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The Structural Quality of Soil Organic Matter under Selected Soil Fertility Management Practices in the Central Highlands of Kenya

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Citation: Githongo, M.; Ngatia, L.; Kiboi, M.; Muriuki, A.; Fliessbach, A.; Musafiri, C.; Fu, R.; Ngetich, F. The Structural Quality of Soil Organic Matter under Selected Soil Fertility Management Practices in the Central Highlands of Kenya. *Sustainability* **2023**, *15*, 6500. https://doi.org/10.3390/su15086500

Academic Editors: Jose Navarro Pedreño and Manuel Miguel Jordan-Vidal

Received: 21 December 2022
Revised: 3 April 2023
Accepted: 4 April 2023
Published: 11 April 2023

Abstract: As influenced by agricultural practices, soil organic matter (SOM) stability is imperative in maintaining soil fertility and crop production. Integrated soil management practices have been recommended for soil fertility improvement by enhancing soil organic matter. We examined the SOM stability under integrated soil management practices for six consecutive cropping seasons in the high agricultural potential area of the Central Highlands of Kenya. The experimental design was a complete randomized block design with fourteen treatments replicated four times. The treatments were minimum (Mt) and conventional tillage (Ct) combined with sole mineral fertilizer (Mf), crop residue combined with mineral fertilizer (RMf), crop residue combined with mineral fertilizer and animal manure (RMfM), crop residue combined with animal manure and *Dolichos Lablab* L. intercrop (RML), crop residue combined with *Tithonia diversifolia* and animal manure (RTiM), and crop residue combined with *Tithonia diversifolia* and phosphate rock (Minjingu) (RTiP), as well as a control (no inputs). SOC was higher in treatments with organic inputs and a combination of organic and inorganic inputs. Treatments with sole mineral fertilizer and no input recorded lower SOC amounts. The C functional groups followed the sequence: alkyl C (53%) > O-alkyl C (17%) > aromatic C (9%) > carboxyl C (8%) > methoxyl C (7%) > phenolic C (6%). The alkyl C proportion was higher in organic inputs treatments, while O-alkyl C was higher in organic and inorganic fertilizer treatment combinations. Methoxyl C, aromatic C, and phenolic C proportion of SOC was greater in crop residue and mineral fertilizer combination, while carboxylic C was lower than the control in most treatments. In addition, the organic inputs treatments had a higher alkyl C/O-alkyl C ratio, increased aliphaticity, and higher hydrophobicity. Applying organic fertilizers individually or in combination with inorganic fertilizers could potentially increase C storage in the soil, thereby enhancing SOC stocks.

Keywords: ^{13}C CPMAS NMR; functional group; soil organic matter stability; soil inputs; soil organic carbon

1. Introduction

Declining soil fertility has pressured food security in sub-Saharan Africa [1,2]. This decline in soil fertility has been revealed by reduced soil organic carbon (SOC) and nutrient contents [3,4]. In the Central Highlands of Kenya, soil fertility decline has been exacerbated by continuous cropping, nutrient mining, and lack of nutrient replenishment [5,6]. Soil organic matter (SOM) is the major reservoir of organic C on the earth's surface and represents a significant C pool [7]. The SOM comprises physical, chemical, and biological processes that improve soil fertility, increase soil moisture, and improve quality [8,9]. To maintain soil fertility, crop production, performance, and environmental stability, SOM storage and stability are prudent [8]. The stability of SOM is its resistance to decomposition or mineralization [10]. Therefore, to understand SOM sensitivity, properties, and functions, it is necessary to know SOM composition and structure [11]. This understanding provides comprehension of SOM's heterogeneous and complex nature in soil [12]. Given the multifaceted interactions that occur through the soil matrix, it is necessary to understand how the stability of SOM is affected by agricultural management practices and how this influences SOM's chemical structure.

Soil organic matter (SOM) contains about 1550 Pg of C globally [13] and about 60% C by mass [14]. Most or all of this pool is assumed to be SOC, except for small amounts of inorganic C in some soils [15]. Using soil inputs has impacted SOC and its stability by enhancing SOC content and storage [16]. Furthermore, studies have shown that adding organic resources provides fresh organic residues and releases soil minerals for organo-mineral complexes that enhance soil C storage [17]. In the Central Highlands of Kenya, smallholder farmers have used organic inputs to improve SOC in the soil, but they contain relatively low nutrients compared with inorganic fertilizers; therefore, a combination of organic and inorganic fertilizers is strongly encouraged [5,18,19]. Additionally, organic and inorganic fertilizer inputs increase yields and provide plant and root biomass C in the soil [20], positively affecting the soil's physical and chemical properties [21]. Studies have shown different influences on the SOC amounts when soil inputs, organic and inorganic, are added to the soil. For example, sole organic input or in combination with inorganic fertilizers tends to increase SOC concentrations [22], whereas sole inorganic fertilization yields inconsistent outcomes [23]. However, the use of soil inputs has exhibited increased SOC in the soil; therefore, it is plausible to evaluate the influence of integrated soil management practices on SOC and SOC composition in the Central Highlands of Kenya.

Using molecular techniques to assess the chemical structure of SOM helps explain the founding paths, decay, and interfaces with espoused agricultural management systems [24]. One such technique is solid-state cross-polarization magic angle spinning ^{13}C nuclear magnetic resonance spectroscopy (CP-MAS ^{13}C-NMR), a fast, accurate, and precise method [25] that has been used to characterize natural organic matter (OM) and SOC [26]. CPMAS ^{13}C NMR spectroscopy can accurately and precisely quantify different C functional groups in mixtures of important SOM source compounds and probably also in SOM of organic surface and mineral topsoil horizons [25]. It is plausible to use CPMAS ^{13}C NMR spectroscopy to understand the complex nature of SOM in the soil under different inputs and tillage in the Central Highlands of Kenya.

Only a few studies in the Central Highlands of Kenya have reported SOC amounts in soils amended with various organic and inorganic soil inputs under conventional tillage (Mucheru-Muna et al. [5]) and minimum tillage (Kiboi et al. [27]). These studies have significantly advanced our understanding of SOC amounts improvement when integrated soil management practices are used. While soil carbon is an indicator of soil health and productivity, limited research has been done in the Central Highlands of Kenya on the stability of soil organic carbon under different soil inputs in maize cropping systems; thus, the impact of SOC contribution to soil quality is lacking. Further, information is scanty about the chemical structure of SOM under these management strategies in the Central Highlands of Kenya. This study's objective was to investigate the quality of SOM in soils under integrated soil management practices in the Central Highlands of Kenya using the ^{13}C cross-polarization magic angle spinning (CP-MAS) NMR.

2. Materials and Methods

2.1. Site Description

We carried out the study in Meru south sub-County, Tharaka Nithi County. The experimental site was at Kangutu Primary School (00°98′ S, 37°08′ E) farm (Figure 1). The sub-County lies 1468 m above sea level (a.s.l) and is located on the Upper Midland 2 (UM2) agroecological zone (AEZ) [28].

