mean effect of the LUMS j;

γ_k = mean effect of the depth k; $\beta\gamma_{jk}$ = interaction effect of the land use j with the depth k;

$\varepsilon_{ij;k}$ = random error in the dependent variable for the LUMS j at depth k in the site i.

Assumptions for the model were that: $\varepsilon_{ij;k} \sim N\left(0,\sigma_k^2\right)$, with σ_k^2 = random variance for errors at depth k; and

$$Cov\left(\varepsilon_{ij;k},\varepsilon_{i'j';k'}\right) = \begin{cases} \omega & \text{if } i = i', j = j' \text{ and } k = k' \\ 0 & \text{if } i \neq i', j \neq j' \end{cases}$$

ω = covariance between errors at different depths.

3. Results and Discussion

3.1. Soil Respiration

Figure 2 shows the carbon dioxide-C mineralization changes in soils from the LUMS within 10 weeks of incubation for the 0-20 cm soil depth. In all LUMS, there was a decline with highest values (485, 260, 275, 250, and 270 $mgkg^{-1}$) recorded in the first 10 days and lowest values (115, 105, 100, 100, and 105 $mgkg^{-1}$) obtained in the last 10 days of experimentation for grassland (savannah), cropland, palm/cocoa, settlement/agroforest, and fallow/forest respectively.

The carbon dioxide-C mineralization rates for the 70 days incubation followed

a similar pattern in all five LUMS wherein an initial high value at the start decreased with time and almost equilibrated to an averagely constant value in the last days of incubation. Figure 3 shows carbon dioxide-C mineralization changes in soils from the LUMS at 20 - 40 cm depth for the same incubation period.

A general trend of decline is still observed with the first 30 days being rapid and the last 40 days gentler. Again, grasslands portray higher values and rates than the rest of the LUMS. The CO_2 emission in both 0 - 20 cm and 20 - 40 cm soil profiles was higher in grassland than other LUMS. The faster release of CO_2 in the early days of incubation implies a rapid depletion of an easily mineralizable carbon fraction, leaving a more resistant fraction of SOC [46] [47] [48]. Carbon mineralization is influenced by different cropping systems [49] or LUMS. Higher CO_2 release in grassland samples could be ascribed to high organic matter content, in agreement with [50] who reported higher CO_2 emissions under grassland than afforested land. Higher microbial respiration rates

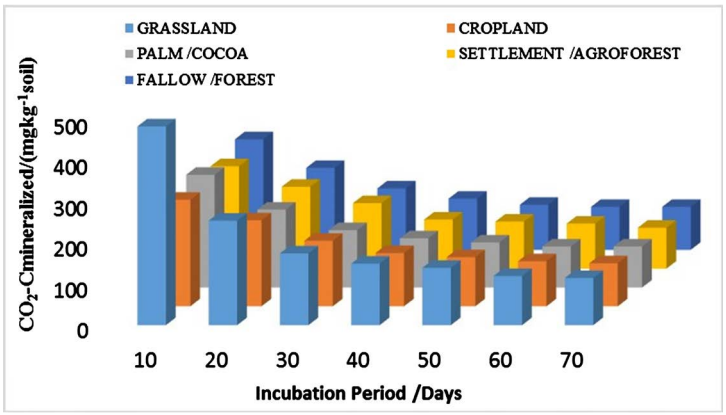

Figure 2. Carbon mineralization rates (0 - 20 cm) for land use and management systems (LUMS) in Mount Bambouto Caldera Area during 70 days of laboratory incubation (n = 10).

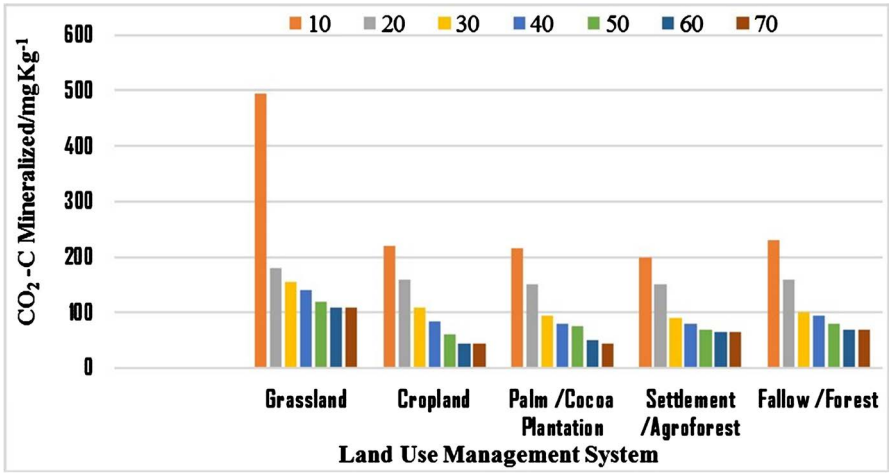

Figure 3. Changes in soil carbon dioxide-C mineralization from land use and management systems (LUMS) in Mount Bambouto Caldera Area (20 - 40 cm).

