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DYNAMICS OF SOIL ORGANIC CARBON AND MICROBIAL ACTIVITIES UNDER DIFFERENT LAND-USE AND AGRO-ECOLOGICAL ZONES OF GHANA

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DECLARATION

I hereby declare that the thesis herein presented for the award of Doctor of Philosophy Degree in Soil Science is as a result of my investigation. All references to other authors' work as sources of information are duly acknowledged.

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DEDICATION

This work is dedicated to the glory of GOD and to my mother CATHERINE M. APEDOE for believing in me.

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My heartfelt gratitude goes first to God, for His divine provision and sustenance throughout my studies, especially during the outbreak of the COVID-19 pandemic.

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ABSTRACT

Soil organic carbon (SOC) plays major roles in maintaining soil productivity, especially in tropical agriculture, where the application of external inputs is low. The SOC stock is affected by a host of factors such as land-use, soil type, organic resource addition and the dynamics of SOC under varying climate conditions. It is the aim of the study to assess the impact of land-use type: namely, forest or uncultivated lands (UC), cultivated lands (CT), and woodlot (WL) under different agro-ecological zones on the dynamics of SOC and microbial activities in some Ghanaian soils. The assessment of the SOC composition involved the determination of a range of chemical SOC fractions including (i) hot water extractable C (HWEOC), (ii) potassium permanganate extractable organic C (POX-C), (iii) acid hydrolysable (HCl-C) and (iv) non-acid hydrolysable (non-HCl-C). Biological fractionation included microbial biomass C (MBC_{mic}) and N (MBN_{mic}). Other SOC dynamics were characterized by the basal respiration (BR), metabolic quotient (qCO_2), microbial quotient (qMIC), mineralization quotient (qM) and carbon mineralized (C_{min}) in a 365-day incubation study. The cumulative C mineralized during the incubation study was fitted to the first order double exponential models that separate C pools into potential mineralizable C (C_0), labile pool (C_1) and recalcitrant pool (C_2) with their respective turn-over rates (k, k_1 and k_2) and half-lives ($t_{1/2}$). The kinetic parameters from the first order equation were correlated with the chemical and biological fractions of C, and the microbial indices correlated with the organic C fractions. The results showed that land-use systems affected the various C pools, with the forest or uncultivated system recording the highest total C (TC) stocks, HWEOC, POX-C, MBC_{mic}, MBN_{mic} and C mineralization. Regarding agro-ecological zones, the savannah zones (Interior, Coastal) recorded lower values of total C, and MBC_{mic}, but higher C values in HWEOC, POX-C, and HCl-C. The MBC_{mic} and MBN_{mic} values followed the order uncultivated >

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woodlot > cultivated across the land-uses systems. With respect to agro-ecological zones, the highest MBC_{mic} and MBN_{mic} were recorded for the Forest-savannah transition zone followed by the Semi-deciduous forest zone. The MBC_{mic} was positively and significantly correlated with the POX-C (r = 0.245*), TC (r = 0.475***), BR (r = 0.541***) and qMIC (r = 0.715***), but negatively significantly correlated with qCO_2 (r = 0.715***). Curve fitted to the incubation data showed that the cultivated land-use of the Interior savannah zone recorded the lowest C_0 values, whereas the Semi-deciduous zone recorded the highest C_0. Most of the C were estimated to be in the C_s (recalcitrant pool) with high half-life. The C_0 was positively correlated with POX-C (r = 0.743****), HWEOC (r = 0.540****), HCl-C (r = 0.663***), non-HCl-C (r = 0.614***), C_{min} (r = 0.984***). The CMI recorded the highest value in UC and WL soils. It was concluded that the conversion of UC lands to CT resulted in a rapid decline in C stored in soils, shifting the hitherto conserved C to labile and recalcitrant forms. Labile fractions of SOC showed a rapid response to land-use changes and can thus be used as a sensitive indicator of SOC dynamics.

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CHAPTER ONE

1 INTRODUCTION

1.1 Background

The conversion of native vegetation to agricultural fields generally leads to a decline in soil organic carbon (SOC) content and land degradation. These land use changes can induce the formation of SOC pools with different and heterogeneously distributed organo-mineral complexes within different-sized primary particles or aggregate fractions (Christensen, 1992; Christensen, 2001). These particle-size or aggregate fraction associated SOC pools and stocks differ in structural and biochemical compositions, stabilities, and turnover rates, and therefore, respond differently to anthropologically induced changes in environmental stresses, such as intensive cultivation.

Conceptually, SOC pools are a continuum of organic materials in all stages of decomposition, transformation, and stabilization. For simplicity, the continuum of materials is classified into three main forms, or pools, namely, the labile or active, the intermediate or slow and passive/inert or recalcitrant pools. The active pool is very reactive, with a rapid turnover rate of days to weeks, and serves as a habitat and substrate for soil microorganisms, powers the food chain and nutrient cycling, maintains soil productivity and is easily oxidized to the atmosphere as carbon dioxide. The slow or intermediate pool has a turnover rate of a year to decades, reacts with soil colloids, slowly mineralized by soil microbes, and replenishes the labile pool. The recalcitrant or passive pool is inert and unreactive, forms complexes (strong reaction) with soil colloids, very slowly used by microbes, with a turnover rate of centuries-millennia, and contributes to the enhancement of the SOC stock and sustainability of the production system (Dai et al.,

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2017; Liu et al., 2017; Wang et al., 2012). Though useful for describing C dynamics in soils, these conceptual pools are not measurable (Elliot et al., 1996; von Lützow et al., 2007). The measurable components of organic matter (OM) are the physical, chemical, and biochemical fractions. It is therefore desirable to correlate SOC pools with the measurable fractions to enhance the overall understanding of the dynamics of SOC in soils.

A large portion of the soil C form either binding agents in soil aggregate fractions or are protected within the aggregates. Since soil aggregates, categorized into macroaggregates (soil particles > 250 µm) and microaggregates (soil particles < 250 µm) (He et al., 2021) are not of the same size, the nature of SOC held in them differ. Macroaggregates are bonded by plant input products i.e., plant roots, fungal hyphae, polysaccharides of microbial and plant origin (He et al., 2021; Mirzaei Aminiyan et al., 2015), and provide little physical protection for C, with the C being easily affected by land-use changes e.g., cultivation, and hence less stable (Wiesmeier et al., 2019). Microaggregates are formed by organo-mineral interactions and occlusion of debris by clay particles, and are less susceptible to change, stabilizing SOC over decades to centuries (Schweizer et al., 2019).

The medium light fractions (intermediate or slow pool) consist of decomposition products with slower turnover rates, while the heavy fractions (recalcitrant pool) are mineral associated OM with lower turnover rates. These fractions of SOC are normally obtained by oxidation with different oxidants of varying degree of strength.

The degree of oxidizability of the light (or labile) OM fractions has been proposed as a carbon management index (CMI) to evaluate the impact of land management on SOC stock (Blair et al., 1995).

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The turnover of SOM and other nutrients are mediated by soil microbial biomass through enzyme activity, which respond to substrate availability within soil aggregate separates. Quantitative information on the microbially-mediated SOM turnover rates or dynamics can be derived from modelling of in-vitro decomposition rates of the SOC. Such information is useful for understanding the processes influencing C mineralization and stability in soils. A variety of models have been used to determine the mineralization rates and kinetic parameters of C mineralization in soils (Alvarez & Alvarez, 2000). The most common used model is the double-exponential first-order equations, which partitions SOC into the labile and recalcitrant pools with different degrees of heterogeneities and stability (Alvarez & Alvarez, 2000; Dodor et al., 2019).

1.2 Problem Statement

The influence of anthropologic and environmental factors on C dynamics has been reported in the literature. In tropical regions for example, land-use and management practices induce changes in C stock in agricultural soils, contributing about 20% of global CO_2 emission (Lal, 2004a). Conversion of natural ecosystem (native vegetation or uncultivated fallow) to agricultural land and intensive cultivation through tillage breaks down soil macroaggregates into smaller units exposing the hitherto protected OC to physical degradation and microbial attack. These anthropogenically induced land-use changes increases C mineralization and loss to the atmosphere as CO_2, as well as soil erosion (Lagomarsino et al., 2011; Sitaula et al., 2004).

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1.3 Justification

Land-use and management practices which offer the least disturbance of soil such as agro-forestry and forest, tend to increase SOC accumulation, which enhances the physical and chemical stability of SOC, due to biochemical reactions, restricting availability and access of microbes to SOC, as well as the diffusion of water, enzymes and oxygen (Guo et al., 2016; Murphy et al., 2011). Apart, Saiz et al. (2015) and Wynn et al. (2017) showed that the type of C and input source (i.e., C3 or C4) affected the magnitude of the decomposition rate of SOM. In other studies, the total soil carbon has been shown to correlate with TC input.

It is also known that SOM decomposition is influenced by environmental conditions such as the soil temperature (Conant et al., 2011; Six et al., 2002) and humidity or wetness (Ramesh et al., 2019; Ramesh et al., 2018). The rapid SOM decline reported in tropical regions are largely attributed to the high temperatures, because the rate of reaction doubles for every 10 ºC rise in temperature. In Ghana for example, average temperatures range from 27 ºC in the southern high rainfall zones to 33 ºC in the northern interior savannah zones, furthermore, high soil moisture conditions provide optimum conditions for microbial activity. Rainfall regimes range from 1100 mm in the northern savannah zones to more than 1500 mm in the semi-deciduous forest zones in the south. The south-west forest zones recorded more than 2000 mm. Therefore, not only land-use change but also the agro-ecological zones with varying climate (temperature, moisture regimes) would impact the SOC dynamics. The interactive effect of land-use changes and agro-ecological zone on SOC dynamics has hitherto not received sufficient study, especially in tropical regions, including Ghana, though the overall SOM management would require a good understanding of this phenomenon. Specific research questions include the following:

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(i) How does land-use type (forest, cultivated) affect the SOC pool size and decomposition rate constant, given that these parameters are determined by C input amount and quality?

(ii) Will change in land use type under the various agro-ecological zones impact SOC pools, their sizes and decomposition rates?

(iii) Is there a relationship between SOC fraction and the kinetic parameter of SOC?

Traditionally, answers to these questions will require the measurement of the SOC under a combination of these land-use and environmental conditions. In addition, indices such as the CMI can be used to indicate how management and land-use influence the lability, stability, and the amount of C, with soils having higher values considered as better managed (Zhang et al., 2020; Zhao et al., 2014).

For a better understanding of the dynamics of SOC in soils, however, a modelling approach would depict how the interactions between land-use types of different agro-ecological zones affect the SOC dynamic parameters, such as the total and different pool sizes, and their rate of decomposition.

A variety of models have been used to determine the mineralization rates and kinetic parameters of C mineralization in soils (Alvarez & Alvarez, 2000). The most commonly used model is the double-exponential first-order equations, which partitions SOC into the labile and recalcitrant pools with different degrees of heterogeneities and stability (Alvarez & Alvarez, 2000; Dodor et al., 2019) and is given by:

$$C_m = C_1\left(1 - e^{-k_1 t_1}\right) + C_2\left(1 - e^{-k_2 t_2}\right) \qquad [1.1]$$

where, C_m is the amount of C mineralized in time t (day), C_1 is the size of the labile mineralizable C pool, and C_2 is size of the stable C pool, and k_1 and k_2 are the corresponding mineralization rate constants (day^{-1}) for each C pool. Two main parameters of interest in equation (1.1) are: (i) the sizes of the SOC pools (C_1 and C_2) and (ii) the decomposition