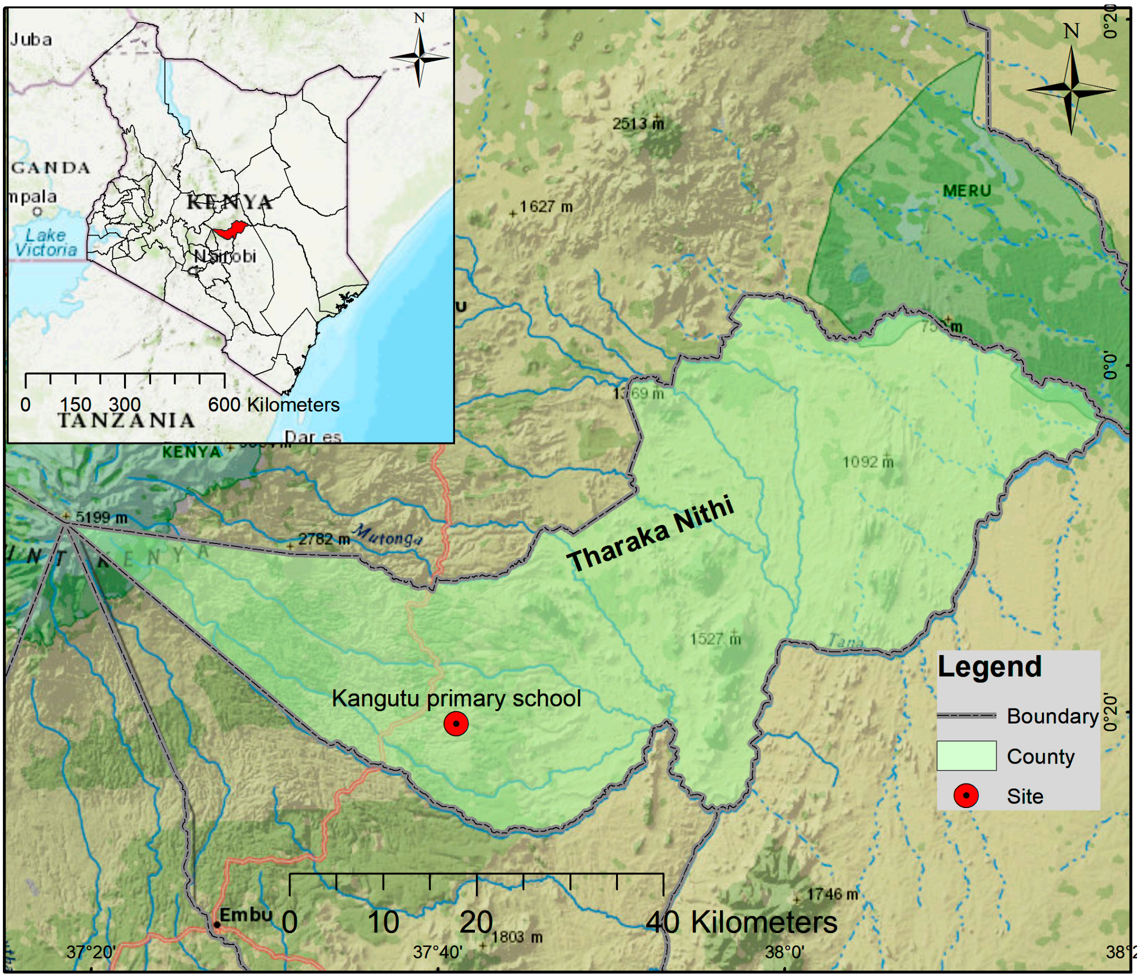

Figure 1. Map of the study area.

The area experiences two rainy seasons annually; March to May (long rains) and October to December (short rains). It receives an annual average rainfall of 1500 mm, while the annual temperatures range from 18.2 to 20.6 °C. [28]. The predominant soils in the area are *Humic Nitisols* which are well-drained, extremely deep, dusky red to dark reddish-brown, friable clay with humic topsoil [28]. However, due to continuous cropping and nutrient mining, these soils require amendments to improve and sustain their fertility [29]. The soil properties of the experimentation site are presented in Table 1.

Table 1. Soil properties of Kangutu experimental site.

Treatment [1]	[2] pH	Total N (g kg^{-1})	TOC (g kg^{-1})	P (mg kg^{-1})	K (g kg^{-1})	Ca (g kg^{-1})	Mg (g kg^{-1})	Mn (g kg^{-1})	Cu (mg kg^{-1})	Fe (mg kg^{-1})	Zn (mg kg^{-1})	Na (g kg^{-1})
CtC	4.5	1.3	15.2	38	2.9	9.5	20.1	13.9	4.2	27	61	2.6
CtMf	4.4	1.4	15.4	82	3.4	12	17.8	20.4	4.3	32	63	2.6
CtRMf	4.5	1.6	17.3	77	3.3	14	24	17.2	3.6	28	58	2.5
CtRMfM	5.2	1.7	19.0	71	7.4	31	30.7	15.4	4.3	23	66	2.8
CtRML	5.1	1.7	18.2	51	8.9	21.5	34	13	3.5	20	59	2.6
CtRTiM	5.1	1.7	18.0	50	9.8	26.5	28.6	12.5	3.7	21	61	3
CtRTiP	4.9	1.6	17.9	74	6.5	19	28.4	18.9	3.5	24	61	4.1
MtC	4.6	1.4	15.8	51	3.9	14	21.8	17.7	4.5	26	63	2.9
MtMf	4.2	1.4	15.0	147	2.7	8	17.4	13.8	4.3	39	64	3
MtRMf	4.4	1.5	16.9	73	4.1	14.5	21.5	15.2	3.9	31	61	2.8
MtRMfM	5.3	1.7	18.8	47	9.1	52.5	32.7	17.5	3.5	19	58	3.4
MtRML	5.2	1.6	18.0	45	9	21.5	35.8	18.7	3.8	17	63	3
MtRTiM	5.0	1.7	17.8	67	6.4	21.5	30.7	15.9	4.4	26	60	3.6
MtRTiP	5.0	1.7	18.4	75	7.8	28	26	13.5	4	24	66	3.1

[1] Treatment: CtC = Conventional tillage Control, CtMf = Conventional tillage + Mineral fertilizer, CtRMf = Conventional tillage + Crop residues + Mineral fertilizer, CtRMfM = Conventional tillage + Crop residues + Mineral fertilizer + Animal manure, CtRML = Conventional tillage + Crop residues + Animal manure + Legume intercrop *(Dolichos Lablab)*, CtRTiM = Conventional tillage + Crop residues + *Tithonia diversifolia* + Animal manure, CtRTiP = Conventional tillage + Crop residues + *Tithonia diversifolia* + Phosphate rock (Minjingu), MtC = Minimum tillage Control, MtMf = Minimum tillage + Mineral fertilizer, MtRMf = Minimum tillage + Crop residues + Mineral fertilizer, MtRMfM = Minimum tillage + Crop residues +Mineral fertilizer + Animal manure, MtRML = Minimum tillage + Crop residues + Animal manure + Legume intercrop *(Dolichos Lablab)*, MtRTiM = Minimum tillage + Crop residues + *Tithonia diversifolia* + Animal manure, MtRTiP = Minimum tillage + Crop residues + *Tithonia diversifolia* + Phosphate rock (Minjingu). [2] Soil chemical analysis done following Ryan et al. [30]: pH using pH meter; Nitrogen by Kjeldahl method; Organic carbon by modified Walkley and Black wet oxidation method; Phosphorus by Spectrophotometer; Potassium and Sodium by Flame Photometer; Calcium, Magnesium, Zinc, Iron, Copper, and Manganese by Atomic Absorption Spectrophotometry.

2.2. Experimental Design

We implemented a randomized complete block design with fourteen treatments (Table 2), replicated four times. The plot size was 6 m by 4.5 m, and the test crop was maize (*Zea mays* L.), variety H516. The plant spacing was 0.75 m between the rows and 0.5 m between plants. We did land preparation two weeks before the onset of the rainy season. Where land plowing in minimum tillage plots, only planting holes were plowed. We incorporated organic inputs (*Tithonia diversifolia* and animal manure) into the soil in the planting holes. In conventional tillage plots, we prepared the land by hand hoeing up to a depth of 15 cm, broadcasted *Tithonia diversifolia* and animal manure on the plots, and incorporated it into the soil using a hand hoe. We planted two weeks after the incorporation of *Tithonia diversifolia* and animal manure. The nutrient quality of *Tithonia diversifolia* and animal manure are described in Table 3. We planted three seeds per hill and later thinned to two seedlings two weeks after emergence resulting in the recommended plant density of 53,333 per hectare [31]. We surface-applied crop residue after thinning at a rate of 5 Mg ha^{-1} per season in treatments with crop residue (Table 2). We applied nitrogen (60 kg N ha^{-1}) per season to meet the recommended nitrogen content for maize in the study area [32]. We used an equivalence of 30 kg N ha^{-1} from organic inputs and 30 kg N ha^{-1} per season in treatments with organic inputs and mineral fertilizer. Inorganic P was supplied using triple superphosphate at 90 kg ha^{-1} per season in treatments with mineral fertilizers during planting. We hand-pulled weeds in treatments under minimum tillage and weeded using a hand hoe in conventional tillage treatments.