had also been reported in grasslands than other land uses [51] [52]. High rates of soil respiration can be attributed to a large pool of labile carbon substrates or rapid oxidation of a smaller pool [53] [52] [49]. Hence, a high basal respiration may be a pointer to ecological stress and degradation or high level of ecosystem productivity. The low CO_2 emissions under palm/cocoa plantations and settlement/agroforests could be attributed to low rate of microbial activity. High SOC and MBC result in high soil respiration [23] [54], which means the high mineralizable carbon in grasslands indicates a more easily decomposable organic matter while the low mineralizable carbon in other LUMS signifies a more difficult to decompose organic matter.

3.2. Kinetics of the Carbon Mineralization

Table 3 shows results of the microbial mineralization activity of soils from LUMS at two depths in Mount Bambouto Caldera Area estimated using the first order equation. In consideration of convergence, statistical parameters of fitting, and significance of estimated values, the first order model, $\left[C_t = C_o\left(1-e^{-kt}\right)\right]$, was selected for the experimental data because it presented a good fit to C-mineralization with a coefficient of determination, R^2, between 0.83 and 0.99 for all the LUMS.

The highest mean value of potentially mineralizable carbon (C_o) (1477.4 $mgCO_2$-C/kg soil) was observed in grassland in the surface layer (0 - 20 cm) while the lowest mean value (543.5 $mgCO_2$-C/kg soil) was recorded in croplands in the 20 - 40 cm soil profile. The soils of grasslands in 0 - 20 cm profile showed a significantly higher rate constant (k) for C mineralization, which was not statistically different from soils of settlement/agro-forest within the same depth.

Table 3. Microbial mineralization activity of soils from LUMS at two depths in Mount Bambouto Caldera Area, estimated using first order equation.

Depth	*LUMS*	C_o ($mgCO_2$-C/kg soil)	k (day^{-1})	$t_{1/2}$ (day)	qCO_2 [($mgCO_2$-Ch^{-1})/g MBC]
0 - 20 cm	Grassland	1477.4 ± 1.7Aa	0.04310 ± 0.0004Aa	21.6 ± 1.1Ca	1.163 ± 0.02Ba
	Cropland	1429.5 ± 1.3ABa	0.02367 ± 0.0002Ca	26.8 ± 1.3Ba	1.135 ± 0.04BCa
	Palm/Cocoa Plantation	613.0 ± 0.8Ca	0.04031 ± 0.0003ABa	25.1 ± 1.4BCa	0.840 ± 0.01Ca
	Settlement/Agro-forest	834.7 ± 0.9BCa	0.04201 ± 0.0001Aa	24.3 ± 1.2BCa	1.235 ± 0.02ABa
	Fallow/forest land	1018.5 ± 1.1Ba	0.03012 ± 0.0002Ba	34.7 ± 1.3Aa	1.848 ± 0.03Aa
20 - 40 cm	Grassland	1415.5 ± 1.2Aa	0.04142 ± 0.0003Aa	24.6 ± 0.9Cb	1.253 ± 0.01BCa
	Cropland	543.5 ± 0.7Cb	0.03813 ± 0.0002ABb	27.8 ± 0.7BCa	1.121 ± 0.05Ca
	Palm/Cocoa Plantation	772.0 ± 0.9BCb	0.03779 ± 0.0003ABb	27.1 ± 0.6BCb	2.018 ± 0.02ABb
	Settlement/Agroforest	795.7 ± 0.8BCa	0.03501 ± 0.0004Bb	30.3 ± 1.2Bb	1.703 ± 0.01Bb
	Fallow /Forest land	1043.5 ± 1.2ABa	0.02505 ± 0.0005Cb	53.1 ± 1.4Ab	2.720 ± 0.02Ab

Note: Different upper case letters (A, B, C, AB, BC) show significant differences at each depth between different LUMS; different lower case letters (a, b) show significant differences in each LUMS between the two depths. LUMS: land use and management system, C_o: potentially mineralizable carbon, k: rate constant of carbon mineralization, $t_{1/2}$: half-life, qCO_2: metabolic quotient.