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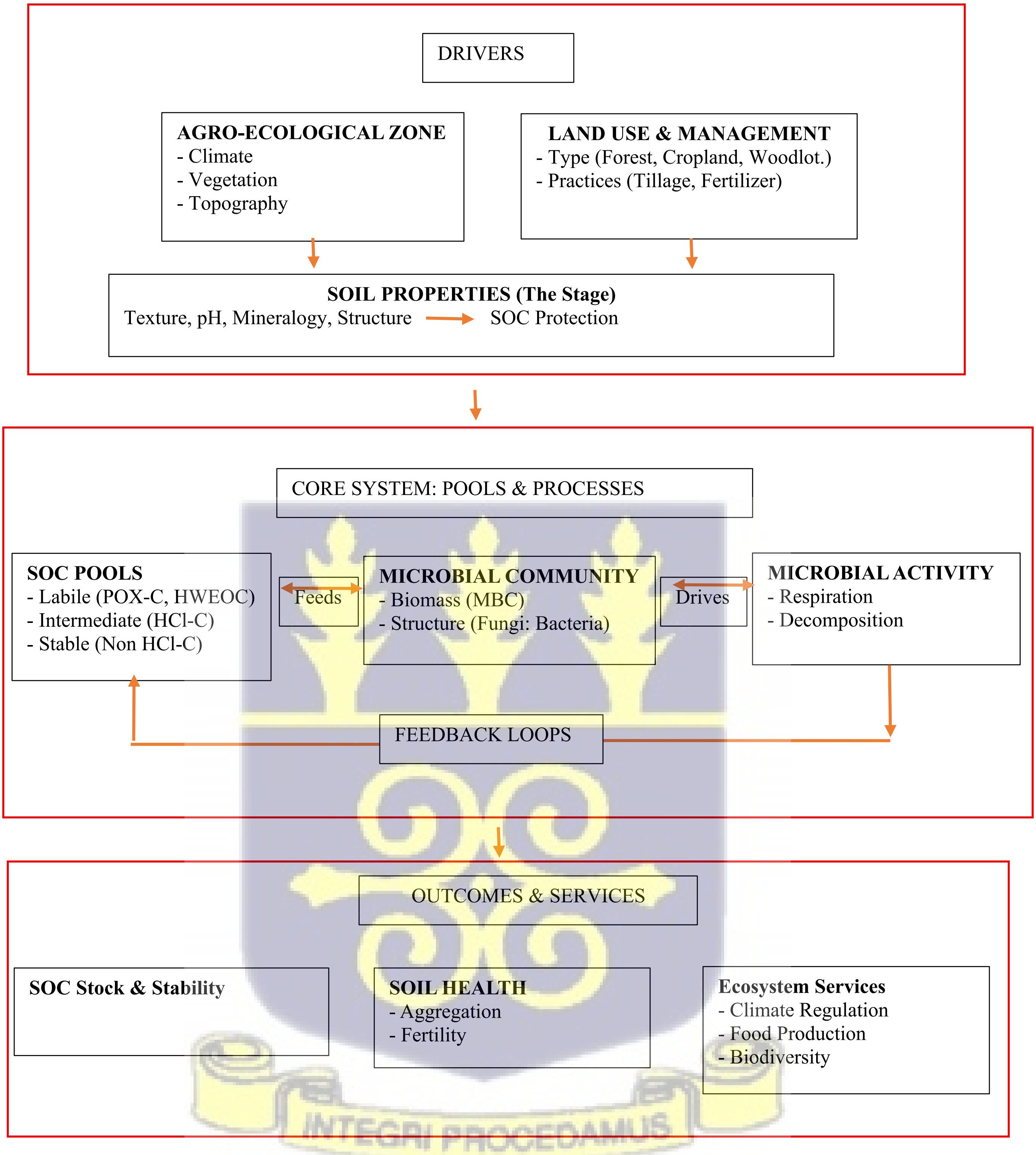
rates, as indicated by the rate constants (k_1 and k_2). These two parameters are captured in the first or second order models used to describe SOC dynamics, and it is of research interest to investigate further how management and land use factors affect these parameters.

The modelling approach enables the further understanding and prediction of the SOM content and SOC stock as a function of land-use and of cropping and forestry practices in different climate and pedogenic context. An understanding of the roles of ecological zones, land management and SOC input is still somewhat unclear, though these are essential for the assessment and management of SOC for sustained soil productivity. To date, studies that seek a modelling approach are lacking in many tropical land-use systems in Ghana.

1.4 Conceptual framework



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1.5 Hypotheses

1. The differing agro-ecological zones and Land-use type affects the chemical and biological fractions of SOC
2. Agro-ecological zones and land-use type impact the microbial activities during the mineralization of SOC
3. Land-use type and ecological zones influence the SOC pools, size and decomposition rates
4. Land-use change affects the lability, stability and amount of SOC
5. A correlation exists between the chemical, and microbiological fractions and kinetic parameters of SOC

H_{01}*: Agro-ecological zone and land use type will have no significant effect on the chemical and biological fractions of SOC*

H_{A1}*: Agro-ecological zone and land use type will significantly affect the chemical and biological fractions of SOC.*

H_{02}*: Agro-ecological zone and land use type will have no significant effect on microbial activities during SOC mineralization.*

H_{A2}*: Agro-ecological zone and land use type will significantly affect microbial activities during SOC mineralization.*

H_{03}*: Land use type under the various agro-ecological zones will have no significant effect on SOC pools, their sizes and decomposition rates.*

H_{A3}*: Land use type under the various agro-ecological zones will significantly affect SOC pools, their sizes and decomposition rates.*

H_{04}*: Land use change will have no significant effect on the lability, stability, and the amount of SOC pools.*

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H_{A4}: Land use change will significantly affect the lability, stability, and the amount of SOC pools.

H_{05}: There is correlation among the SOC fractions and kinetic parameters

H_{A5}: There is no correlation among the SOC fractions and kinetic parameters

1.6 Objectives of the study

It is the aim of this study to investigate the impact of land-use type under different agro-ecological zones on the dynamics of SOC and microbial activities in some Ghanaian soils.

In particular, the study was designed to determine:

i. the SOC in soils derived from varied agro-ecological zones of Ghana, and their various chemical and biological fractions
ii. determine by role of microbial activities during the mineralization of SOC in the soils from different agro-ecological zones, and land-use type
iii. the type of SOC pools and their sizes as well as the decomposition rates as influ enced by the land-use type and agro-ecological zone, and
iv. the land-use effect on the lability, stability and the amount of SOC using the concept of CMI.
v. the correlation between the SOC fractions and kinetic parameters

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CHAPTER TWO

2 LITERATURE REVIEW

2.1 Carbon in soils

Soil carbon exists in two forms, namely organic and inorganic carbon (Fig 2.1). The soil inorganic carbon (SIC) is made up of minerals formed either from the weathering of bedrock or the reaction of soil minerals with atmospheric carbon dioxides (CO_2) producing carbonated (CO_3^{-2}) and bicarbonate (HCO_3^-) compounds of Mg^{+2}, Ca^{+2}, K^+ and Na^+ (Johns, 2017; Lal, 2016). Soil inorganic carbon is dominant in the arid and semi-arid regions and salt-affected soils. It has no soil enhancing property such as water holding capacity, nor does it serve as a nutrient source for microorganisms. Hence, it is a more stable compound and a significant carbon pool worldwide.

Soil organic C (SOC), on the other hand, is the largest pool of terrestrial C globally, with about 1550 Gt C, about 3.3-4.5 times that held by the biotic and atmospheric pools (Lal, 2004a; Tian et al., 2015). The SOC forms about 45-60% of Soil Organic Matter, SOM (Lal, 2016), which has a high surface area and charge density, and which reacts with minerals and clay to form organo-mineral complexes with different turnover rates (Dungait et al., 2012). The SOC is derived from dead and decaying biomass of plants litter, roots, animals, dead and living microorganisms, producing a diverse mixture of C containing compounds. The physicochemical and biological properties of soil are influenced by SOM. Through the mineralization of SOC, plant nutrients become available, and soil physical parameters such as water retention and aggregate stability are enhanced. Soil organic matter mineralization also results in the emission of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) contributing to global warming and hence climate change.

The SOC usually exists in 2 forms: (i) protected form, with a long mean residence time (MRT) due to its physical, chemical, biological, and ecological protection mechanism, and (ii) the unprotected form, which is easily degraded hence has a short mean residence time.

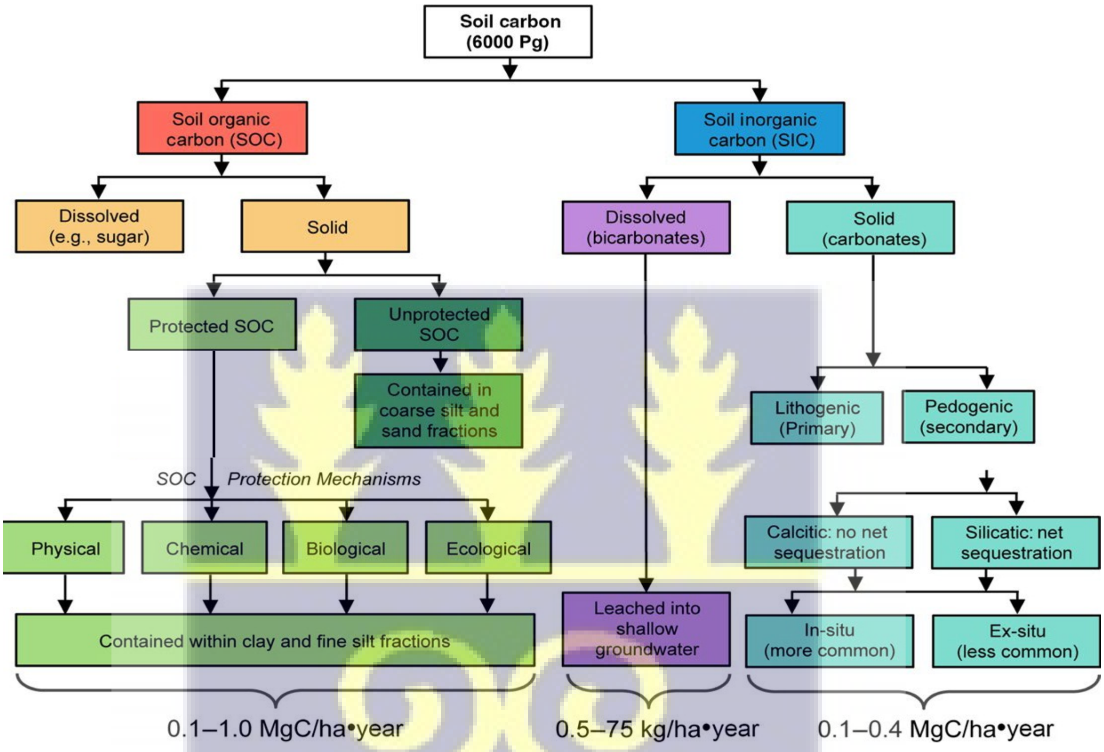

Fig 2.1:Types of organic and inorganic carbon pools in soil and a range of sequestration in diverse soils and ecoregions (adapted from Soil health and carbon management. Lal (2016))

2.2 Chemical composition of organic carbon

Soil organic C is composed of polysaccharides from plant residues, root exudates, soil animals and microorganisms. A detailed description of the constituents is presented below.

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2.2.1 *Plant sources of soil organic carbon*

2.2.1.1 Starch

Starch is plant polymer synthesized through photosynthesis, from glucose and stored in the plastids in gains forms of 1-100 nm in leaf of green plants and amyloplasts in roots, tubers, stems, fruits, and seeds, and serves as energy storage compounds for the maintenance of cells in plants. It also serves as a primary source of energy for non-photosynthetic organisms. It is made up of two glucose polymers (*alpha*-glucan), amylose and amylopectin. Amylose consists of a long chain of 1-4-glucose units (unbranched) and makes up about 30% or one-third of the total starch (Robyt, 2008). The number of glucose residues (degree of polymerization (DP)) varies with its botanical origin (Tester et al., 2004).

Amylopectin is a much larger molecule which is heavily branched and is made up of about 95% short α, 1-4 linked and 5% α, 1-6-glucose bonds. The amylopectin is insoluble in water while amylose is soluble in water making the starch insoluble in cold water and alcohol.

Starch is ready hydrolyzed by soil microorganisms such as bacteria, fungi and actinomycetes, converting it to glycogen which serves as a carbon and energy source. Starch is degraded by enzymes known as amylases. α-Amylase catalyzes the cleavage of glucosyl bonds (α, 1-4 glycosidic bonds) in the inner part of amylose and amylopectin chain to form dextrin, glucose, and maltose. The maltose residues from then nonreducing (second glucose-glucose bond) end of the starch molecule are then cleaved by β-Amylase. β-glycosidase then degrades the maltose, dextrin, and short-chained glucan to glucose (Horwarth, 2015).

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2.2.1.2 Hemicellulose

Hemicellulose is the second most abundant plant polysaccharide and accounts for about 20-35% of dry biomass (Zhou et al., 2016). Hemicellulose is made up of building blocks such as pentoses (arabinose and xylose), altering units of hexoses (mannose, glucose, and galactose), hexuronic acids, acetyl group, rhamnose and fucose (Brunner, 2014; Zhou et al., 2016). Hemicelluloses are made up of branched or linear polymers associated with each other and other cell wall constituents i.e., cellulose, through hydrogen and covalent bonding earning the name "cross-linking glycans" (Machmudah et al., 2017).