Table 2. Field treatments implemented in the Kangutu experimentation site.

Treatments	Abbreviations
Minimum tillage Control	MtC
Minimum tillage + Sole Mineral fertilizer	MtMf
Minimum tillage + Crop residues + Animal manure + Legume intercrop (*Dolichos Lablab*)	MtRML
Minimum tillage + Crop residues + *Tithonia diversifolia* + Phosphate rock (Minjingu)	MtRTiP
Minimum tillage + Crop residues + Mineral fertilizer + Animal manure	MtRMfM

Table 2. *Cont.*

Treatments	Abbreviations
Minimum tillage + Crop residues + *Tithonia diversifolia* + Animal manure	MtRTiM
Minimum tillage + Crop residues + Mineral fertilizer	MtRMf
Conventional tillage Control	CtC
Conventional tillage + Sole Mineral fertilizer	CtMf
Conventional tillage + Crop residues + Animal manure + Legume intercrop (*Dolichos Lablab*)	CtRML
Conventional tillage + Crop residues + *Tithonia diversifolia* + Phosphate rock (Minjingu)	CtRTiP
Conventional tillage + Crop residues + Mineral fertilizer + Animal manure	CtRMfM
Conventional tillage + Crop residues + *Tithonia diversifolia* + Animal manure	CtRTiM
Conventional tillage + Crop residues + Mineral fertilizer	CtRMf

Table 3. Nutrient composition (%) of animal manure and *Tithonia diversifolia* applied in the soil at the Kangutu site.

Organic Input	Nutrient Amount (%)							
	N	P	C	C/N	ADF [1]	Cellulose	Lignin	Polyphenols
Animal manure	1.70 [b2]	0.53 [a]	42.06 [a]	16.30 [a]	37.31 [b]	21.75 [a]	27.94 [a]	0.18 [a]
Tithonia. diversifolia	3.32 [a]	0.14 [a]	41.30 [a]	11.41 [b]	49.59 [a]	18.08 [a]	12.88 [b]	0.14 [a]

[1] ADF = Acid Detergent Fibre. [2] Means with the same letter in each column are not statistically different at $p < 0.05$.

2.3. Soil Sampling

We collected the soil samples at the end of the long rains 2019 season, after six consecutive cropping seasons since the experiment's establishment. We sampled approximately 50 g of soil from each plot from 0–15 cm depth using the Eijkelkamp gouge auger. We put the sample into 60 mL plastic vials, labelled them, and shipped them to the National High Magnetic Field Laboratory, USA, for nuclear magnetic resonance (NMR) analysis. We also sampled for the soil's physical properties by collecting approximately 1 kg of soil from each of the plots at a depth of 0–20 cm using the Eijkelkamp gouge auger.

2.4. ^{13}C-CPMAS NMR Characterization

The solid-state ^{13}C CPMAS ssNMR spectra were collected using a Bruker 300 MHz DRX NMR spectrometer. The spectrometer had a Bruker 4.0 mm double resonance MAS NMR probe. Samples were placed in a zirconium oxide rotor with a diameter of 4 mm and Kel-F caps. A spinning speed of 9.5 kHz ±3 Hz was applied, and recycle delay was set to 2 s at RT using Bruker pneumatic MAS control unit. A ramped ^{1}H pulse (from 35 to 50 kHz) by ^{13}C RF field where a 4.0 µs ^{1}H $\pi/2$ pulse followed by a ^{1}H spin-lock field of 45 kHz for 1 ms contact time enhanced all ^{13}C signals from ^{1}H. Depending on the sensitivity of the sample, the number of accumulated scans varied between 10,000 and 500,000. Carbon chemical shifts were referenced to the carbonyl carbon signal of glycine at 176.4 ppm. For quantification of different C species, the ^{13}C NMR spectra were divided into six chemical shift regions which were assigned to specific C functional groups according to Knicker [33]; alkyl (0–45 ppm), methoxyl (45–60 ppm), O-alkyl (60–110 ppm), aromatic (110–140 ppm), phenolic (140–160 ppm), and carboxyl (160–220 ppm). The percent C of the functional group was converted to g functional group C kg^{-1} sample using organic C values of the soil samples.

2.5. Statistical Analysis

We analyzed the data using one-way ANOVA in SAS version 9.4 Software. We used the least significant difference (LSD) to compare the means of the soil variables under different soil management practices treatments at $p \leq 0.05$.

3. Results

3.1. Effect of Different Soil Inputs and Tillage on Soil Organic Carbon

Soil organic carbon (SOC) was significantly ($p < 0.0001$) higher under CtRML, CtRTiM, MtRML, MtRTiM, CtRMfM, MtRMfM, CtRMf, MtRTiP, MtRMf, CtRTiP, and MtMf by 108, 87, 87, 69, 56, 51, 50, 39, 36, 7, and 3% compared with the control (CtC) (Figure 2). In contrast, CtMf (22.65 g kg^{-1}C) treatment decreased SOC content by 16% compared with CtC (27.11 g kg^{-1}C).

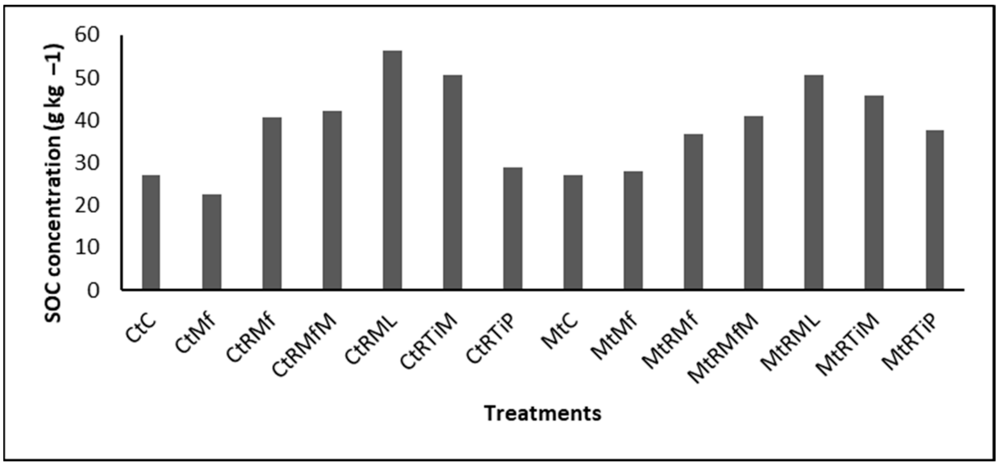

Figure 2. Soil organic carbon under different soil inputs and tillage. CtC = Conventional tillage Control, CtMf = Conventional tillage + Mineral fertilizer, CtRMf = Conventionaltillage + Crop residues + Mineral fertilizer, CtRMfM = Conventional tillage + Crop residues + Mineral fertilizer + Animal manure, CtRML = Conventional tillage + Crop residues + Animal manure + Legume intercrop *(Dolichos Lablab)*, CtRTiM = Conventional tillage + Crop residues + *Tithonia diversifolia* + Animal manure, CtRTiP = Conventionaltillage + Crop residues + *Tithonia diversifolia* + Phosphate rock (Minjingu), MtC = Minimum tillage Control, MtMf = Minimum tillage + Mineral fertilizer, MtRMf = Minimum tillage + Crop residues + Mineral fertilizer, MtRMfM = Minimum tillage + Crop residues + Mineral fertilizer + Animal manure, MtRML = Minimum tillage + Crop residues + Animal manure + Legume intercrop *(Dolichos Lablab)*, MtRTiM = Minimum tillage + Crop residues + *Tithonia diversifolia* + Animal manure, MtRTiP = Minimum tillage + Crop residues + *Tithonia diversifolia* + Phosphate rock (Minjingu). Treatment means were significantly different at $p < 0.0001$.