Cropland and fallow/forest land had k values which were significantly lower than other LUMS in 0 - 20 cm soil profile. The half-life ($t_{1/2}$) in fallow/forest lands was significantly higher than those of other LUMS at both levels while the lowest value of $t_{1/2}$ was recorded in grassland irrespective of soil depth.

The use of the first order kinetic model to describe C-mineralization of soil organic matter presupposes that microbial biomass is constant and the rate of decomposition depends on available substrate. Other studies [18] [17] [10] [55] [6] have also fitted C-mineralization data with the first order model. Generally, decreases in potentially mineralizable carbon (C_o) are either associated with a low microbial activity or residues that are more difficult to decompose. Therefore, the high values of C_o observed in grassland at the 0 - 20 cm depth suggest residues that are easier to decompose or associated with high microbial activity. Microbial biomass carbon (MBC) is the living or active pool in models that simulate organic carbon turnover in soils. The size of MBC directly affects the model output [56] [57]. Hence, differences in SOC and MBC in LUMS could be important contributors to differences observed in the outputs of carbon kinetic models. High half-life values are generally associated with ecosystem stress [58]. Consequently, the higher value of half-life observed in fallow/forest lands insinuates low carbon mineralization rate and greater stress of the ecosystem.

The mean values of qCO_2 in fallow/forest land were higher than other LUMS at both levels. The highest value of qCO_2 was recorded in fallow/forest land at the 20 - 40 cm. Carbon kinetics parameters were significantly influenced by depth of sampling. In 0 - 20 cm, mean values of qCO_2 recorded in palm/cocoa plantation and fallow/forest land were significantly lower than the values in 20 - 40 cm respectively.

High MBC and soil respiration generally indicate better soil quality [59] but do not always show the same trend. Therefore, metabolic quotient (qCO_2) is employed to evaluate efficiency of soil microbial biomass in utilizing organic carbon [60]. High values of qCO_2 are interpreted as a high requirement of maintenance energy or lower metabolic efficiency. Ecologically, high qCO_2 reflects high maintenance carbon demand [58] while low qCO_2 suggests more stable ecosystems. These findings corroborate other results [61].

3.3. Soil Organic Carbon, Microbial Biomass Carbon, Total Mineralized Carbon and Initial Potential Rate of Carbon Mineralization

Table 4 summarizes SOC, MBC, C_t, and $C_o{}^*k$ as impacted by LUMS and soil depth in Mount Bambouto Caldera Area.

Grassland soils had significantly ($p < 0.001$) higher SOC and MBC than other LUMS except settlement/agro-forest where SOC did not differ. Mean values of SOC between cropland and palm/cocoa plantations did not show any significant statistical difference. The carbon mineralized during the 70 days of incubation in grassland was significantly higher than in other LUMS. The C_t observed in fallow/forest lands was significantly lower than other LUMS. Also, mean values of

Table 4. SOC, MBC, C_t and $C_o{}^*k$ impacted by land use and management systems and soil depth, with standard error and P-values of ANOVA.

LUMS	SOC [g/kg soil]	MBC [mg/kg soil]	C_t [mg CO_2-C/kg soil]	$C_o{}^*k$ [mg CO_2-C/kg soil day]
Grassland	5.0 ± 0.6a	794.8 ± 1.9a	639.3 ± 1.1a	47.1 ± 0.7a
Cropland	4.0 ± 0.3ab	487.6 ± 0.9b	346.8 ± 0.8bc	22.2 ± 0.3bc
Palm/Cocoa Plantation	4.0 ± 0.2ab	668.9 ± 1.2ab	509.5 ± 0.4ab	37.1 ± 0.5ab
Settlement/Agroforest	5.0 ± 0.1a	493.6 ± 0.8b	445.9 ± 0.2b	30.3 ± 0.2b
Fallow/Forest Land	3.0 ± 0.3b	198.6 ± 0.5c	159.7 ± 0.1c	14.8 ± 0.1c
S.e	0.1	45.66	24.90	24.90
DEPTH (D)				
0 - 20 cm	4.2 ± 0.8	527 ± 1.3a	226.1 ± 1.2a	26.9 ± 0.4a
20 - 40 cm	4.3 ± 0.6	434 ± 1.1b	421.9 ± 1.6b	30.2 ± 0.5b
S.e	0.1	14.57	9.92	0.82
ANOVA				
LUMS	***	***	***	***
Depth (D)	ns	***	***	*
LUMS × D	ns	ns	ns	ns