The main feature of this group is that they do not aggregate with themselves and do not form microfibrils, but rather acts as binding agents between cellulose, lignin, and fibrils, providing structural strength to the cell walls (Rugen et al., 2017). It also contributes to plant cell wall flexibility and water retention due to its hydrophilic nature. The structure and composition of hemicellulose vary depending on their botanical origin. Xylans are the main constituents in hemicellulose. They form about 20-30% of the secondary cell wall in both woody and herbaceous plant biomass in dicots and up to 50% in monocots i.e., some grasses and cereals (Horwarth, 2015). Hemicellulose is amorphous with little strength hence easily hydrolyzed.

2.2.1.3 Cellulose

Cellulose is the most abundant bio-synthesized polymers (plant polysaccharide) which consists of about 15-30% of the primary cell wall and a large part of the secondary cell wall in plants (woody species). Cellobiose, the basic building block of cellulose is made up of about 100 to 14000 glucopyranose molecules linked by β-1, 4- glycoside bonds to form D-glucan chains. These chain forms cross-linkages with each other via hydrogen

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bonding forming para-crystalline assemblages known as microfibrils. The microfibrils are held together by intra-molecular hydrogen bonds and inter-molecular van der Waal forces forming fibrils with highly ordered crystalline regions and more dis-organized amorphous regions making it resistant to degradation (Bai et al., 2019; Brigham, 2018; Kögel-Knabner & Amelung, 2014).

The decomposition of cellulose is brought about by the action of cellulases (collectively known as cellobiases), a group of enzymes consisting of endoglucanases which cleaves the β,1-4 linkages on both soluble and insoluble glucose chains to produce cello-oligosaccharides and glucose, exo-glucanase that act on the cellulose chain to produce cellobiose and cellotriose and β-glucosidase which hydrolyses the different glucose chains fragments produced to glucose. The cellulase enzymes cleave specific bonds found within the microfibril network, which disturb and depolymerizes the cellulose structure into short chain glucose (Horwarth, 2015).

2.2.1.4 Pectin

Pectin is a high molecular weight carbohydrate polymer (Flutto, 2003), present in middle lamellae of plant cells and contribute to the cell structure (Smith, 2003). Pectin has a linear structure consisting of galacturonic acid residues linked via α-1, 4-glycosidic bonds (Mudgil, 2017). They are found in young plant tissues and acts as a space-filling hydrophilic gel in the plant cell. Pectin is thought to influence cell wall porosity, pH and cell-to-cell adhesion (Ansell & Mwaikambo, 2009).

Pectinases (EC 3.2.1.15) are a group of enzymes that degrade pectin by depolymerization or de-esertification reaction. Three types of pectinases have been described in the degradation of pectin: (i) pectin methyl esterase (EC 3.1.1.11), which removes the methloxyl residue from pectin chain that affect the solubility and open it up to attack by

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other enzymes, (ii) poly-galaturonases (endo-, EC 3.2.1.15 and exo-, EC 3.2.1.67), which splits the glycosidic bonds between galacturonic molecules and (iii) protein trans-eliminase or pectic lyases (EC 4.2.2.10), which cleave α, 1-4 linkages, thus forming unsaturated derivatives of galacturonic acid (Ramos & Malcata, 2011).

2.2.1.5 Lignin

Lignin is one of the abundant biosynthesized polymers. In the secondary cell walls of plant, the rigidity and hydrophobic nature of some specialized cells is contributed by lignin and provide mechanical support and water transport (Hayes et al., 2017; Nair et al., 2017). Lignin constitutes about 15-40% of woody tissues in vascular plant and protects plant against the attacks of microorganisms. Lignin is a highly branched three-dimensional polymer composed of phenol units (*p*-coumaryl, coniferyl and sinapyl) with strong intramolecular bonding (Hayes et al., 2017; McDonald & Donaldson, 2001; Xu, 2010).

The nonspecific structure, dense nature and hydrophobicity of lignin make it very difficult to degrade or attack by microorganisms. Fungi are the main microorganisms that are efficient in lignin degradation and play an important role in the C cycle. Based on the decaying substrate produced by fungi, they are grouped into soft, white, and brown rot fungi. The cleavage of the C_α-C_β bonds phenylpropanoids produces carboxylic acid units (Zabel & Morrell, 2020a, 2020b).

2.2.1.6 Root's exudates

Root exudates (mucilage) are mainly secreted by plant root cells (Bending, 2017). They are also found in the seed coats of various plants such as flaxseed, certain seaweeds, and plantain seeds (Cui et al., 2011), and by some rhizosphere microbes (Bending, 2017).

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Mucilage is a thick glutinous substance, and forms gel when in contact with soil. It consists of protein, polysaccharides that contain pentose sugars, hexose and uronic acids linked by glycosidic bonds (Bending, 2017; Ciudad-Mulero et al., 2019). In soil, it forms "rhizosheath" or mucigel (Neumann & Römheld, 2012) by binding microbes together with organic and inorganic soil particles and roots. As the water potential in soil drops due to plant uptake, the mucigels shrink, which then leads to a tighter association of soil particles within the rhizosheaths and thus help maintain soil hydraulic conductivity in the rhizosphere. Mucilage protects the root meristem and improve aggregation in soil (Bending, 2003; Neumann & Römheld, 2012).

2.2.2 Animal sources of soil organic carbon

2.2.2.1 Chitin

Chitin is a major component of the skin (exoskeletons) of arthropods and the cell wall of fungi (He & Wu, 2016). It is a linear homopolymer that consists of N-acetyl-D-glucosamine units linked by β- 1,4 bonds (Niaounakis, 2015). Chitin is classified into three different crystalline forms: α-, β- and γ-chitin, due to the different microfibrils orientation. The partial N-deacetylation of chitin due to enzyme hydrolysis or the presence of strong acid leads to the production of chitosan. Due to the rigid and compact crystalline structure and strong intra- and inter-molecular hydrogen bonding, chitosan tends to be insoluble in alkaline solution and water (Luzi et al., 2019).

Chitin is degraded by a group of chitinolytic enzymes known as chitinases which consists of chitinase (EC 3.2.1.14) and N-acetyl-β-glucosaminidase (EC 3.2.1.30). These chitinolytic enzymes are mainly synthesized by fungi and some bacteria. Chitinase (EC 3.2.1.14) catalyzes depolymerization of the chitin chain to yield oligomers with many N-acetylglucosamine units, dimer and chitobiose through the hydrolysis of the β- 1, 4

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gycosidic bonds at the reducing end of the chain (exo-chitinase) or randomly along the chain (endo-chitinase). N-acetylglucosaminidase hydrolysis diacetylchitobiose to N-acetylglucosamine (Gooday, 1990a, 1990b).

2.2.2.2 Glycogen

Glycogen is a glucose polysaccharide with an α- 1, 4 linkage and 10% α- 1, 6 branch linkages found in most mammalian cells, insects, and microorganisms (Rocha Leão, 2003). It serves as an energy reserve in mammals where it is in the liver, skeletal muscles, and fat cells. In bacteria, glycogen is accumulated under growth limiting environmental conditions such as in the lag phase of the growth cycle where P, N and S are limited (Preiss, 2010). Glycogen is highly soluble in water and increased branching increases its solubility (Engelking, 2015).

2.2.3 Humic substances

Humic substances are natural occurring heterogenous organic substances (MacCarthy et al., 2015), that have undergone extensive transformations (Tranvik, 2014), and influence many physical and chemical processes in soil. Its formation is linked to the behaviour of microbes (Gautam et al., 2021). In the terrestrial ecosystem, humic substances are considered as a key component forming about 60% of SOM and about 50% of SOC (Kelleher & Simpson, 2006; Trevisan et al., 2010), and can be considered as the most important source of transient refractory organic carbon in the earth (Gautam et al., 2021). They are chemically complex (heterogeneous in structure and composition), interact with the mineral phase of the soil and cannot be degraded by microorganisms due to their recalcitrant nature. Humic substances are a mixture of smaller molecules, seated with aliphatic chains. aromatic rings and ionizable functional groups, interacting with each other to form aggregated colloids (Rose et al., 2014). The major functional groups

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in humic substances are carboxyl, alcohol, phenolic hydroxyl, and carbonyl. The gradual increase in negative charge as pH increase in humic substances is due to dissociation of protons of functional groups such as carboxylic groups in acidic medium (low pH) and the phenolic groups at high pH (alkaline medium), creating a double layer (Kinniburgh et al., 1998). In soil, they interact with oxides, metal ions hydroxides, mineral and organic compounds forming complex compounds that are both soluble and insoluble in water. In relation to the different solubility in acidic and alkaline pH, humic substances were classified operationally into humin and humic and fulvic acids (Trevisan et al., 2010).

2.2.3.1 Humic acids

Humic acid is a fraction of humic substances that is not soluble in water under acidic conditions ($pH < 2$) but is soluble at higher pH values (alkaline conditions) and considered the most abundant organic molecule (naturally occurring) on the earth. It is composed of C chains and about 35% C rings (Pettit, 2006), with many anionic oxygen groups i.e., carboxyl, phenolic hydroxyl, alcoholic hydroxyl, and aliphatic carboxyl, that interact with metal cations forming complexes through ionic bonding (Fageria et al., 2002). The higher elemental composition of extracted humic acid from forest lands compared to cultivated land (maize) (Allard, 2006) showed a high C/N ratio of the humic acid in the forest soil than the cultivated, indicating a higher microbial contribution and humification degree in the latter. There is an increasing degree of chemical maturity of humic acid transformation when grassland is converted to arable or fallow lands (Ch’ng et al., 2011).

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2.2.3.2 Fulvic acids

Fulvic acid is soluble in water under all pH (acid, neutral and alkaline) conditions. It has twice as much cation exchange capacity than humic acid and the most effective C containing chelating compound (Pettit, 2006). Fulvic acid is a highly oxidized, and biologically stable naturally occurring complexing agent, that can complex di- and tri-valent metal ions and hydroxylated metal compounds and that can interact with clay minerals (Schnitzer, 1969).

2.2.3.3 Humins

Humin is a fraction of humic substances that is not soluble in water at any pH value. It is highly resistant to degradation and is the humic substance with the highest molecular weight ranging from $1x10^5$ to $1x10^7$ Da. Humin has a high C content (more than 60%), with high fungal melanin and paraffinic substances, and is more strongly bonded to minerals compared to the humic and fulvic acids (Horwarth, 2015; Pettit, 2008).

2.3 Measurable organic carbon fractions in soils

The dynamics of SOC in soils are often described in terms of pool sizes because they can be assigned to turnover rates to predict SOC quantities at different times of C decomposition processes. Depending on the details of C dynamics in a model, different numbers of pools are defined. Some models such as NUTMON (Smaling & Fresco, 1993) recognize only two pools, namely the labile and non-labile pools. In other models, three pools are recognized, namely the active, slow, and passive pools (Gijsman et al., 2002) and others may recognize more than 3 pools. These pools are, however, not measurable. Hence, the SOC is often determined in the following terms.

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2.3.1 Total organic carbon

The fraction of carbon stored in organic matter or bound in organic compound is the total organic carbon (TOC) in soil. The TOC comprises endogenous decayed material such as glucose, cellulose, hemicellulose, etc., and the by-products of metabolic activities of living organisms such as microbes e.g., suberans and chitin, and exogenous sources such as organic manure, compost, organic dyes, and fertilizers (Bolan et al., 2011). Data by Oppong et al. (2017), showed that the TOC for forest soils in Ghana range from 20-50 g kg^{-1} compared with <10 g kg^{-1} for most cultivated soils.

Several works have been done on carbon content in Ghanaian soils over the years (Adu-Bredu et al., 2008; Dowuona et al., 1998; Dowuona et al., 2011; Quaye et al., 2021). A study by Bessah et al. (2016) on the organic C stocks of major land-use (savanna woodland, mango, cashew and teak plantation and crop lands) in the Kintampo North Municipality on 34 plots recorded stocks ranging between 4.95 and 21.18 t/ha, 3.42 and 16.07 t/ha, 1.38 and 12.74 t/ha and 9.80 and 49.63 t/ha for the depths 0–10 cm, 10–20 cm, 20–30 cm and 0–30 cm, respectively. They also observed the highest stock in the Savannah woodlot and attributed this to the undisturbed nature of the ecosystem at the time of the study.

Djagbletey et al. (2018), also studied C stock distribution in above ground and aggregate fractions in the Guinea savanna zone of Ghana, with stocks ranging from 4.80 to 12.62 Mg C ha^{-1} in soils from the Klupene, Sinsablegbinni, and Kenikeni forest reserves. They also observed the highest C stock in the silt and clay-sized fractions. A study on acidic soils by Bonsu et al. (2011), at Ainyinasi concluded that, the reserve with higher vegetative cover had the highest C stock and the variation in the monthly rainfall and temperature influences C stocks in grass. The low fertility of acidic soils

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limits sequestration of C in soils. Secondly, the conversion of tropical forests into rubber plantations, limits the soil ability to sequester C due to poor litter fall and difficulty in the decomposition of leaves. Lastly, the regeneration of a cut tropical forest into a secondary forest leads to a decrease in the C density.