3.2. Effect of Different Soil Inputs and Tillage on Soil Organic Matter Structure

The results of CPMAS NMR are shown in Figure 3. Briefly, alkyl C was significantly ($p < 0.0001$) higher under MtRML, CtRML, MtRTiM, MtRMfM, CtRTiM, MtRTiP, CtRMf, CtRMfM, MtC, and MtMf by 118, 116, 95, 69, 68, 57, 42, 36, 6, and 4% compared with the control. Methoxyl C was significantly ($p < 0.0001$) higher under all the treatments with CtRMf, MtMf, MtRTiP, MtRML, MtRTiM, CtRMfM, CtRML, CtRTiM, CtMf, MtRMfM, MtRMf, CtRTiP, and MtC higher by 71, 41, 39, 35, 34, 31, 31, 29, 19, 18, 18, 14, and 14% compared with the control. O-alkyl was significantly ($p < 0.0001$) higher under all the treatments with CtRTiP, MtRMf, CtRMf, CtRMfM, CtRTiM, CtMf, MtMf, CtRML, MtRTiP MtRMfM, MtRML, MtRTiM, and MtC higher by 234, 232, 142, 127, 88, 83, 61, 45, 25, 17, 16, 11, and 4% compared with the control. Aromatic C was significantly ($p < 0.0001$) higher under MtRMf, CtRTiP, CtRMfM, CtMf, CtRMf, CtRMf, CtRTiM, MtMf, and CtRML by 174, 139, 71, 46, 35, 28, 21, and 10 % compared with the control. Phenolic C was significantly ($p < 0.0001$) higher under MtRMf, CtRTiP, CtRMfM, CtMf, CtRTiM, and CtRMf by 83, 44, 19, 18, 6, and 1% compared with the control. In the carboxylic C group, the control treatment was significantly ($p < 0.0001$) higher than all the other treatments except for CtRTiP, which was 1% higher than the control. In summary, CtRTiP was highest in O-alkyl C and carboxylic C, MtRMf was highest in aromatic C and phenolic C, MtRML was highest in alkyl C, and CtRML was highest in the methoxyl C carbon group.

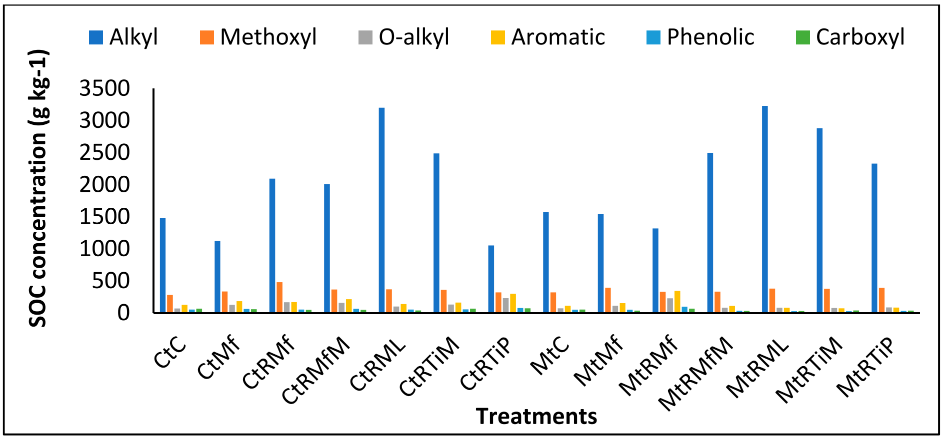

Figure 3. Dynamics of the relative abundances of alkyl C, methoxyl C, O-alkyl C, aromatic C, phenolic C, and carboxyl C in different soil inputs and tillage practices as determined by ^{13}C CPMAS NMR.

3.3. Effect of Different Soil Inputs and Tillage on Carbon Group Ratios

The aliphatic/aromatic ratio was lowest under MtRMf (4.27) and highest under MtRTiM (34.27) was the highest. The alkyl C/O-alkyl C ratio was lowest under CtRTiP (4.78) and highest under MtRML (40.34). The Hydrophobic C/Hydrophilic C ratio was the lowest under CtRTiP (2.30) and highest under MtRML (6.86) (Figure 4).

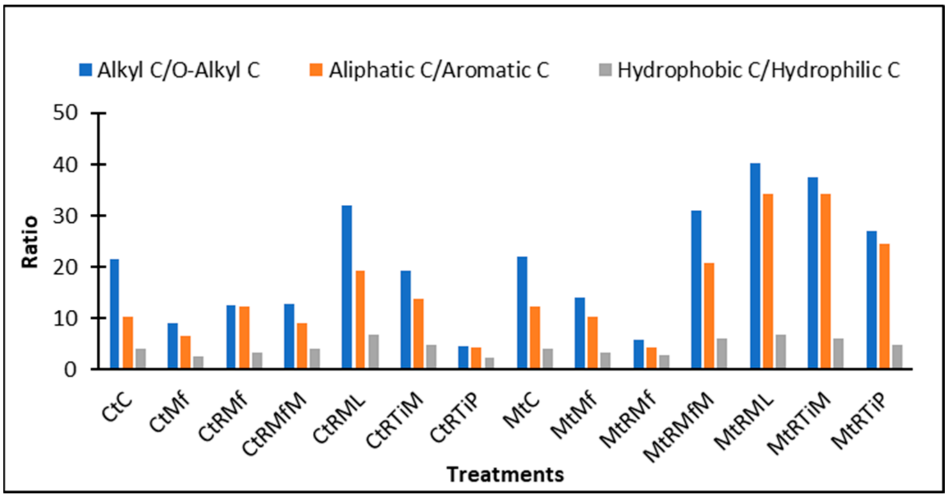

Figure 4. The ratios of alkyl C/O-alkyl C; Aliphaticity and hydrophobicity of SOM under different soil management practices. Aliphatic/Aromatic = (Alkyl-C + O-alkyl-C)/Aromatics-C; Hydrophobic-C/Hydrophilic-C = (Alkyl-C + Aromatic-C)/ (O-alkyl-C + Carboxyl C).

4. Discussion

The soil's organic carbon content and alkyl C were significantly increased in treatments with organic inputs, indicating the importance of organic and inorganic inputs in increasing soil organic carbon, thereby impacting soil fertility. The carbon functional groups of methoxyl C, aromatic C, and phenolic C were higher in the treatment combination of crop residues and mineral fertilizer. This shows the importance of mineral fertilizer in the soil's carbon stability.

In this study, the soil carbon content varied under integrated soil inputs and tillage treatments compared to the control. Treatments with crop residues, animal manure, and legume intercropping had higher SOC content than control. This is attributed to organic matter input from the legume intercrop, crop residue, and manure, leading to high C input and increasing the SOC [34]. The legume intercrop promoted N inputs and increased substrate efficiency as an energy source for soil biology [35], thereby increasing microbial activity and SOC. Crop residue, *Tithonia diversifolia*, and animal manure treatments had higher SOC as they provided an organic C source to the soil. The animal manure had a higher lignin content than *Tithonia diversifolia*, which slowed decomposition (Table 3). Thus, the humus of the slowly decomposing manure may preserve released nutrients from the fast-decaying *Tithonia diversifolia* within the rhizosphere, fostering a C increase in the soil. This agrees with a study by Margenot et al. [36], who indicated that organic matter inputs increased microbial enzymatic activity, potentially increasing stable SOC stocks.

Crop residues, mineral fertilizer, and animal manure treatments had significantly higher SOC content than the control attributing this to organic carbon addition to the soil [37]. Further, soil N from the inorganic fertilizer addition enhanced C storage in the soil [38]. This agrees with Guo et al. [39] in Eastern China, which reported higher SOC amounts in treatments combining organic (cattle manure) and inorganic fertilizers than in treatments with sole chemical fertilizer and control. Treatments with crop residue, *Tithonia diversifolia*, and rock phosphate had higher SOC than the control endorsing this to the addition of organic C from *Tithonia diversifolia*, which could have influenced the structural properties by enmeshing primary soil particles via root action and enhancing microbial activities by producing cementing agents [40].