Note: LUMS: land use and management system, SOC: soil organic carbon, MBC: microbial biomass carbon, C_t: total carbon mineralized in 70 days, $C_o{}^*k$: initial potential rate of C mineralization, S.e: standard error, †Mean values with similar letters (a, b, c, ab, bc) in each column indicate non-significant differences at *p < 0.05, ***P < 0.001, ns = not significant

$C_o{}^*k$ recorded in grassland were significantly higher than other LUMS and fallow/forest lands presented the lowest value. The values of C_t and $C_o{}^*k$ were significantly higher in 20 - 40 cm than 0 - 20 cm depths. Low SOC in forest/fallow lands could be attributed to low carbon inputs through biomass return as well as C losses through soil erosion. Meta-analyses of land use change experiments [62] [59] showed that the conversion of grassland/savannah to cropland resulted in significant losses of SOC, whereas the conversion of forest to grassland did not cause SOC losses. The increase in carbon content in grasslands suggests that such soils serve as carbon sinks in the ecosystem.

3.4. Correlation between Soil Variables

Soil organic carbon (SOC) was used to predict C_o in 70 days, which was evaluated using linear regression on eighty observations (**Figure 4**).

Figure 4(f) summarizes **Figures 4(a)-(e)**, and shows a moderate positive correlation between SOC and C_o with a correlation coefficient, r, of 0.56 and coefficient of determination, R^2, of 0.34 representing a potentially mineralizable percentage of 34% of the SOC. The relationship between qCO_2 and MBC:SOC (**Figure 5**) shows that both soil biological parameters have an inverse relationship; with qCO_2 decreasing with increasing MBC:SOC for all LUMS.