Adu-Bredu et al. (2008), in a study on C stock under four land-use systems (natural forest, teak plantation, fallow and cultivated lands in 3 agro-ecological zones namely moist evergreen forest, dry semi-deciduous forest and savanna zones observed varying trends of C stocks under the different land-use systems in each ecological zone with the least stock in the cultivated lands of the moist evergreen (86.95, 72.30, 93.47 and 87.21 Mg C ha-1) and dry semi-deciduous forest zones (56.72, 28.37, 30.88 and 47.57 Mg C ha-1) but teak plantation in the savanna zone (34.05, 32.02, 32.14 and 23.64 Mg C ha-1 for the fallow, cultivated, natural forest and teak stand, respectively).

2.3.2 Particulate organic carbon

Particulate organic carbon (POC) comprises primarily of plant debris, but also fungal hyphae, spores, fauna skeleton, a portion of the soil microbial biomass and humified materials (Haynes, 2005). It has a particle size range from 53µm-2mm, forms about 2-25% of the total organic C in soils and a turnover rate of about 2-50 years. It plays major roles in soil aggregation where macroaggregates are formed around particles of decaying plant debris which contain cores of POC and production of water extractable organic carbon and serves as an energy source for soil microbial biomass (Awale et al., 2017; Gregorich et al., 2006).

2.3.3 Dissolved organic carbon

The total organic carbon from root exudates, plant litter, microbial biomass, or humus, in soil solution that passes through a 0.45 mm filter is classified as dissolved organic

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carbon (DOC). It is mainly the carbon found in soil solution and the most mobile and actively cycling organic matter fraction and influences many biogeochemical processes. It also acts as a carbon source for anaerobic organisms in the soil (Bolan et al., 2011). As a major controlling factor in soil formation, DOC is very active in many chemical and biological processes in soils. High concentration of DOC is promoted by conditions which enhance high mineralization such as high microbial activity (Laik et al., 2009). In cultivated and pastoral soils, the major source of DOC is plant residues, accounting for about 0.05 - 0.4% of SOC, while litter and throughfall serve as the major source in forest soils, accounting for about 0.25-2% (Ghani et al., 2003; Haynes, 2005; Laik et al., 2009). Zhang and He (2015) reported significant changes in soil DOC with varying land use types.

2.4 Methods of soil organic carbon fractionation

Due to the complexity of SOC, different procedures are employed to extract different fractions.

2.4.1 Hot water extractable organic carbon

The hot water extractable organic carbon (HWEOC) includes C-substrates as well as other associated nutrients (such as N, P, and S), and therefore its turnover is crucial in nutrient cycling (Gregorich et al., 2006). It contains carbohydrates mainly, and N-rich compounds and forms about 1-5% of the total SOC. This fraction is believed to be readily available to soil microorganisms, since it is bound loosely to soil mineral and in soil solution (Bongiorno et al., 2019). Due to its sensitivity to land-use and management, HWEOC is used as an indicator to management changes and as a proxy for organic compounds that promote aggregation in soil (Balesdent, 1996; Haynes, 2005). The

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HWEOC is the most active pool of SOC and forms a part of DOC and microbial biomass. The HWEOC has a strong correlation with readily mineralizable OM, soil respiration and microbial biomass, and may seemingly be less dependent on seasonal variation (Heller & Weiß, 2015).

The HWEOC consist of carbohydrates mostly originating from microorganisms, plant root exudates and decomposed humic substances that play a role in aggregation and interact mostly with the <53 µm fractions of soil due to their reactive surfaces (Ghani et al., 2002).

2.4.2 Potassium permanganate oxidizable soil organic carbon

The potassium permanganate oxidizable organic carbon (POX-C) forms about 13-28% of SOC. It includes labile humus materials and polysaccharides and all organic compounds that are easily oxidized by $KMnO_4$. POXC accumulation in soil is a sign of long-term SOM stability (Culman et al., 2012; Hurisso et al., 2016). The potassium permanganate oxidizable carbon (POX-C) of soils, often termed as active carbon pool serves as a sensitive indicator of initial changes in soils due to management practices (Mandal et al., 2011). Based on its susceptibility to oxidation with weak potassium permanganate ($KMnO_4$) solution and microbial oxidation, the POXC fraction of SOC can be characterized (Weil et al., 2003).

2.4.3 Acid hydrolysable organic carbon

Acid hydrolysable organic carbon consists of polysaccharides, proteins, and fatty acids (including hemicellulose and cellulose). This fraction is extracted by acids, usually at high temperature, through the cleaving of organic bonds by dissociated water molecules. Hydrochloric acid (HCl) and sulphuric acid (H_2SO_4) at concentrations 6 M and

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1 M respectively have been used extensively in the extraction and characterization of C based on their reactivity (Paul et al., 2006). An estimate of about 30-80% of SOC is solubilized through reflux acid hydrolysis with 6 M HCl (Paul et al., 2006), 32-37% by 1.5 M H_2SO_4 (Chan et al., 2002) and 22-40% by 5 M H_2SO_4 (Rovira & Vallejo, 2000, 2002). Acid hydrolysis extracts about 65-80% of the carbohydrate contents in soil and about 5-16 time that of hot water (Puget et al., 1999).

2.4.4 Non-acid hydrolysable organic carbon

Non-acid hydrolysable organic carbon is the organic carbon fraction made up of long-chain alkyls, waxes, lignin, and other aromatics, including pyrogenic C, which are resistant to acid treatment. The recombination of carbohydrates and proteins as a result of acid treatment forms melanoidins, and these affect the composition of the HCl-insoluble fraction. According to Marschner et al. (2008), this fraction is resistant to microbial decomposition, and persists in the soil environment for a longtime (several years).

2.4.5 Microbial biomass carbon

Microbial biomass carbon (MBC_{mic}) is a carbon fraction that is included in diverse multi-pool models of SOC dynamics as an estimate of the soil biological activity. This represents the living fraction of SOC and is estimated to be about 1-4% of the total organic carbon in soil. It also gives an indication of the microbiota in soils response to environmental changes, soil pollution, site disturbance and management (Carter et al., 1999). The MBC_{mic} plays an important role in the stabilization processes of SOC as it forms about 80% of C in stable SOC fractions (Wiesmeier et al., 2019).

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2.5 Factors affecting soil organic carbon dynamics

Soil organic carbon (SOC) dynamics are affected by an interplay of numerous factors. These include the amount and quality of SOC input, which in turn depends on agro-ecological zones, land use and management practices, the soil biological, chemical, and physical characteristics and process.

2.5.1 Climatic factors

Climatic factors such as rainfall and temperature are the key drivers to the storage of SOC as they influence carbon input and decomposition in the soil.

Temperature is a key rate determining factor in organic carbon decomposition. Generally, reaction rate doubles with 10 ºC rise in temperature. Biochemically, SOC decomposition is dependent on temperature in two ways: (i) the intrinsic temperature dependency, where microbial metabolism and enzyme kinetics are directly influenced by temperature and (ii) extrinsic temperature dependency where temperature controls carbon substrate solubility and diffusion indirectly (Conant et al., 2011). Tropical regions have higher decomposition rates (Ramesh et al., 2019), and hence SOC decomposition rates are often observed to be higher (Six et al., 2002).

With regards to rainfall, ecosystems such as forests promotes higher biomass C input than savannah zone. A study by Srinivasarao et al. (2014) reported a significant correlation of SOC to mean annual rainfall on the influence of rainfall on soil carbon fractions under different crop production in tropical India. Increase rainfall increases soil moisture content, resulting in greater biomass production, providing more residues and hence more food for soil biota. Rainfall also changes the environment for species richness and plant growth, increasing SOC content through litter fall and root exudates. The biological processes involved in the change of the soil redox potential, pH, nutrient

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availability, mineralogy, and weathering are also affected indirectly (Ramesh et al., 2019). The production of CO_2 by microbial and root respiration are both influenced by soil moisture. Substrate decomposition by microorganisms is improved by wet soil conditions. However, when the soil moisture content decreases as a result of less rainfall, CO_2 production is enhanced through microbial respiration. Soil moisture also has an indirect control on the decomposition process of carbon as it serves as a diffusion medium for degradative enzymes and carbon substrates. When the thickness of the water film is reduced, diffusion to microsites for reaction is inhibited (Ramesh et al., 2019). On the other hand, high soil moisture slows the rate of diffusion of oxygen to reaction sites, creating an anaerobic condition which usually slow the degradative pathway of enzymes due to low energy.

2.5.2 Agro-ecology and Land-use effect on soil organic carbon

It is common observation that SOC varies with agro-ecological zones. Forest soils tend to store high amounts of C in the soil. Data by Dawoe (2009) for forest systems within the high rainfall semi-deciduous zones in Ghana indicated about 67.4 ton C ha^{-1}, compared to savannah zones with 12.62 ton C ha^{-1} (Djagbletey et al., 2018). Atsivor et al. (2001) showed that even within the relatively low rainfall zones, forest still recorded high SOC stocks. Recent findings by Owoade et al. (2021) corroborated these findings. Whereas forest carbon emanates largely from litter addition (Ding et al., 2021), rapid root turnover is the major source of SOC in savannah eco-systems (Zhou et al., 2019). Timpong-Jones et al. (2013) measured a 0.58-to-7.12-ton ha^{-1} of grassland biomass in the southern savannah zones of Ghana. The SOC and its fractions such as POC and labile and non-labile C are influenced by the forest type. The composition and density of the forest can impact on the SOC pools. About 61% of the TOC is in the labile form

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hence there is direct relationship between SOC composition and tree species (Laik et al., 2009; Quideau et al., 2001; Ramesh et al., 2019).

In grasslands, biomass is predominantly herbaceous, which has a short growing season. It is easily affected by drought, species composition which affects its carbon input.

2.5.3 Cultivation and management effects on soil organic carbon

The conversion of forest lands for cultivation purposes leads to a decrease in soil C via erosion, changes in the quantity and quality of organic residues added, and the disturbance of soil which leads to an accelerated decomposition of SOC as soil temperature and aeration are increased and soil aggregates disrupted (Wiesmeier et al., 2019). Cultivation alters the amount of organic input from both above and below ground plant litter through the of wide spacing of plants, removal of harvested produce and burning and removal of crop residues. It also influences the rate of decomposition of these inputs and the release of CO_2 into the atmosphere by decomposer communities annually. Compared to the native vegetation, long-term cultivation results in a characteristic increase in the bulk density of the soil (Dominy & Haynes, 2002; Haynes, 2005).

Cultivation affects soil aggregation in many ways by exposing subsurface soils to the surface and breaking down of macroaggregates to release labile SOC by increasing decomposition rate. The exposed soils are also subjected to a drying and wetting cycle and the impact of raindrops leading to the disruption of aggregates whilst natural forest or undisturbed bare land and woodlot increase surface accumulation of litter, via reduced contact with soil microorganisms which slow rate to decomposition (Six et al., 2000).

Unlike cultivation, the application of organic manure mostly leads to C accumulation with time. The rate of C accumulation depends on the type of manure applied. Easily

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decomposable manure such as green manure add to the labile C that would increase the SOC in the short-run but the SOC declines rapidly thereafter (Bayorbor et al., 2006) and their impact on fertility enhancement is short-lived. Manure that have high phenol and lignin content e.g. farmyard manure, form highly stable complexes that resist decomposition when applied (Tian et al., 1992). Thus, the quantity and quality of organic inputs, influence largely the decomposition of OM. Long-term manure application enhances stable soil aggregates and the associated SOC pool. Organic manures combined with conservation tillage could considerably improve soil carbon sequestration capability (Ramesh et al., 2019).

The application of inorganic fertilizer may increase the quantity and quality of crop residues, but may not necessarily lead to increase in SOC. This is because the applied fertilizer may lead to changes in the ionic concentration and pH of soil, affecting soil aggregation negatively. There may be an increase in the labile fraction of C with the application of N fertilizer, and the stabilization of recalcitrant fractions. Soil organic C release due to clay dispersion by NH_4^+ for microbial action upon the application of NH_4^+ fertilizer has been reported (Haynes & Naidu, 1998; Neff et al., 2002; Ramesh et al., 2019). The conversion of NH_4^+ to NO_3^- via nitrification eliminates this effect.