We observed higher SOC from crop residues and mineral fertilizer treatments. The addition of carbon through crop residue and root biomass due to N addition from mineral fertilizer in these treatments increased SOC. The SOC amounts in convention and minimum tillage treatments were similar except for the CtMf treatment, which was lower than the control (Figure 2). The reduction of carbon in CtMf could result from mineral N immobilization and N mining from SOM by the microorganisms, as the microbes utilized the available mineral N as an energy source in contrast with the control where the root biomass provided the essential plant-derived OM.

The amount of soil inputs added to the soil could have influenced OC content in the soil and no-tillage [41]. Dimassi et al. [42] suggested that soil inputs produced similar SOC amounts under different tillage practices (conventional and minimum tillage), as in our study, except for CtMf treatment. Though studies showed conventional and minimum tillage practices do not significantly influence SOC [43,44], others revealed decreased SOC when conventional tillag. For instance, Assunção et al. [45] reported that minimum tillage increased the amount of SOC compared to conventional tillage.

4.1. Effect of Integrated Soil Inputs and Tillage on SOM Structure

The stability of soil organic matter depends on the mechanisms of interaction of organic carbon in the soil [46]. In our study, alkyl C (0–45 ppm) dominated soil organic C, followed by O-alkyl C (61–110 ppm), as also found by Schweizer et al. [47]. Organic input addition accelerated the decomposition of labile C compared to recalcitrant C components [48]. Plant litter contained high amounts of cutins in leaf cuticles and suberins found outside roots [49,50]. These alkyl C components are preserved during SOM decompositions [51,52]. Thus, adding organic inputs lower th excessive decomposition of soil hydrophobic components, increasing SOM amounts similar to [53,54].

Microbial community preferentially decomposes labile C, and the products contributing to the formation of stable C [55]. The alkyl C from organic and inorganic combination was contrary to Zhang et al. [56], who attributed their findings to slower decomposition of the organic inputs in the treatment combinations. The slower decomposition results from applying organic manure and fresh plant litter from *Tithonia diversifolia* [57]. Microbial community structure and its microorganisms lead to a higher alkyl C in minimum tillage treatments, as alkyl C is the most persistent stable fraction derived from soil microorganisms' metabolic products [58].

The methoxyl C was higher in crop residue, and mineral fertilizer treatment combination compared with the control. The higher methoxyl C proportion from crop residue and mineral fertilizer treatment combination was attributed to the fact that the methoxyl C chemical structure is recalcitrant, thus, not prone to degradation by microorganisms [59].

The mineral fertilizer provided mineral N input, which encouraged plant root growth. Therefore, it is possible that plant roots were the main organic input, and this would explain the recalcitrant lignin accumulation. However, the higher O-alkyl C proportion of CtRTiP, MtRMf, CtRMf, and CtRMfM treatments could be ascribed to the presence of certain defense mechanisms of O-alkyl C constituents [60]. In addition, the inorganic fertilizer stimulates Mf decomposition due to increased microbial activity [61], increasing hydrolytic enzymatic activities, and reduced oxidative enzymes, decreasing the decomposition of more resistant OM and possibly increasing SOC storage [60]. Further, the high O-alkyl C proportions under integrated organic and inorganic fertilizer addition could influence soil physical and biological properties and clay mineral adsorption of polysaccharides [23]. This, in turn, could impact aggregation and soil particles' structural activity, leading to soil C sequestration [62].

The findings on aromatic C proportion of SOC agreed with Luan et al. [16], who reported that aromatic C was lower in the soils that received organic inputs (20.8%–23.9%) and greater in the soils that received sole mineral fertilizer (26.6%) than the control. In contrast, a previous study by Zhang et al. [63] indicated that aromatic C was lower in treatments with the addition of organic inputs than those without the addition of organic inputs. The variances could explain the varying results in the quality of organic inputs, soil type, and environmental conditions [64]. However, the higher phenolic C in MtRMf and CtRTiP treatments could be attributed to lignin degradation as phenolic C in the soil is derived from microbial degradation of lignin in dead plant remains [65]. Phenolic C is selectively preserved by the microorganisms, and thus resistant to degradation [66].

4.2. Effect of Different Soil Inputs and Tillage on Carbon Group Ratios

The alkyl/O-alkyl (AL/OA) ratio has been used to indicate the relative degree of SOC decomposition or the degree of humification of the SOM [59], and a low value indicates a better quality of SOC [65]. The low soil alkyl C/O-alkyl C ratio in CtRTiP and MtRMf treatments suggest that SOC decomposed more slowly. This may be a result of the addition of carbohydrates and cellulose structures to the soil organic matter. A study by Schoebitz and Vidal [67] reported that combining organic and inorganic soil inputs led to efficient nutrient usage, enhancing soil C. Organic and inorganic inputs integration limits carbon mineralization, possibly due to the formation of compounds resistant to microbial activity, leading to increased C storage [55]. Thus, these fertilization combinations could delay the decomposition process, leading to C sequestration in the soil. The organic inputs treatment consumed more labile C, leading to increased recalcitrant C [68]. This was contradictory to a study by Wang et al. [20], who found that adding mineral fertilizers consumed more labile C, resulting in a higher alkyl C/O-alkyl C ratio than organic inputs treatments.

The aliphatic C/aromatic C (AL/AR) ratio predicts SOM chemical composition's complexity [59]. The highest aliphaticC/aromatic C ratio in MtRTiM and lowest in MtRMf treatment indicated that the MtRTiM treatment had C functional groups with a simpler molecular structure, less condensation, and a less aromatic structure. High aliphaticity indicates that the treatment may improve the decomposition potential of SOC [61,69]. The increased aliphaticity under MtRTiM and MtRML treatments may result from the selective preservation of lignin structures during microbial degradation when specific microorganisms and oxidative enzymes degrade lignin and have low biomass or weak enzymatic activity [60]. Zhao et al. [70] found that smaller fungi populations and weak oxidative enzymatic activities in soils under organic inputs treatments. This contradicts a study by Chang et al. [71], who observed that aliphatic C/aromatic C increased with increasing disturbance intensity. The findings could be attributed to the presence of recalcitrant C and that microbial community structure that could have decreased alkyl C with increasing soil disturbances.

The high hydrophobic C/hydrophilic C ratio under crop residue, animal manure, and legume intercrop treatment combination could be attributed to the addition of organic inputs, indicating that SOM was highly protected from microbial decomposition [72] as free lipids formed a hydrophobic coating around the soil organic matter [73]. This contradicts Zhang et al. [67], who reported a lower hydrophobicity of SOM in treatments under organic inputs than in chemical fertilizer treatment. Studies by Zhang et al. [69] have indicated that a higher value of aliphatic C/aromatic C and hydrophobic C/hydrophilic C ratio suggested that the soil organic matter was more aliphatic and hydrophobic. Most of the minimum tillage treatments had higher than conventional tillage treatments. The higher hydrophobic C/hydrophilic C ratio in minimum tillage could be explained by SOM aggregation due to reduced tillage, temporarily cementing material from simple polysaccharide secretion to hyphae and roots and leading to short-term stability and stable complex aromatic substances [74].

5. Conclusions

Our results showed treatment with crop residues, animal manure, legume intercrop, and *Tithonia diversifolia* (CtRML, CtRTiM, MtRML, and MtRTiM) unswervingly increased the amount of OC in the soil. This underscores the importance of organic inputs in improving SOC in the soil and the intricate nutrient synergy in the combination of organic and inorganic inputs treatments, which also increase SOC. We showed that organic inputs increase alkyl C, and combining organic and inorganic inputs increases O-alkyl C. This underscores the importance of both sole organic and combination organic/inorganic inputs in SOC stability. Smallholder farmers in the Central Highlands of Kenya could increase yields and improve SOC stocks by adding organic and inorganic inputs. We further established that adding crop residues as mulch and mineral fertilizer increased methoxyl C, aromatic C, and phenolic C functional groups. This shows the importance of mineral fertilizer addition with mulch to improve the decomposition of SOM. In our study, organic inputs treatments had a higher value of aliphatic C/aromatic C and hydrophobic C/hydrophilic C ratio and, therefore, were more aliphatic and hydrophobic. This underpins the importance of organic inputs in SOC stability and storage. A combination of organic and inorganic soil inputs in the study showed a low alkyl C/O-alkyl C ratio showing a better quality SOC that did not decompose readily. Therefore, this study highlights the possibility of improving crop production by improving SOC stability in the soil, which would increase soil fertility through different soil fertility management practices. There is a need to encourage smallholder farmers to embrace different soil fertility management practices to improve the soil fertility status and crop performance and productivity.