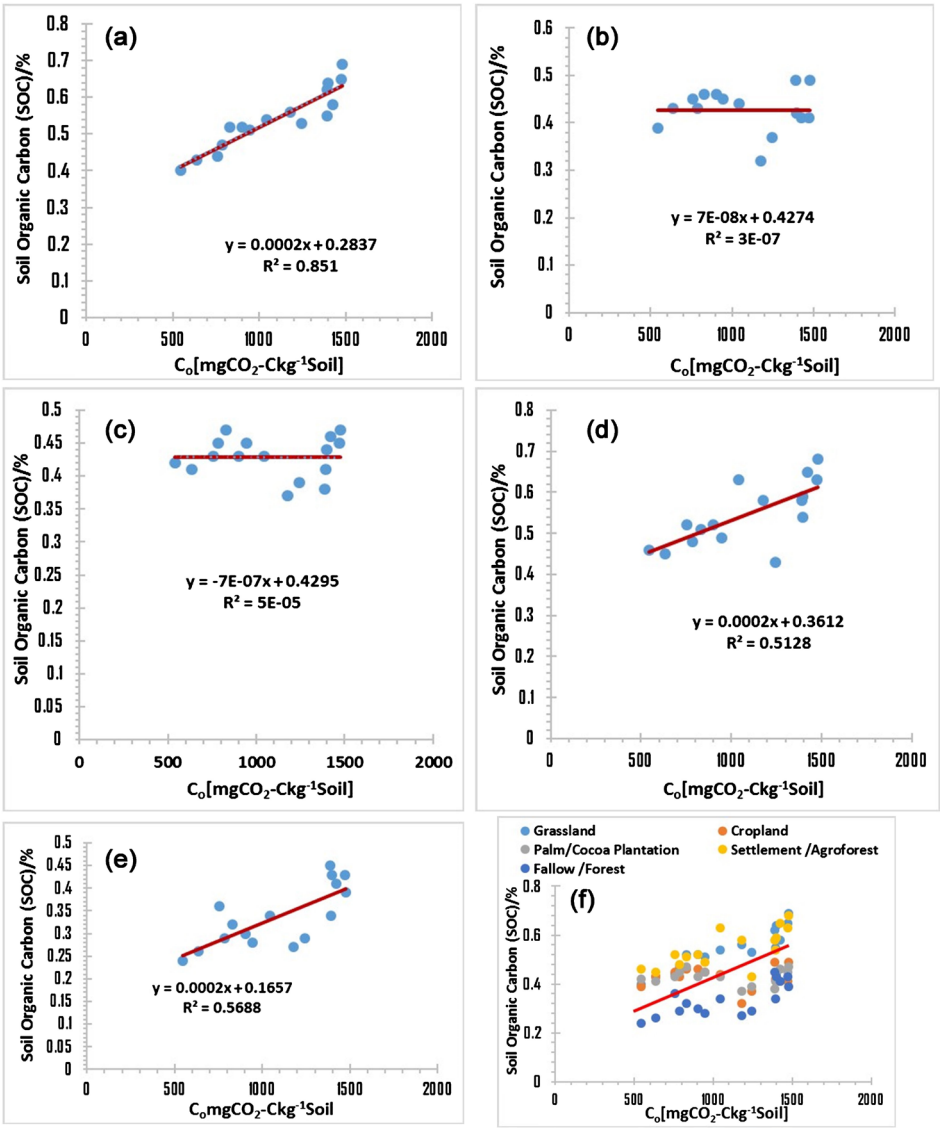

Figure 4. Linear regression between SOC and C_o for land use and management systems (LUMS) in Mount Bambouto Caldera Area. (a) Grasslands; (b) Croplands; (c) Palm/Cocoa Plantation; (d) Settlement/Agroforest; (e) Fallow/Forest Lands; (f) All LUMS. y = 324.07x + 371.49, $R^2 = 0.34$, r = 0.56**, $p < 0.01$, n = 80.

Figure 5(f) summarizes (a)-(e), and shows a moderately strong negative correlation between metabolic quotient and MBC:SOC fraction with a correlation coefficient, *r*, −0.53 and coefficient of determination, R^2, 0.28 representing 28% of the MBC:SOC fraction. While fallow/forest lands portray the highest qCO_2 with lowest MBC:SOC, grassland showed the lowest level qCO_2 and highest MBC:SOC. Palm/cocoa plantations followed grassland though qCO_2 values for grassland were averagely higher while cropland and settlement/agro-forest were similar with no remarkable differences. Correlation coefficients (*r*) between some physical, chemical and microbiological parameters (**Table 5**) show a positive correlation between SOC and C mineralization parameters (C_t, C_o, k and $C_o^* k$) estimated using the first-order mineralization model.