Phosphorus stimulates SOC sequestration indirectly through a variety of mechanisms. Soil P boosts plant biomass by promoting shoot and root growth. Arbuscular mycorrhizal fungi, which aid in the production of soil aggregates that sequester SOC, are affected by soil P concentration. Phosphorus regulates aggregate bonding molecules such as Ca^{2+} and Al^{3+} phosphates. Secondary nutrients like calcium and magnesium promote the development of organo-mineral complexes, which improve SOC stability. Magnesium has been shown to have negative impacts on SOC stability when compared to

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Ca because it promotes clay dispersion. However, the severity of such detrimental effects is determined by clay type and soil ionic concentrations (Haynes & Naidu, 1998; Ramesh et al., 2019; Zhang & Norton, 2002).

Worldwide, the application of lime, or liming materials to the soil to counter acidity is a common practice, to boost crop production in acid soils. In Ghana, about 70 % soils in the high rainfall zones are classified as acidic, having pH between 3 to 5.5. Despite the high rainfall, crop yields continue to be low (maize 1.7 ton ha^{-1} MoFA, 2011) due to acid soil infertility, Al and Mn toxicity (Owusu-Bennoah & Acquaye, 1988). The application of lime increases the pH of soil, which tends to enhance microbial activity, leading to the rapid mineralization of SOC. Thus, Kowalenko and Ihnat (2013) reported decreased total SOC of limed soil compared to their un-limed counterpart in a plot experiment. In general however, most studies have observed no change or increase in SOC by liming (Costa, 2012; Munoz et al., 2012). Some researchers also reported that the increase in SOC may be attributed to the Ca^{2+} in the liming material, which forms cation bridges between the SOC (humified) and clay (Six et al., 2004) to enhance aggregation.

Tillage is another management factor that affects the SOC. Generally, the intensity (extent of soil-residue mixing and depth of soil disturbance), timing and frequency of soil disturbance, determine how much a tillage technique enhances the turnover of SOM. Inversion tillage usually increases soil-residue contact, as it buries almost all residues, enhancing their decomposition (Cookson et al., 2008). Tillage also aids microbial SOM decomposition by controlling soil temperature, providing oxygen through soil aeration, and dispersing soil aggregates (Six et al., 2000) and exposing new surfaces to microbial attack (Indoria et al., 2017). Tillage-induced changes in soil edaphic characteristics can also have a major impact on crop production and ultimately, the amount of residue input in soils (Payne et al., 2000). According to Srinivasarao et al. (2014), the soils physical,

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chemical, and biological characteristics are degraded due to tillage and thus SOC is lost via intensive and continuous tillage practices and traditional management practices.

2.6 Effect of soil properties on soil organic carbon

2.6.1 Texture

Soil texture plays an important role in the stabilization of carbon and the rate of SOC sequestration in soils (Lal, 2004b). Sandy and sandy loam soils tend to contain low amount of organic carbon due to their low clay content and hence low capacity to protect SOC for a long period of time. Skjemstad and Head (1993) observed that organic matter was physically protected within the clay and silt aggregates, preventing microbial attack resulting in the sequestration of carbon in the soil on the study based on soil micro-aggregates. As clay content in soil increases, SOC content also increases. This is as a result of the complexation of clay and organic carbon which hinders decomposition actively. Secondly, high clay content in soil increases the probability of aggregate formation and hence the macro-aggregate formed prevent microbial utilization of the organic matter i.e., mineralization (Ramesh et al., 2019).

High silt and clay content in soils tend to increase their capacity of sequestering C than sandier soils. Due to their fine texture which slows the rate of decomposition as a result of low O_2, which inhibits the aerobic activities of microbes. Also, the physical and chemical stability of SOC by soil minerals is more effective (Zacháry et al., 2018). The fine particle size of silt and clay results in a surface area which is far greater than sand fraction. Secondly, the minerals found in these fine-sized fractions have reactive surfaces which increases their SOM binding capacity (Zacháry et al., 2018). The rate of decomposition of OM associated with different sized particles tend to decrease in the order: sand > clay > silt (Gregorich et al., 1989).

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2.6.2 *Topography*

The topography of an area affects erosion, distribution and redistribution of water, soil particles and organic matter across the landscape thus affecting SOC. Organic matter content is higher at the toe slope of a hill or mountain compared to the upper slope. This is as a result of wetter conditions at the bottom slope than that of the middle or upper slope. Secondly, as erosion and run-off occur, organic matter is transferred from the upper to the lowest point in the landscape. Similarly, north-facing slopes (Northern Hemisphere) tend to have higher organic matter compared to south-facing slope (Southern Hemisphere) due to lower temperatures in the Northern Hemisphere (Ramesh et al., 2019). An area with a convex curvature and steep slope, turn to lead to high water discharge whiles low inclination and concave curvature enhance water accumulation. These affects the amount of water in the soil influencing biomass productions, microbial activity and SOC input and output (Ramesh et al., 2019).

2.6.3 *Soil aggregation*

The physical protection of SOC by soil aggregates can be considered an important mechanism in the stabilization of C (Lützow et al., 2006). Soil biota (living components) and the materials they produce (non-living components of organic matter) play an important role in aggregation through occlusion of organic matter. The biomolecule produced and exuded by roots and microbes in soil and the free and occluded POC are believed to be the primary organic matter components that contribute to aggregate formation and stability (Bolan et al., 2011; Six et al., 2002). The spatial separation of microorganisms and substrate is the main way by which aggregates protect SOC physically from microbial degradation. This mechanism can include the reduced diffusion of

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oxygen, water and other resources into aggregates through pore network, reducing accessibility to decomposers (Kravchenko et al., 2019). Furthermore, plant root and fungal hyphae network that ensnare microaggregates, become biochemical binders for macroaggregates upon the death fungal and root assemblages coalescing microaggregates into macroaggregates (Bolan et al., 2011; Wiesmeier et al., 2019).

2.6.4 Mineralogy

The mineralogy of the soil can play a major role in SOC accretion. Clay minerals, as a component of mineral materials in soils, play an important role in the stability of organic carbon. Clay fractions are made up of a heterogenous mixture of mineral phases varying in their surface properties namely: (i) primary mineral (e.g., feldspar and quartz), (ii) phyllosilicates (e.g., smectites, kaolinites), (iii) metal oxides and hydroxides (e.g., goethite, ferrihydrite), (iv) short-range order alumino-silicate minerals (e.g., imogolite, allophane), (v) carbonates and (vi) gypsum. These minerals at varying degrees protect SOC from enzymatic degradation. Soils abundant in kaolinite clay in a tropical environment tend to support rapid decay of SOC hence its inability to preserve SOM levels (Ramesh et al., 2019).

The sorption of organic C to the soil mineral matrix is generally attributed to the large surface area of the clay minerals within the soil. Soils dominated with clay minerals with high surface area (expandable clay e.g., smectite and vermiculite with surface area 800 m^2 g^{-1}) are, therefore, expected to adsorb more humic substances compared to those with a low surface area (non-expanding clay e.g., kaolinite and mica with surface area ranging from 10-70 m^2 g^{-1}) (Wiesmeier et al., 2019). The variation and degree of bond strength between clay minerals and SOC is influenced immensely by the properties of

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the clay minerals. For example, despite the relatively high clay content (>30%) of Akuse series (2:1 Vertisol) in Ghana, the SOC is low (10 g kg^{-1}) (Mutala, 2012; Osei et al., 2017), which is not significantly different from that found for kaolinite 1:1 minerals. Thus, clay mineral affects the microstructure and pore system of soil, provide adsorptive surfaces for organic molecules, and preserve SOC from biodegradation through the formation and dynamics of aggregates (Ramesh et al., 2019).

The adsorption of SOC to the soil mineral surface is brought about by different mechanisms such as ligand exchange, polyvalent cation bridges and weak interactions e.g., hydrogen bonding, hydrophobic interactions and van der Waals forces. The adsorption of SOC through ligand exchange decreases as pH increases in minerals with pH dependent charges (Kögel-Knabner & Amelung, 2021). Gu et al. (1994) reported a maximum sorption between pH 4.3- 4.7 corresponding to the pK_a of carboxyl (-COOH) groups in minerals.

Apart from pH, Al and Fe and their oxides and hydroxides (sesquioxides) contribute significantly to the stabilization of organic matter. Organic materials can be retained through the coagulation and stabilization of large colloidal association and aggregates at higher charge density (Cincotta et al., 2019). In acidic soils, Fe^{2+} and Al^{3+} form organo-mineral complexes by binding with organic ligands in soil through cation bridges when a short range ordered mineral surface containing either Al^{3+} or Fe^{2+} bonds with organic matter. The Fe and Al content of soil significantly influence the formation and stability of aggregates via organo-mineral associations and mineral-mineral interactions. This is brought about by the occlusion of organic matter at the microstructure level of clay by oxides of Fe and Al, phyllosilicate coating by Fe and Al oxides through the electrostatic interaction of organic matter and Al^{3+} or the adsorption of organic anions by Fe^{3+}. The

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high Fe and Al oxides makes organo-oxide complex soils richer in SOM (Wiesmeier et al., 2019).

The presence of Ca^{2+} and Mg^{2+} affects the SOC. One important mechanism in SOC stabilization is the production of electrostatic bridge between clay mineral (soil mineral phase) and SOM, forming an organic matter-cation-mineral cation bridges as a result of the presence of polyvalent cations such as Ca^{2+} and Mg^{2+} (in neutral and alkaline soils), which nullify the SOC and mineral surface charges (e.g., COO^-) creating a neutral condition on the exchange sites. The cross-linking or chelation of polyvalent cations with organic matter is another means by which SOC is protected from microbial decomposition and stabilized (Kaiser et al., 2007; Wiesmeier et al., 2019). According to Baldock and Skjemstad (2000), metal ions such as Ca^{2+} have been considered in many studies as a potential SOC stabilizing agent. The stabilizing effect of Ca on organic C from losses due to decomposition is the main reason for the high SOC content found in calcareous soils (Ramesh et al., 2019).

2.6.5 Soil chemical factors

A host of soil chemical properties also affect the SOC. Soil pH changes the dynamics and decomposition of SOC through chemical and biological processes. The pH of soil may influence solubility of humic SOC through protonation and deprotonation reaction. An increase in the pH of soil increases the amount of dissolved organic carbon (DOC), while a decrease in pH (acidic conditions), decreases it. The decrease in electrostatic repulsion among molecules, because of increased ionic strength, leading to the compression of the diffuse double layer around an ion, and thus, increases the formation of large humic aggregates and intermolecular H-bonds through the protonation of functional groups e.g., phenolate and carboxylate. Humic acid completely dissolves at pH 9

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or higher. This is due to increased charge density which occurs as a result of decreased occupation of binding sites by protons at high pH (Cincotta et al., 2019; Ramesh et al., 2019).

The increase of negative charge on both soil minerals and SOC at high pH promotes soil minerals, iron oxide or aluminum hydroxide desorption of SOC. The adsorption of SOC onto clay minerals may increase, decrease, or has no effect with decreasing soil pH. The availability of substrate, nutrient and solubility of metal cations affect soil microbial activity, composition, and growth, and these are influenced by changes in the soil pH. The optimal pH for microbial growth is in the neutral range of 6.5-7.5 (Wang & Niu, 2014), therefore, changes in soil pH influences the decomposition of SOC as it affects the soil microbial activity. More energy is required for maintenance at the expense of microbial growth under Al toxicity or extremely low pH conditions. Compared to bacteria, fungi use carbon substrates more efficiently and are more resistant to low pH due to their thick cell wall and hyphae, these, changes in the soil pH may induce a shift in the fungi-to-bacteria ratio in the soil and hence decomposition of carbon (Ramesh et al., 2019).

2.6.6 Soil biological factors

Soil microbial community forms the living part of SOM, and these mediate the decomposition and turnover of SOM for nutrient and energy needed for their growth and maintenance, playing an important role in the biogeochemical cycle (Kavamura & Esposito, 2010). The nature of the organic material and the nature of the microorganisms present in the soil affect the rate of decomposition (Ramesh et al., 2019). Microbes such as fungi and actinomycetes tend to exhibit a high carbon use efficiency compared to aerobic bacteria. Organisms with low carbon use efficiency tend to respire higher proportions of

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metabolized C as CO_2 whilst those with high carbon use efficiency give the opposite. The seasonal variation in soil temperature and moisture affects the community structure and activity (C and N mineralization) of microbes whilst the soil C input (crop residue retention, manure, compost, biochar, and fertilizer) affects the biomass pool size (Carter et al., 1999; Murphy et al., 2007). Strickland and Rousk (2010) reported a higher proportion of C storage in soils dominated by fungi than that dominated by bacteria. Therefore, reduced SOC turnover and hence increased C sequestration via enhanced soil fungi activity has been acknowledged as a potential option (Ramesh et al., 2019). For tropical zones such as Ghana, research interest in microbial community structure has focused largely on N-fixation than SOC. The data with respect to SOC is generally lacking.