Author Contributions: Conceptualization, M.G. and M.K.; methodology, M.G., L.N., M.K., R.F. and F.N.; validation, C.M.; formal analysis, M.G., R.F., L.N. and F.N.; investigation, M.G., M.K. and F.N.; resources, F.N., A.M. and A.F.; data curation, M.G.; writing—original draft preparation, M.G. and F.N.; writing—review and editing, C.M., A.F., L.N., F.N. and A.M.; visualization, M.G. and F.N.; supervision, F.N., A.F. and M.K.; project administration, A.M. and M.K.; funding acquisition, A.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Swiss Agency for Development and Cooperation (SDC) and the Swiss National Science Foundation (SNSF) in the Swiss Programme for Research on Global Issues for Development (r4d programme), Grant No. 152224. The APC was partially funded by the Swiss National Science Foundation (SNSF).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Acknowledgments: We would like to thank the Research Institute of Organic Agriculture (FiBL), for technical support through the farmer-driven organic resource management to build soil fertility (ORM4Soil) project. The authors would also like to thank the National High Magnetic Field Laboratory, which is supported by the National Science Foundation Cooperative Agreement No. DMR-1644779 and the State of Florida for the NMR analysis. We thank Kangutu Primary School in Meru south sub-County for providing the experimental site.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Githongo, M.; Kiboi, M.; Ngetich, F.; Musafiri, C.; Muriuki, A.; Fliessbach, A. The effect of minimum tillage and animal manure on maize yields and soil organic carbon in sub-Saharan Africa: A meta-analysis. *Environ. Challenges* **2021**, *5*, 100340. [CrossRef]
2. Oduor, N.; Kiboi, M.N.; Muriuki, A.; Adamtey, N.; Musafiri, C.M.; Ngetich, F.K. Soil management strategies enhanced crop yield, soil moisture, and water productivity in Nitisols of the Upper Eastern Kenya. *Environ. Challenges* **2021**, *5*, 100375. [CrossRef]
3. Githongo, M.W.; Musafiri, C.M.; Macharia, J.M.; Kiboi, M.N.; Fliessbach, A.; Muriuki, A.; Ngetich, F.K. Greenhouse Gas Fluxes from Selected Soil Fertility Management Practices in Humic Nitisols of Upper Eastern Kenya. *Sustainability* **2022**, *14*, 1938. [CrossRef]
4. Kintché, K.; Guibert, H.; Sogbedji, J.; Levêque, J.; Bonfoh, B.; Tittonell, P. Long-term mineral fertilizer use and maize residue incorporation do not compensate for carbon and nutrient losses from a Ferralsol under continuous maize–cotton cropping. *Field Crops Res.* **2015**, *184*, 192–200. [CrossRef]
5. Mucheru-Muna, M.; Mugendi, D.; Pypers, P.; Mugwe, J.; Kung'U, J.; Vanlauwe, B.; Merckx, R. Enhancing maize productivity and profitability using organic inputs and mineral fertilizer in central kenya small-hold farms. *Exp. Agric.* **2013**, *50*, 250–269. [CrossRef]
6. Ngetich, F.K.; Mairura, F.S.; Musafiri, C.M.; Kiboi, M.N.; Shisanya, C.A. Smallholders' coping strategies in response to climate variability in semi-arid agro-ecozones of Upper Eastern Kenya. *Soc. Sci. Humanit. Open* **2022**, *6*, 100319. [CrossRef]
7. Schmidt, M.W.I.; Torn, M.S.; Abiven, S.; Dittmar, T.; Guggenberger, G.; Janssens, I.A.; Kleber, M.; Kögel-Knabner, I.; Lehmann, J.; Manning, D.A.C.; et al. Persistence of soil organic matter as an ecosystem property. *Nature* **2011**, *478*, 49–56. [CrossRef]
8. Lehmann, J.; Kleber, M. The contentious nature of soil organic matter. *Nature* **2015**, *528*, 60–68. [CrossRef]
9. Omenda, J.A.; Ngetich, K.F.; Kiboi, M.N.; Mucheru-Muna, M.W.; Mugendi, D.N. Soil Organic Carbon and Acid Phosphatase Enzyme Activity Response to Phosphate Rock and Organic Inputs in Acidic Soils of Central Highlands of Kenya in Maize. *Int. J. Plant Soil Sci.* **2019**, *30*, 1–13. [CrossRef]
10. Stone, M.M.; Plante, A.F. Relating the biological stability of soil organic matter to energy availability in deep tropical soil profiles. *Soil Biol. Biochem.* **2015**, *89*, 162–171. [CrossRef]
11. Mao, J.; Cao, X.; Olk, D.C.; Chu, W.; Schmidt-Rohr, K. Advanced solid-state NMR spectroscopy of natural organic matter. *Prog. Nucl. Magn. Reson. Spectrosc.* **2017**, *100*, 17–51. [CrossRef] [PubMed]
12. Piccolo, A.; Spaccini, R.; Drosos, M.; Vinci, G.; Cozzolino, V. The Molecular Composition of Humus Carbon: Recalcitrance and Reactivity in Soils. In *The Future of Soil Carbon: Its Conservation and Formation*; Academic Press: Cambridge, MA, USA, 2018; pp. 87–124. [CrossRef]
13. Lal, R. Soil carbon sequestration to mitigate climate change. *Geoderma* **2004**, *123*, 1–22. [CrossRef]
14. FAO. *Soil Organic Carbon: The Hidden Potential*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2017.
15. FAO and ITPS. *Status of the World's Soil Resources, Rome (SWSR)—Main Report*; Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils: Rome, Italy, 2015; p. 650.
16. Luan, H.; Gao, W.; Huang, S.; Tang, J.; Li, M.; Zhang, H.; Chen, X. Partial substitution of chemical fertilizer with organic amendments affects soil organic carbon composition and stability in a greenhouse vegetable production system. *Soil Tillage Res.* **2019**, *191*, 185–196. [CrossRef]
17. Yu, G.; Xiao, J.; Hu, S.; Polizzotto, M.L.; Zhao, F.; McGrath, S.P.; Li, H.; Ran, W.; Shen, Q. Mineral Availability as a Key Regulator of Soil Carbon Storage. *Environ. Sci. Technol.* **2017**, *51*, 4960–4969. [CrossRef]
18. Musafiri, C.M.; Macharia, J.M.; Ng'Etich, O.K.; Kiboi, M.N.; Okeyo, J.; Shisanya, C.A.; Okwuosa, E.A.; Mugendi, D.N.; Ngetich, F.K. Farming systems' typologies analysis to inform agricultural greenhouse gas emissions potential from smallholder rain-fed farms in Kenya. *Sci. Afr.* **2020**, *8*, e00458. [CrossRef]
19. Otieno, E.; Kiboi, M.; Gian, N.; Muriuki, A.; Musafiri, C.; Ngetich, F. Uptake of integrated soil fertility management technologies in heterogeneous smallholder farms in sub-humid tropics. *Environ. Challenges* **2021**, *5*, 100394. [CrossRef]
20. Wang, Q.; Huang, Q.; Zhang, L.; Zhang, J.; Shen, Q.; Ran, W. The effects of compost in a rice–wheat cropping system on aggregate size, carbon and nitrogen content of the size–density fraction and chemical composition of soil organic matter, as shown by 13C CP NMR spectroscopy. *Soil Use Manag.* **2012**, *28*, 337–346. [CrossRef]
21. Panettieri, M.; Berns, A.; Knicker, H.; Murillo, J.; Madejón, E. Evaluation of seasonal variability of soil biogeochemical properties in aggregate-size fractioned soil under different tillages. *Soil Tillage Res.* **2015**, *151*, 39–49. [CrossRef]
22. Bhattacharyya, R.; Prakash, V.; Kundu, S.; Srivastva, A.K.; Gupta, H.S.; Mitra, S. Long term effects of fertilization on carbon and nitrogen sequestration and aggregate associated carbon and nitrogen in the Indian sub-Himalayas. *Nutr. Cycl. Agroecosystems* **2009**, *86*, 1–16. [CrossRef]
23. He, Y.; He, X.; Xu, M.; Zhang, W.; Yang, X.; Huang, S. Long-term fertilization increases soil organic carbon and alters its chemical composition in three wheat-maize cropping sites across central and south China. *Soil Tillage Res.* **2018**, *177*, 79–87. [CrossRef]
24. Blanco-Moure, N.; Gracia, R.; Bielsa, A.C.; López, M.V. Soil organic matter fractions as affected by tillage and soil texture under semiarid Mediterranean conditions. *Soil. Tillage. Res.* **2016**, *155*, 381–389. [CrossRef]
25. Prietzel, J.; Müller, S.; Kögel-Knabner, I.; Thieme, J.; Jaye, C.; Fischer, D. Comparison of soil organic carbon speciation using C NEXAFS and CPMAS 13C NMR spectroscopy. *Sci. Total. Environ.* **2018**, *628*, 906–918. [CrossRef] [PubMed]