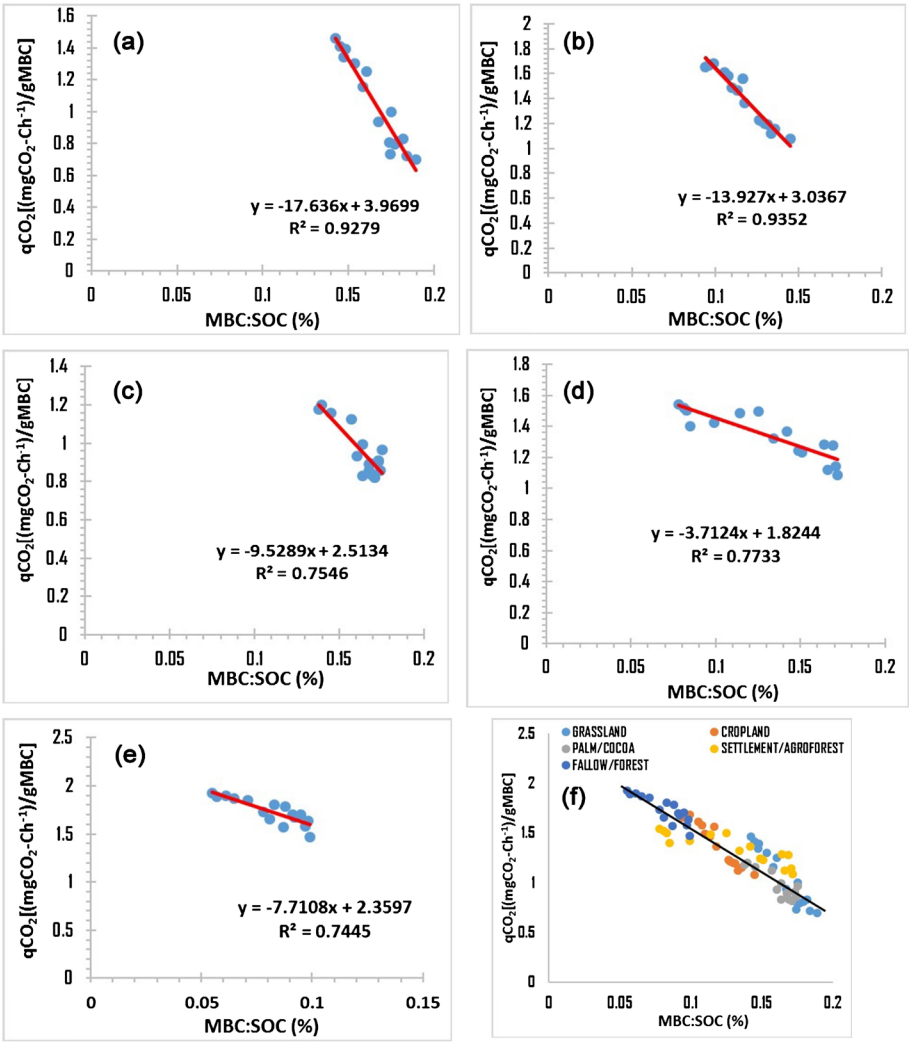

Figure 5. Linear regression between qCO_2 and MBC:SOC for land use and management systems (LUMS) in Mount Bambouto Caldera. (a) Grassland; (b) Cropland; (c) Palm/Cocoa Plantation; (d) Settlement/Agroforest; (e) Fallow/Forest Lands; (f) All LUMS. y = −432.04x + 355.49, R^2 = 0.28, r = −0.53**, P < 0.001, n = 80.

Table 5. Spearman correlation coefficients between soil characteristics and C-mineralization parameters of the first order model.

Parameter	C_t	C_o	k	C_o*k	$t_{1/2}$	qCO_2
Sand	ns	ns	0.263*	ns	−0.263*	ns
Clay	0.273*	0.331*	ns	0.257*	ns	0.220*
pH	0.351**	ns	0.381**	0.368**	−0.383**	−0.370**
SOC	0.637**	0.434**	0.312*	0.615*	−0.312*	ns
TN	0.611**	0.415**	0.333*	0.616**	−0.340*	ns
MBC	0.631**	0.362**	0.324*	0.595**	−0.323*	−0.656***
MBN	0.421**	0.270*	ns	0.517**	ns	−0.867***

Note: C_t = total carbon mineralized in 70 days, C_o = potentially mineralizable C, k = C mineralization rate, C_o*k = initial potential rate of C mineralization, $t_{1/2}$ = half-life, SOC = soil organic carbon, TN = total nitrogen, MBC = microbial biomass carbon, MBN = microbial biomass nitrogen, ns = not significant, *p < 0.05, **p < 0.01 and ***p < 0.001.

Carbon mineralization parameters also had significant positive associations with MBC even though both SOC and MBC negatively correlated with $t_{1/2}$. Good correlation (r = 0.61, 0.42 and 0.62) was also observed between TN and C_p, TN and C_o, and TN and $C_o{}^*k$ respectively. Correlation between qCO_2 and MBN as well as qCO_2 and MBC was negative and statistically significant ($p < 0.001$).

Good correlation between MBC or SOC and C mineralization parameters intimates that C mineralization is influenced by the availability of MBC and SOC for microbial activity. The negative correlation between soil variables with an inverse relationship between qCO_2 and microbial quotient (MBC:SOC) depicts that higher values of qCO_2 may signify difficulties in using organic substrates during microbial activity as a result of low levels of MBC:SOC. Low MBC:SOC ratio had been reported as an indication of deficiency in available carbon in the soil [63]. MBC:SOC has also been reported as an effective early indicator of the amelioration or deterioration of soil quality [64] [59].

4. Conclusion

More CO_2-C was mineralized in grassland than other LUMS, indicating higher rate of microbial activity and carbon cycling. Land use change from grassland to other LUMS caused a decrease in SOC and MBC. Grasslands enhanced more SOC accumulation and decomposition and were found better carbon sinks than other LUMS. Parameters estimated using the first-order model such as C_o, $C_o{}^*k$ and qCO_2 were better discriminators among LUMS. Therefore, together with SOC and MBC, they were sensitive to LU changes, and could be taken as indicators of good soil quality. Hence, changes in LUMS affect the mineralization kinetics of SOC and calls for interdisciplinary stakeholders (NGOs, conservationists, researchers, and local officials in charge of agriculture and environmental protection) to engage in awareness campaigns directed at communities, CIGs, and traditional authorities, on the rapid degradation of soils and the resulting negative effects.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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