Soil microorganisms serve as the main source of soil enzymes (Tabatabai, 2018), and mediate and catalyse biochemical processes such as mineralization and cycling of nutrients, formation, and decomposition of organic matter (Trasar-Cepeda et al., 2000). Soil enzymes can be intracellular, cell-associated, or free (extracellular) enzymes. The group of enzymes in the soils determines the metabolic processes and vary due to soil type, amount of organic matter, activity and composition of living organisms and the intensity of their biological processes. Soil enzymes catalyse many vital processes that are important in the life processes of microorganisms in the soil, stabilizing the soil structure and organic matter formation (Dick, 1997). The binding and immobilization of soil extracellular enzymes by humic substances and clay particles protect them against proteolysis and maintain their activities under unfavourable environmental conditions (Benitez et al., 2005).

The β-glucosidase is prominent and common enzyme in the soil (Eivazi & Tabatabai, 1988), which catalyses the hydrolysis and biodegradation of various glucosides present

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in plant debris decomposing in the ecosystem e.g., cellobiose to glucose (Martinez & Tabatabai, 1997). The β-glucosidase activity is the most predominant glycosidase in soil involved in the last limiting step of cellulose degradation (Acosta-Martínez et al., 2007) and sensitive to pH and soil management (Acosta-Martinez & Tabatabai, 2000). The product of β-glycosidase serves as a carbon source (glucose) for microorganisms in the soil and good indicator of soil quality, as it may reflect the soils capacity to stabilize organic matter and past biological activities.

N-acetyl-β-D-glucosaminidase (EC 3.2.1.30) also known as β-hexosaminidase (EC 3.2.1.52) in enzyme nomenclature (Parham & Deng, 2000) is one of the three enzymes involved in the degradation of chitin through the hydrolyses of glycosidic bonds in chitin and release acetyl-glucosamine. It is an important enzyme in the cycling of both C and N in soil as it participates in the conversion of chitin, one of the most abundant biopolymers on the earth serving as an important transient pool of organic C and N in soils (Ekenler & Tabatabai, 2002).

2.7 Modelling of soil organic carbon dynamics

Interest in modelling SOC dynamics began many decades ago due to the recognition that the SOC can change rapidly in soil, in response to management and also vary spatially with agro-ecology (Smith et al., 1997). Currently, several published models for SOC are available (Alvarez & Alvarez, 2000; Jenkinson & Rayner, 1977; Parton et al., 1992; Riffaldi et al., 1996). However, much work has been published by Six et al. (2000), Parton et al. (2007) and Parton et al. (2015). The CENTURY model by Parton et al. (1992) is approved world-wide for SOC modelling and a tropicalized version has been incorporated in the DSSAT crop model by Tsuji et al. (1994). The Rothamsted

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SOC model (ROTH-C) by Jenkinson and Rayner (1977) is also popularly used in describing SOC dynamics in soils. A review of SOC-mediated soil properties and processes of relevance to tropical conditions has also been published by Porter et al. (2010). All the models rely on the pool concept, whereby the organic resource is considered to compose a number of pools. There are up to 5 pools in some models (ROTH-C) and include plant residue forms. In DSSAT, the residues are considered separate from SOC pools, which, for simplicity identify 3 pools (active, slow, and passive). The SOC pools in the CENTURY model also consist of 3 pools (active, slow, and passive) including above and belowground litter pools and a surface microbial pool, associated with decomposing surface litter. Kinetic models have been developed under different reaction orders. For SOC dynamics, the first-order reaction is the most popular. This is modified by climatic and edaphic factors and states the rate of decomposition of a material to be proportional to its concentration (Parton et al., 2015). Dodor et al. (2019) and Liyanage et al. (2021) stated that first order and the two-phased mechanism of the double exponential are both influenced by the SOM properties.

Dawidson and Nilsson (2000) used CENTURY model to estimate C sequestration in soils from the Upper East Region of Ghana and concluded that land-use affected the SOC simulated. Secondly, the model underestimated the C content under continuous cultivation with manure application and overestimated the C content in the fallow areas by 10%. Though SOC modelling is also important for nitrogen release and management, SOC modelling activity in Ghana has remained very low. In recent times, graduate research work is beginning to deliver some relevant data for such activities. This study is one of those seeking to derive data that will support SOC modelling under varied ecosystems and land use conditions.

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2.8 Carbon management index

The Carbon Management Index (CMI) is an assessment of the capacity of management systems to promote soil quality enhancement (Vieira et al., 2007). It expresses soil quality regarding the accrual of total C in the proportion of labile C fraction compared to a reference soil. Though no fixed value was given, Blair et al. (1995) assumed that the native natural ecosystem (forest/ undisturbed lands) had a CMI value of 100% and used it as a reference in their experiment. Based on this assumption, the CMI of management or land-use systems may be estimated as either high or low. By integrating the properties of SOM, the CMI depicts the effects of land use on TOC levels. Though the value is not significant, the difference shows how management and land-use influence the lability, stability, and amount of C, with soils having higher value considered as better managed (Zhang et al., 2020; Zhao et al., 2014).

According to De Bona et al. (2008), CMI value greater than 100 stipulates a positive effect on the total organic C whilst values lesser than 100 show a negative effect. Carbon management index is estimated as a product of the carbon pool index (CPI) and lability index (LI) and expressed as a fraction or percentage.

$$CMI = CPI \times LI \times 100 \qquad [2.1]$$

where CMI = carbon management index

$$CPI = \frac{total\ carbon\,(sample)}{total\ carbon\,(reference)} \qquad [2.2]$$

$$LI = \frac{lability\ of\ carbon\,(sample)}{lability\ of\ carbon\,(reference)} \qquad [2.3]$$

$$L = \frac{labile\ carbon}{non-labile\ carbon} \qquad [2.4]$$

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The CPI is used to describe any change in TOC pool size as a result of land use. This is derived as a proportion of the reference total C (TOC in forest/ undisturbed soil) from the sample total C (TOC in the cultivated soil) (Blair et al., 1995). The CPI is used to express the variance in TOC caused by land use changes, with lower CPI values indicating higher C loss (Guimarães et al., 2013; Ramesh et al., 2018). A CPI > 1 indicates SOM-related benefits and soil quality improvements. According to reports, the SOM lability factors, when combined with CMI, assist to recognize changes in SOM state more efficiently than C stocks alone. The lability index (LI) compares SOM lability under different land uses to SOM lability in reference soil. The lability (L) is the ratio of C oxidized by $KMnO_4$ and C not oxidized by $KMnO_4$. The loss of labile C is very important since its turnover releases nutrients for uptake.

A study on soil carbon pools and carbon management index under different land use systems in the central Himalayan region by Kalambukattu et al. (2013), reported forest showing the highest CMI. Gong et al. (2009), also observed an increase in the CMI of soils applied with manure alone or in combination with N fertilizer than those with fertilizer application only in an 18-year wheat-maize system. Higher CMI values are suggested to be attributed not only to increased organic matter accumulation, but also to SOM quality, such as C/N ratio, chemical characteristics, and so on, which ultimately influences the degree of SOM lability (Tirol-Padre & Ladha, 2004).

Tsatsu (2015) reported a lower SOC in three management systems (fertilized, unfertilized, and manured) in Ghana compared to the control (reference), with a difference of about 10 g kg^{-1} at Savelugu in the Guinea savannah zone. The author also reported CMI values of 24 and 29 in the unfertilized and fertilized soils in Savelugu, 49.8 and 50.4 in

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the manured soils of Dambia and Nyankpala series, respectively, compared to the reference, in a study on the impact of nutrient management options on soil organic carbon pools and maize yield in northern Ghana. Much more assessment of SOC in response to management, especially expressed in terms of CMI are needed for the Ghanian situation, where, as for many tropical regions, rapid soil degradation is evident due to poor management.

2.9 Summary, gaps identified and the way forward

Soil organic carbon plays an important role in sustainable crop production owing to its contribution to soil structure and water retention, total CEC and cycling of nutrients to close the loop. In tropical environments where organic matter undergoes rapid mineralization, the buildup of SOC, also known as SOC stock, is slowed. As different sources of organic matter with varying decomposition rates are added to soils, an interplay of land use type and the activities of soil microbial communities account for the formation of different fractions SOC (chemical and biological fractions). Considering the extensive literature on soil organic carbon, the baseline data on SOC, their fractions are thus crucial for gaining insight into how the SOC is partition into the various fractions with land-use type under various agro-ecological zones. The labile fraction of SOC will then be used to determine the carbon management index to throw more light on the land-use effect on the lability and stability of SOC. Beyond monitoring data on SOC and their pools as a response to land use change, the ability to predict the impact of a given land use change on the stocks will help in ascertaining the need for intervention.

The impact of land use changes on the empirically derived kinetic parameters of C mineralization, and their potential association with experimentally measurable microbiochemical activities involved in C cycling in soils have not been investigated in tropical

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climates, including Ghana. Organic C in various fractions differ in their mineralization or degradative potential, therefore until more attention is paid to the different organic C fractions involved in C turnover, the mechanisms involved in the mineralization of organic C would not be properly explained. An incubation study would be carried out to determine the microbial activities during C mineralization and their respective indices of soil health. The CO_2 evolved from the incubation study will then be fitted into a first order and double exponential equation model to recategorizes SOC into pools namely, potential mineralizable, labile, and stable/recalcitrant C pools and their various decomposition rates. A relationship between the modelled pools and sizes and the various SOC fractions would then be established.

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CHAPTER THREE

3 MATERIALS AND METHODS

3.1 Site description and soil sampling

The soils used in this study were sampled from four agro-ecological zones in Ghana namely: the interior savannah, forest-savannah transition, semi-deciduous forest, and coastal savannah zones (Fig 1), under three different land-use systems: uncultivated (Plate 3.1), cultivated (Plate 3.2) and woodlot lands (Plate 3.3). The agro-ecological zones were selected to give a fair representation of the country while the sampling sites were randomly selected. The various soil sampling sites within the agro-ecological zones and land-use history are summarised in Table 3.1.

The Interior savannah zone covers an area of about 14,790,000 ha. It has unimodal rainfall pattern with a mean annual rainfall of 1100 mm and annual temperature ranging from 25 to more than 33 °C (mean 28 °C). The growing period ranges in this zone ranges from 180-200 days from March to September with the dominant land-use systems being annual crops, cash crops and livestock. Soils found in the interior savannah zone are mainly Lixisol (young soils with weak to moderate horizon development, mostly from colluvial and alluvial materials), Luvisol and Plinthosols, shallow to moderately deep, medium to light textured and developed over Voltaian sandstone, granite, phyllite and schists with low organic C, N and P. The main crops grown include sorghum, maize, groundnut, millet, yam, and cowpea. In this zone, soils were sampled from Bawku, classified as Berenyasi-Kupela series (local classification), or as Eutric-Gleysol according to the FAO (1990). The soils sampled at Walewale is classified as Mimi series (local classification), and Ferric Lixisol according to the FAO (1990).