26. Pisani, O.; Hills, K.M.; Courtier-Murias, D.; Haddix, M.L.; Paul, E.A.; Conant, R.T.; Simpson, A.J.; Arhonditsis, G.B.; Simpson, M.J. Accumulation of aliphatic compounds in soil with increasing mean annual temperature. *Org. Geochem.* **2014**, *76*, 118–127. [CrossRef]
27. Kiboi, M.; Ngetich, K.; Mugendi, D.; Muriuki, A.; Adamtey, N.; Fliessbach, A. Microbial biomass and acid phosphomonoesterase activity in soils of the Central Highlands of Kenya. *Geoderma Reg.* **2018**, *15*, e00193. [CrossRef]
28. Jaetzold, R.; Schmidt, H.; Hornte, Z.B.; Shisanya, C.A. Farm Management Handbook of Kenya. In *Natural Conditions and Farm Information*, 2nd ed.; Vol.11/C. Eastern Province; Ministry of Agriculture/GTZ: Nairobi, Kenya, 2007.
29. Kiboi, M.; Ngetich, K.; Fliessbach, A.; Muriuki, A.; Mugendi, D. Soil fertility inputs and tillage influence on maize crop performance and soil water content in the Central Highlands of Kenya. *Agric. Water Manag.* **2019**, *217*, 316–331. [CrossRef]
30. Ryan, J.G.; Estefan, G.; Rashid, A. *Soil-Plant-Analysis Soil and Plant Analysis Laboratory Manual*, 2nd ed.; International Center for Agricultural Research in the Dry Lands (ICARDA): Beirut, Lebanon; National Agricultural Research Center (NARC): Islamabad, Pakistan, 2001; pp. 46–48.
31. Mucheru-Muna, M.; Mugendi, D.; Kung'U, J.; Mugwe, J.; Bationo, A. Effects of organic and mineral fertilizer inputs on maize yield and soil chemical properties in a maize cropping system in Meru South District, Kenya. *Agrofor. Syst.* **2007**, *69*, 189–197. [CrossRef]
32. Fertiliser Use Recommendation Project (FURP). *Fertiliser Use Recommendation Project (FURP) Description of First Priority Trial Site in the Various Districts Final Report*; National Agricultural Research Laboratories: Nairobi, Kenya, 1987; Volume 24.
33. Knicker, H. Solid state CPMAS 13C and 15N NMR spectroscopy in organic geochemistry and how spin dynamics can either aggravate or improve spectra interpretation. *Org. Geochem.* **2011**, *42*, 867–890. [CrossRef]
34. Arb, C.; von Bünemanna, E.; Schmalz, H.; Portmann, M.; Adamtey, N.; Musyoka, M.; Frossard, E.; Fliessbach, A. Soil quality and phosphorus status after nine years of organic and conventional farming at two input levels in the Central Highlands of Kenya. *Geoderma* **2020**, *362*, e114112. [CrossRef]
35. Nyawade, S.O.; Karanja, N.N.; Gachene, C.K.; Gitari, H.I.; Schulte-Geldermann, E.; Parker, M.L. Short-term dynamics of soil organic matter fractions and microbial activity in smallholder potato-legume intercropping systems. *Appl. Soil Ecol.* **2019**, *142*, 123–135. [CrossRef]
36. Margenot, A.J.; Paul, B.K.; Sommer, R.R.; Pulleman, M.M.; Parikh, S.J.; Jackson, L.E.; Fonte, S.J. Can conservation agriculture improve phosphorus (P) availability in weathered soils? Effects of tillage and residue management on soil P status after 9 years in a Kenyan Oxisol. *Soil Tillage Res.* **2017**, *166*, 157–166. [CrossRef]
37. Bharali, A.; Baruah, K.K.; Bhattacharyya, P.; Gorh, D. Integrated nutrient management in wheat grown in a northeast India soil: Impacts on soil organic carbon fractions in relation to grain yield. *Soil Tillage Res.* **2017**, *168*, 81–91. [CrossRef]
38. Shryock, B.; Littke, K.; Ciol, M.; Briggs, D.; Harrison, R. Effects of urea fertilization on carbon sequestration in Douglas fir plantations of the coastal Pacific Northwest. *For. Ecol. Manag.* **2014**, *318*, 341–348. [CrossRef]
39. Guo, L.; Wu, G.; Li, Y.; Li, C.; Liu, W.; Meng, J.; Liu, H.; Yu, X.; Jiang, G. Effects of cattle manure compost combined with chemical fertilizer on topsoil organic matter, bulk density and earthworm activity in a wheat–maize rotation system in Eastern China. *Soil Tillage Res.* **2015**, *156*, 140–147. [CrossRef]
40. Adekiya, A.O. Green manures and poultry feather effects on soil characteristics, growth, yield, and mineral contents of tomato. *Sci. Hortic.* **2019**, *257*, 108721. [CrossRef]
41. Autret, B.; Mary, B.; Chenu, C.; Balabane, M.; Girardin, C.; Bertrand, M.; Grandeau, G.; Beaudoin, N. Alternative arable cropping systems: A key to increase soil organic carbon storage? Results from a 16 year field experiment. *Agric. Ecosyst. Environ.* **2016**, *232*, 150–164. [CrossRef]
42. Dimassi, B.; Mary, B.; Wylleman, R.; Labreuche, J.; Couture, D.; Piraux, F.; Cohan, J.-P. Long-term effect of contrasted tillage and crop management on soil carbon dynamics during 41 years. *Agric. Ecosyst. Environ.* **2014**, *188*, 134–146. [CrossRef]
43. Cheesman, S.; Thierfelder, C.; Eash, N.S.; Kassie, G.T.; Frossard, E. Soil carbon stocks in conservation agriculture systems of Southern Africa. *Soil Tillage Res.* **2016**, *156*, 99–109. [CrossRef]
44. Palm, C.; Blanco-Canqui, H.; DeClerck, F.; Gatere, L.; Grace, P. Conservation agriculture and ecosystem services: An overview. *Agric. Ecosyst. Environ.* **2014**, *187*, 87–105. [CrossRef]
45. Assunção, S.A.; Pereira, M.G.; Rosset, J.S.; Berbara, R.L.L.; García, A.C. Carbon input and the structural quality of soil organic matter as a function of agricultural management in a tropical climate region of Brazil. *Sci. Total. Environ.* **2019**, *658*, 901–911. [CrossRef]
46. Ferreira, C.D.R.; Neto, E.C.D.S.; Pereira, M.G.; Guedes, J.D.N.; Rosset, J.S.; dos Anjos, L.H.C. Dynamics of soil aggregation and organic carbon fractions over 23 years of no-till management. *Soil Tillage Res.* **2020**, *198*, 104533. [CrossRef]
47. Schweizer, S.; Bucka, F.; Markus Graf-Rosenfellner, M.; Kögel-Knabner, I. Soil microaggregate size composition and organic matter distribution as affected by clay content. *Geoderma* **2019**, *355*, e113901. [CrossRef]
48. Wang, H.; Nie, Y.; Butterly, C.R.; Lei Wang, L.; Chen, Q.; Tian, W.; Song, B.; Xi, Y.; Wang, Y. Fertilization alters mi-crobial community composition and functional patterns by changing the chemical nature of soil organic carbon: A field study in a Halosol. *Geoderma* **2017**, *292*, 17–24. [CrossRef]
49. Kolattukudy, P.; Walton, T. The biochemistry of plant cuticular lipids. In *Progress in the Chemistry of Fats and Other Lipids*; Holman, R.T., Ed.; Pergamon Press: Oxford, UK, 1972; Volume 13, pp. 121–167.