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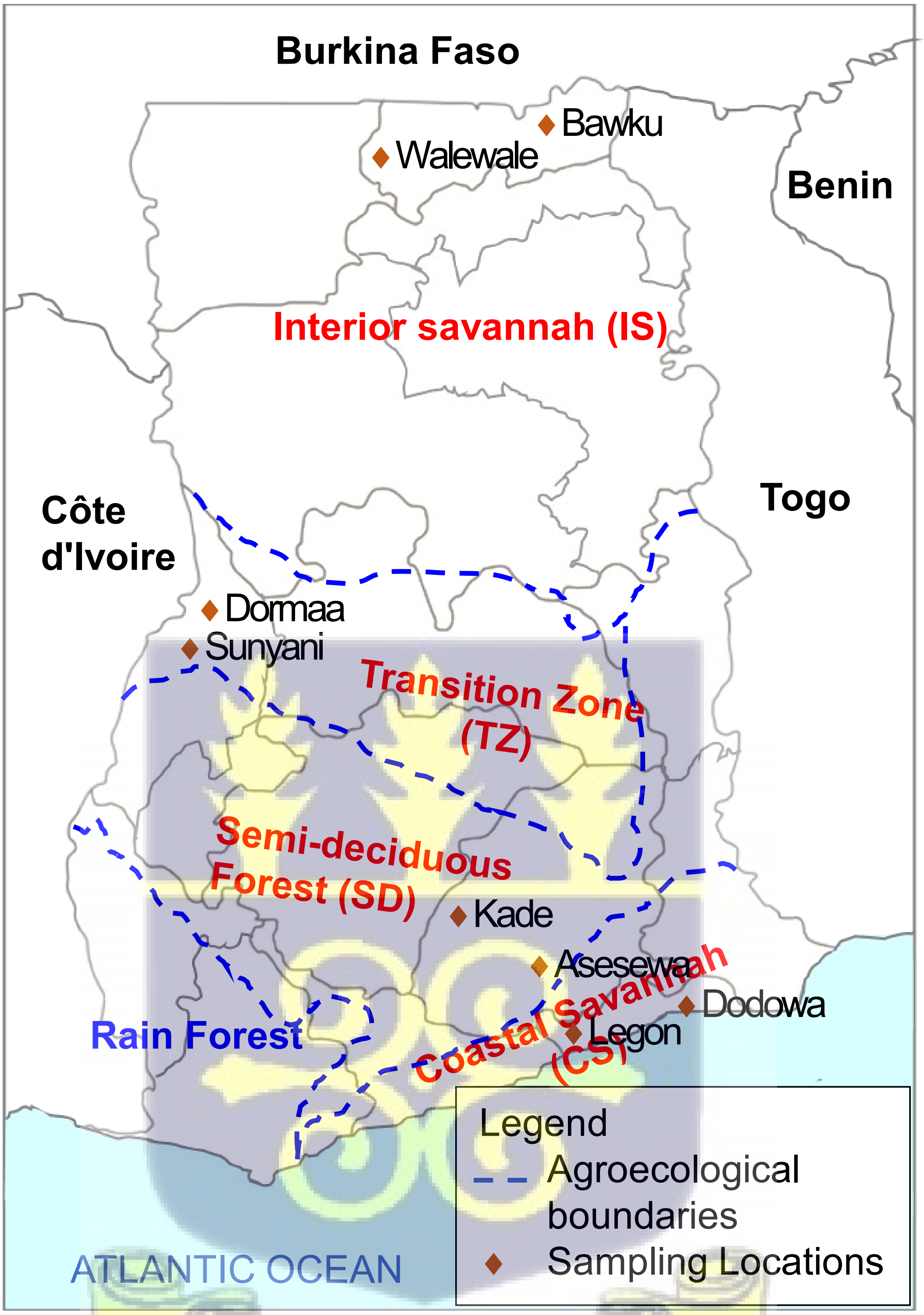

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Fig. 3.1:Agro-ecological zones and sampling sites in Ghana.

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Plate 3.1: Uncultivated land-use

Plate 3.2: Cultivated land-use

Plate 3.3: Woodlot land-use

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Table 3.1: Description of sampling sites used for the study

Agro-ecological zone	Site	Land use	Description
Interior Savannah (IS)	Bawku	ncultivated	Bare land with patches of grassland
		cultivated	Maize intensively cultivated for over five years
		woodlot	Neem and shrubs
	Wale-wale	uncultivated	Bare grassland with sparse trees
		cultivated	Maize intensively cultivated for over five years
		woodlot	Neem and shrubs
Transitional (TZ)	Dormaa	uncultivated	Primary Forest
		cultivated	Maize intensively cultivated for over five years
		woodlot	Teak plantation over 10 years
	Sunyani	uncultivated	Primary Forest
		cultivated	Cassava, intensively cultivated for over five years
		woodlot	Teak plantation over 10 years
Semi-Deciduous (SD)	Asesewa	uncultivated	Primary Forest
		cultivated	Cocoyam and maize mixed cropped
		woodlot	Teak plantation over 20 years
	Kade	uncultivated	Primary Forest
		cultivated	Plantain plantation cultivated over 20 years
		woodlot	Rubber plantations over 20 years
Coastal Savannah (CS)	Dodowa	uncultivated	Primary Forest
		cultivated	Cassava and maize inter crop intensively cultivated over 10 years
		woodlot	Teak plantation
	Legon	uncultivated	Patches of fallow land with sparse trees and shrubs over 20 years
		cultivated	Maize intensively cultivated for over 10 years
		woodlot	Leucaena cultivated over 40 years

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The forest-savannah transition covers an area of 6,630,000 ha. It has a bimodal rainfall pattern with an average annual rainfall of 1300 mm yr^{-1} and an annual temperature range of 17-33 °C. The growing season ranges from 200-220 days from April to July for the major season and 61 days from September to October in the minor season. The dominant land-use system are annual and cash crops. The soils are developed mainly over granites, phyllites, sandstones and quartzites, with moderately deep and concretionary soils. The soils sampled at both Dormaa, and Sunyani are classified as Ferric Acrisols according to the FAO (1990).

The Semi-deciduous zone covers an area of about 740,000 ha. It also has a bimodal rainfall pattern with a mean annual rainfall of 1500 mm yr^{-1} and annual temperature range from 24 to 28 °C, with a growing season ranging from 150-160 days from March to July for the major season and 90 days from September to November in the minor season. The dominant land-use systems are forest and plantation crops. The soils are mainly Acrisols and Lixisols, developed over granites and phyllite. They are deep, easily tilled and offer very little resistance to root growth. Cocoa, cassava, plantain, maize, oil palm are the main crops grown in this zone. The soils sampled at Asesewa is Yaua-otrokpe series classified as Lithic Leptosol according to the FAO (1990). The soil sampled at Kade is classified as Kokofu series (local classification) or Typic Plinthustult according to the FAO (Dwomo & Dedzoe, 2010).

The Coastal savannah covers an area of about 580,000 ha. It has bimodal rainfall pattern with a mean annual rainfall of 800 mm yr^{-1} and 27°C as the mean annual temperature. The growing season ranges from 110-100 day from April to July for the major season and 50 days from September to November for the minor season. The dominant land-use system is annual crops, and the vegetation is mainly coastal grassland and scrub. Soils are developed over Togo quartzite schist, phyllites, shales. They are moderately heavy

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to medium textured, deep to very deep, gravelly to non-gravelly and highly susceptible to erosion. The soil sampled at Dodowa is Beraku-kabo series (local classification), classified as Gleyic Cambisol according to the FAO (1990). The soil sampled at Legon is Toje series (local classification), Rhodic Kandiustalf by Eze (2008) according to the FAO (2003). It is a well-drained soil with Low Activity Clay (LAC) which is dominated by kaolinite clay with little amount of goethite and hematite (Dowuona et al., 1998) .

3.2 Soil sampling

A field survey was conducted to identify 2 locations in each ecological zone where similar farming practices were adopted for the differing land use types. Farmer fields were adopted owing to the difficulty in acquiring lands which in most cases were far from native forests and woodlots. At each location, a representative soil from a soil association/ complex on which the various land use types existed was selected. Within each land use type, soil samples were collected from 20 grids at 20 cm depth with an auger. The soils were sampled at the time of the season where husbandry practices were low, and microbial activities were near equilibrium. The field moist soils were passed through a 2 mm sieve, bagged, labelled, kept under ice and trans-ported to the laboratory for analyses and incubation studies. The 20 soil samples were composited and thereafter subsamples were air-dried for laboratory analyses. All analyses were done in triplicates. Triplicate core samples were taken from undisturbed points for bulk density determination.

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3.3 Soils analyses

3.3.1 Physical properties

3.3.1.1 Particle size analysis

The particle size distributions of the soils were determined by the Bouyoucos (1962) hydrometer method as modified by Day (2015). Forty grams (40 g) of 2 mm sieved soil samples were weighed into 500 mL beakers. To destroy the organic matter present in the soil samples, 10 mL of 30% hydrogen peroxide (H_2O_2) was added. One millilitre (1 mL) of Glacial acetic acid was also pipetted into the beaker. The mixture was stirred and observed closely till completion of the reaction (cessation of bubbling and fizzing). Increment of 10 mL H_2O_2 were added up to 30 mL. Additional of acetic acid was added as required to prevent violent H_2O_2 reaction. The samples were then heated on a hot plate of 100-110 °C until the digestion was completed.

The suspension was transferred into 250 mL dispersing bottles and 100 mL of 5% Sodium Hexametaphosphate (Calgon) solution was added. The suspension was agitated at 180 strokes per minute on a reciprocating shaker for 2 hrs, transferred into 1 L graduated sedimentation cylinders and made up to the mark with distilled water. A plunger was lowered into the cylinders to agitate the suspension thoroughly. Hydrometer readings were taken for silt plus clay particles 5 min after the agitation. The suspensions were allowed to equilibrate for 5 hours, after which a second hydrometer measurement was taken for clay particle density. The sand fraction was determined by passing the suspension through a 47 µm sieve, thoroughly rinsing away any residual silt or clay particles with tap water, and then weighing the remaining material in a pre-weighed moisture can. This material was then subjected to oven drying at 105 ºC for 24 hours.

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The sand, after being dried in an oven, was cooled in a desiccator containing silica gel and weighed using a mechanical balance. The particle size distributions for the soil samples were calculated as follows:

$$\%\,clay = \frac{hydrometer\ reading\ at\ 5\,hrs}{40\,g} \times 100 \qquad [3.1]$$

$$\%\,silt = \frac{hydrometer\ reading\ at\ 5\,min - hydrometer\ reading\ at\ 5\,hrs}{40\,g} \times 100 \qquad [3.2]$$

$$\%\,sand = \frac{weight\ of\ oven\ dried\ sample}{40\,g} = 100 \qquad [3.3]$$

where 40 = weight of soil sample in grams

3.3.1.2 Clay ratio

The clay ratio of soil was determined as described by Bouyoucos (1935) as follows:

$$clay\ ratio = \frac{(sand + silt)}{clay} \qquad [3.4]$$

3.3.1.3 Bulk Density

The core sample technique as described by (Blake & Hartge, 1986) was used to determine the bulk densities of the various sampled soils. The vegetation cover was removed, and a cylindrical soil core was extracted with a mallet and core sampler. The surrounding soil was carefully excavated to avoid disturbance. The ends of the core were trimmed to ensure levelling, capped, and placed in labelled polybags and transported to the laboratory.

In the laboratory, the various soil samples were emptied into clean moisture cans with known weight (W1) and dried at 105 ˚C for 72 hrs (3 days) and the weight (W2) taken

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after cooling in a desiccator. The bulk density was calculated with the formula below (Blake, 1965).

$$\rho_{b\left(kg\,m^{-3}\right)}=\frac{M}{\left(\pi d^2/4\right)h}\left(kg\,m^{-3}\right) \qquad [3.5]$$

where ρ_b= Bulk density of soil

M= mass of soil = W2-W1 (g)

W2 = Weight in gram taken after oven drying the moisture can and its contents (g).

W1 = Weight in gram of empty moisture can (g).

$\pi\ d^2/4$= area of core base (cm^2)

d= diameter of core (cm)

h= height of core (cm)

π = 3.142

$\left(\pi\, d^2/4\right)h=$¿ volume of core (i.e., volume of soil)

3.3.1.4 Water holding capacity

Five hundred grams (500 g) soil was weighed into perforated plastic pots of 15 cm diameter and 20 cm height lined with filter paper and saturated with water. The top of the pots was covered with a plastic to prevent evaporation and allowed to drain for 3 days. Subsamples were then taken, weighed and oven dried at 105 ºC for 24 hr and the dry weight measured after cooling in a desiccator. The gravimetric water content (θg) was determined as the difference in mass between the mass of moist and oven-dried soils. The percent water content at field capacity was computed as follows:

$$\%\,\theta g=\frac{weight\ of\ wet\ soil-weight\ of\ oven\ dried\ soil}{weight\ of\ wet\ soil}\times 100\left(g\,g^{-1}\right) \qquad [3.6]$$

This was converted to the volumetric water content as

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$$\theta v = \theta g \times \rho b. \qquad [3.7]$$

3.3.2 Chemical Analysis

3.3.2.1 Soil pH

Twenty grams (20 g) of the soils (2 mm sieved) were weighed into a 50 mL beaker and 20 mL of distilled water added to give soil: water ratio of 1:1. The soil-water suspension was stirred continuously for about 30 min and then left to stand for one hour. The glass electrode pH meter (OAKTON, -pH/mV/Conductivity/°C/°F meter PC-2700) was standardized with two aqueous solutions of pH 4 and 7 before use in measuring the pH of the supernatant.

3.3.2.2 Total Nitrogen and Carbon

The total N and C content of the soil were determined on < 0.5-mm air dried samples by dry combustion using LECO CNS analyser, (LECO Corp., St Joseph, Michigan. USA).