50. Heredia, A. Biophysical and biochemical characteristics of cutin, a plant barrier biopolymer. *Biochim. Biophys. Acta Gen. Subj.* **2002**, *1620*, 1–7. [CrossRef]
51. Mikutta, R.; Kleber, M.; Torn, M.S.; Jahn, R. Stabilization of soil organic matter: Association with minerals or chemical recalcitrance? *Biogeochemistry* **2006**, *77*, 25–56. [CrossRef]
52. Schöning, I.; Morgenroth, G.; Kögel-Knabner, I. O/N-alkyl and alkyl C are stabilised in fine particle size fractions of forest soils. *Biogeochemistry* **2005**, *73*, 475–497. [CrossRef]
53. Piccolo, A.; Spaccini, R.; Cozzolino, V.; Nuzzo, A.; Drosos, M.; Zavattaro, L.; Grignani, G.; Puglisi, E.; Trevisan, M. Effective carbon sequestration in Italian agricultural soils by in situ polymerization of soil organic matter under biomimetic photo-catalysis. *Land Degrad. Develop.* **2018**, *29*, 485–494. [CrossRef]
54. Gerke, J. Carbon Accumulation in Arable Soils: Mechanisms and the Effect of Cultivation Practices and Organic Fertilizers. *Agronomy* **2021**, *11*, 1079. [CrossRef]
55. Cotrufo, M.; Wallenstein, M.; Boot, C.; Denef, K.; Paul, E. The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: Do labile plant inputs form stable soil organic matter? *Glob. Change Biol.* **2013**, *19*, 988–995. [CrossRef]
56. Zhang, J.C.; Zhang, L.; Wang, P.; Huang, Q.W.; Yu, G.; Li, D.C.; Shen, Q.R.; Ran, W. The role of non-crystalline Fe in the increase of SOC after long-term organic manure application to the red soil of southern China. *Eur. J. Soil Sci.* **2013**, *64*, 797–804. [CrossRef]
57. Wang, X.; Toner, B.M.; Yoo, K. Mineral vs. organic matter supply as a limiting factor for the formation of mineral-associated organic matter in forest and agricultural soils. *Sci. Total. Environ.* **2019**, *692*, 344–353. [CrossRef]
58. Ussiri, D.; Johnson, C. Characterization of organic matter in a northern hardwood forest soil by 13C NMR spectroscopy and chemical methods. *Geoderma* **2003**, *111*, 123–149. [CrossRef]
59. Zhao, N.; Lu, Y.Z. Effects of different fertilization treatments on soil humic acid structure characteristics. *Spectrosc. Spectr. Anal.* **2012**, *32*, 1856–1859.
60. Li, Z.; Zhao, B.; Wang, Q.; Cao, X.; Zhang, J. Differences in Chemical Composition of Soil Organic Carbon Resulting From Long-Term Fertilization Strategies. *PLoS ONE* **2015**, *10*, e0124359. [CrossRef] [PubMed]
61. Cusack, D.F.; Torn, M.S.; McDOWELL, W.H.; Silver, W.L. The response of heterotrophic activity and carbon cycling to nitrogen additions and warming in two tropical soils. *Glob. Chang. Biol.* **2010**, *16*, 2555–2572. [CrossRef]
62. Chen, L.; Li, F.; Li, W.; Ning, Q.; Li, J.; Zhang, J.; Ma, D.; Zhang, C. Organic amendment mitigates the negative impacts of mineral fertilization on bacterial communities in Shajiang black soil. *Appl. Soil Ecol.* **2019**, *150*, 103457. [CrossRef]
63. Zhang, J.; Cao, Z.; Feng, G.; Li, M.; Li, C.; Gao, Q.; Wang, L. Effects of Integrated Soil-Crop System Management on Soil Organic Carbon Characteristics in a Primosol in Northeast China. *Pedosphere* **2017**, *27*, 957–967. [CrossRef]
64. Mi, W.; Wu, L.; Brookes, P.C.; Liu, Y.; Zhang, X.; Yang, X. Changes in soil organic carbon fractions under integrated management systems in a low-productivity paddy soil given different organic amendments and chemical fertilizers. *Soil Tillage Res.* **2016**, *163*, 64–70. [CrossRef]
65. Djurdjević, L.; Dinić, A.; Mitrović, M.; Pavlović, P.; Tešević, V. Phenolic acids distribution in a peat of the relict community with Serbian spruce in the Tara Mt. Forest reserve (Serbia). *Eur. J. Soil Biol.* **2003**, *39*, 97–103. [CrossRef]
66. Chavez-Vergara, B.; Merino, A.; Vázquez-Marrufo, G.; García-Oliva, F. Organic matter dynamics and microbial activity during decomposition of forest floor under two native neo-tropical oak species in a temperate deciduous forest in Mexico. *Geoderma* **2014**, *235*, 133–145. [CrossRef]
67. Schoebitz, M.; Vidal, G. Microbial consortium and pig slurry to improve chemical properties of degraded soil and nutrient plant uptake. *J. Soil Sci. Plant Nutri.* **2016**, *16*, 226–236. [CrossRef]
68. Zhang, X.; Xin, X.; Zhu, A.; Zhang, J.; Yang, W. Effects of tillage and residue managements on organic C accumula-tion and soil aggregation in a sandy loam soil of the North China Plain. *Catena* **2017**, *156*, 176–183. [CrossRef]
69. Shen, D.; Ye, C.; Hu, Z.; Chen, X.; Guo, H.; Li, J.; Du, G.; Adl, S.; Liu, M. Increased chemical stability but decreased physical protection of soil organic carbon in response to nutrient amendment in a Tibetan alpine meadow. *Soil Biol. Biochem.* **2018**, *126*, 11–21. [CrossRef]
70. Zhao, B.; Chen, J.; Zhang, J.; Xin, X.; Hao, X. How different long-term fertilization strategies influence crop yield and soil properties in a maize field in the North China Plain. *J. Plant Nutr. Soil Sci.* **2013**, *176*, 99–109. [CrossRef]
71. Chang, J.; Zhu, J.; Xu, L.; Su, H.; Gao, Y.; Cai, X.; Peng, T.; Wen, X.; Zhang, J.; He, N. Rational land-use types in the karst regions of China: Insights from soil organic matter composition and stability. *Catena* **2018**, *160*, 345–353. [CrossRef]
72. de Blas, E.; Rodríguez-Alleres, M.; Almendros, G. Speciation of lipid and humic fractions in soils under pine and eucalyptus forest in northwest Spain and its effect on water repellency. *Geoderma* **2010**, *155*, 242–248. [CrossRef]
73. Sarker, T.C.; Incerti, G.; Spaccini, R.; Piccolo, A.; Mazzoleni, S.; Bonanomi, G. Linking organic matter chemistry with soil aggregate stability: Insight from 13C NMR spectroscopy. *Soil Biol. Biochem.* **2018**, *117*, 175–184. [CrossRef]
74. Liu, M.; Hu, F.; Chen, X. A review on mechanisms of soil organic carbon stabilization. *Acta Ecol. Sin.* **2007**, *27*, 2642–2650.