3.3.2.3 Percent (%) Organic Carbon

The soil organic carbon content was determined by the wet oxidation method described by Walkley and Black (1934). Half gram (0.5 g) of soil (0.5 mm sieved) was weighed into a 250 mL Erlenmeyer flask and 10 mL of 1N potassium dichromate ($K_2Cr_2O_7$) solution and 20 mL of concentrated sulphuric acid (H_2SO_4) were added. The flask was swirled and then allowed to stand for 30 min. Two hundred (200) millilitres of distilled water and 10 mL of orthophosphoric acid was added to stop any further oxidation. The unreduced $K_2Cr_2O_7$ was titrated with 0.2 N ammonium ferrous sulphate using barium diphenylamine sulphate as indicator. The percent organic carbon was calculated as:

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$$\%C=\frac{0.3\times(10-TN)\times 1.33}{W}\times 100 \qquad [3.8]$$

where % C = Percent organic carbon

T = Titre value (mL)

N = Normality of Fe $(NH_4)_2(SO_4)_2$

W = Weight of soil sample (g)

0.003= Milliequivalent weight of carbon (g)

1.33= correction factor (*f*)

3.3.2.4 Available Nitrogen

Ten grams (10 g) of 2 mm sieved soil sample was weighed into a 100 ml extraction bottle and, 50 ml of 2 M KCl was added and shaken on a reciprocating shaker at 180 strokes per min for 30 min. The supernatant was filtered through a No 42 Whatman filter paper. Ten millilitres (10 mL) aliquot of the filtrate was then taken into a 250 mL Kjeldahl distillation flask and 0.2 g of MgO powder was added, swirled, and distilled for ammonia (NH_3)-N using of VELP SCIENTIFICAN UDK-129 distillation unit. The NH_3-N liberated was collected in 5 mL of 2% boric acid (containing a methylene blue and methyl red indicator mixture), to 50 mL.

After the distillation, 1 mL of 0.2 M Sulphamic acid (H_3NO_3S) was added and swirled to remove any nitrite present in the solution. One fifth of a gram (0.2 g) of Devarda's alloy was added to reduce the NO_3^--N to NH_3^+-N and the distillation process repeated. The two (2) distillates were titrated against 0.01M HCl and the concentration of NO_3^- / NH_4^+ kg^{-1} soil calculated as follows:

$$NO_3^{-¿}/NH_{¿}^{+¿}=\frac{M_{HCl}\times V_{HCl}\times 10^{-3}\times V_{KCl}\times 1000\,mg}{Volume\ of\ aliquot\times weight\ of\ soil\,(g)}¿¿ \qquad [3.9]$$

where:

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M HCl = Molarity of the HCl (mol L^{-1})

V HCl = Titre of the HCl (mL)

V KCl = Volume of KCl extractant (mL)

14 = Molecular weight of N

3.3.3 *Other chemical determinations*

Though not directly indicated as the aims of the study, a number of additional chemical analyses were carried out because they indirectly influence the SOM and its decomposition in soils as discussed in Chapter 2. The determination procedures are detailed below.

3.3.3.1 Total phosphorus

The total phosphorus content of the soil samples was determined by following digestion of 2 g of 0.5 mm sieved soil with 25 mL mixture of concentrated HNO_3 and 60 % $HClO_4$ in the ratio of 2:3. The digestion was continued until the soil mixture turned creamy and the evolution of white fumes of $HClO_4^-$ ceased. The digest was cooled with 20 mL of distilled water, filtered into a 100 mL volumetric flask using a No. 42 Whatman filter paper and made to the mark. Phosphorus in the filtrate was determined using the (Watanabe & Olsen, 1965) molybdate blue-ascorbic acid colour development method. The resultant colour intensity was read on a Cole Parmar Spectrophotometer S/N: KPX1507156019 at 712 nm wavelength and total P in the soil samples were calculated as follows:

$$P_{(mg\,kg^{-1})} = \frac{spectrophotometer\ reading\ (mg\ L^{-1}) \times volume\ of\ extract}{volume\ of\ aliquot \times weight\ of\ soil\ sample} \qquad [3.10]$$

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3.3.3.2 Available phosphorus

Available P in soil samples was determined following the procedure of Mehlich (1973). Mehlich No. 3 extraction reagent was prepared by dissolving 34.73 g of NH_4F in 150 mL of distilled water in a 250 mL beaker. After dissolution, 18.2625 g of EDTA was added and dissolved. The solution was then transferred into a 250 mL volumetric flask, made to volume with distilled water and transferred into a storage container, labelled as NH_4F-EDTA stock, and stored. Forty grams of NH_4NO_3 was dissolved in approximately 1500 mL of distilled water in a 2 L beaker. Eight millilitres (8 mL) of the NH_4F-EDTA stock solution, was added, followed by 23 mL of glacial acetic acid (CH_3COOH) and 1.64 mL of concentrated nitric acid (HNO_3). Every addition was followed by swirling to ensure mixing of the reagents. The solution was brought to pH of 2.5 and then transferred into a 2L volumetric flask and made to the mark with distilled water. This solution was stored as Mehlich No. 3 extraction. A scoop of 5 mL of 2 mm sieved soil was weighed and transferred into a clean 100 mL extraction bottle. A 50 mL volume of the Mehlich No. 3 extraction solution was added, stopped, and shaken on a reciprocating shaker for 5 min. The suspension was immediately filtered through a Whatman No. 42 filter paper and the available P in the filtrate determined as described in section 3.4.4.

3.3.3.3 Exchangeable bases determination

A 5 mL aliquot of the filtrates from section 3.3.2.5 was pipetted into 50 mL volumetric flask and made up to the mark with deionized water. A Perkin Elmer atomic absorption spectrometer (Analyst 800) was calibrated with the appropriate standards for Ca, Mg K and Na and the absorbance for each element determined. Exchangeable bases were calculated as:

$$X_{\left(cmol_c kg^{-1}\right)} = \frac{R \times volume\ of\ extract \times 10^{-3}(g) \times 10^{2}(cmol) \times E}{weight\ of\ soil \times 10^{6}(\mu g) \times M} \qquad [3.11]$$

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where M = Atomic mass of atom (Ca= 40, Mg= 24, Na= 23 and K= 39)

R = AAS (Atomic absorption spectroscopy) reading in mg L^{-1}

E = Charge of Ca

X = Cation to be determined

3.3.3.4 Cation exchange capacity

Ten grams (10 g) of the soil samples (2 mm sieved) were weighed into a 200 mL extraction bottles and 100 mL of 1N ammonium acetate (NH_4OAc) solution buffered at pH 7.0 was added. The bottles were shaken on a reciprocating shaker at 180 strokes per min for 1 hr. The soil suspension was then filtered through a No. 42 Whatman filter paper into new clean container (container 1). The soil sediments on the filter paper were washed with 100 mL of 99% ethanol of the excess ammonium acetate, after which 100 mL of 1 M acidified KCl was used to displace the NH_4^+ from the exchange sites of the soil and collected in a clean container (container 2). Ten millilitres (10 mL) aliquot of the filtrate from container 2 was placed into a 250 mL Kjeldahl distillation flask and 5 mL of 40% NaOH was added and distilled as described in section 3.4.3. and the cation exchange capacity of the soils determined.

3.3.3.5 Ammonium oxalate extractable iron and aluminium

Acid ammonium oxalate extractable iron (Fe) and aluminium (Al) were determined by the method of Schwertmann (1964). A milled sample weighing 0.5 g was placed in a 50 mL centrifuge tube. A solution of acid ammonium oxalate in 10 mL was added. The solution was prepared by dissolving 28.3 g of Ammonium oxalate in a litre of deionised water and labeled (A) and 25.2 g of oxalic acid in a litre of deionised water labeled (B)

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separately. Seven hundred ml (700 mL) of 'A' and 535 ml of 'B' were mixed and adjusted to pH 3.0. The soil suspension was shaken in the dark at room temperature for 4 h, centrifuged for 10 mins at 3500 rpm and filtered through 0.45 µm filter paper. One millilitre (1 mL) of the filtrate was diluted using 4 mL of 2000 ppm sodium as sodium chloride solution. Iron and aluminium standards were prepared (Fe, 0 to 25 ppm; and Al, 0 to 25 ppm) and used to construct a calibration curve on the atomic absorption spectrophotometer (AAS). The amount of Fe and Al were determined using the relationship.

3.3.3.6 Bicarbonate citrate dithionite extractable iron and aluminium

Bicarbonate citrate dithionite extractable Fe and Al determined by the method of Mehra and Jackson (1960). A 0.5 g milled sample was put into a 15 mL centrifuge tube, and a 5 mL aliquot of bicarbonate-citrate buffer was added. The bicarbonate-citrate buffer solution was prepared as follows: One liter of 0.3 M sodium citrate and 250 mL of 1 M sodium bicarbonate solution were mixed. An amount of 0.2 g of sodium dithionite was added using a calibrated scoop, the mixture was mixed well, and the tube was put into a water bath at 80 ºC. Stirring was done every 3 min for the 15-minute extraction period. The tubes were removed, 1 mL of saturated NaCl (4 M) solution added, mixed and soil suspension centrifuged for 5 min. at 3500 rpm. The clear supernatant was poured off into a 100 mL volumetric flask. The extraction was repeated after the soil residue was loosened using the vortex mixer. The sample suspension was then washed twice, each with 5 ml and 1 ml of bicarbonate-citrate buffer solution and saturated NaCl solution respectively. The soil suspension was centrifuged each time after washing and the clear supernatant poured into the 100 ml volumetric flask. The extract was then made to volume with distilled water. The amount of Fe and Al were determined as described in section 3.3.2.8.

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3.4 Microbiological properties

3.4.1 Soil microbial biomass carbon and nitrogen

The microbial biomass carbon and nitrogen of the soil was determined by the chloroform-fumigation-incubation extraction method of Jenkinson and Powlson (1976). Ten grams (10 g) of field moist soil (2 mm sieved) was weighed and placed into a 50 mL beaker and placed in a desiccator lined with moist paper towels to prevent the desiccation during the fumigation. A 50 mL beaker containing 30 mL ethanol-free chloroform and boiling chips was placed in the middle of the desiccator, ends greased and evacuated with a vacuum pump until the chloroform boiled vigorously for 5 min. The procedure was repeated three times at 15 min intervals, letting air pass back into the desiccator to facilitate the distribution of the chloroform throughout the soils. The valve on the desiccator was closed, and the desiccator was left in the dark for 5 days. Non-fumigated soils were included in a separate desiccator. All the sample were in triplicates.

After 5 days, the fumigated samples were re-evacuated for 10 min and then transferred into 100 mL extraction bottles. Fifty millilitres (50 mL) of 0.5 M K_2SO_4 solution were added to the soil samples, shaken on a mechanical shaker at 180 strokes per min for 1 hr, and then filtered through a No. 42 Whatman. Ten millilitres (10 mL) of the extract were pipetted into Erlenmeyer flasks, 2 mL of 0.4 N of $K_2Cr_2O_7$ and 15 mL of a mixture concentrated H_2SO_4 and H_3PO_4 (2:1 v/v) solutions were added, refluxed for 30 min, and diluted with 25 mL of deionized water. The excess dichromate was titrated with 40 mM $Fe(NH_4)_2(SO_4)_2.6H_2O$ solution using barium diphenylamine sulphanate as indicator. Moisture was determined from loss in weight after drying at 105 ºC for 48 hr. The soil extractable organic C was determined as follows:

$$C_{\mu g\, mL^{-1}} = \left[HB - sample/CB\right] \times N \times \left[VD/VS \times E \times 1000\right] \qquad [3.12]$$

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where HB = Hot blank (refluxed)

CB = cold blank (unrefluxed)

N = Normality of $K_2Cr_2O_7$

VD = Added volume of $K_2Cr_2O_7$ (mL)

VS = Added volume of sample (mL)

$$C_{\mu g\, g^{-1} soil} = C_{\mu g\, mL^{-1}} \times (VK + SW / DW) \qquad [3.13]$$

VK = Added volume of K_2SO_4

SW = Soil water

DW = Dry weight of soil

The microbial biomass C was then determined as follows:

$$\text{Microbial biomass} = E / K_{EC} \qquad [3.14]$$

where K_{EC} = 0.38 (Vance et al., 1987)

E = The difference of fumigated and unfumigated extractable organic C

Microbial biomass nitrogen was determined by steam distillation described by (Mulvaney, 1996). An aliquot of 10 mL of the extract was pipetted into a Kjeldahl flask, 5 mL of 40% NaOH was added, and distilled. The ammonia (NH_3) released was collected in 5 mL of 2% boric acid containing a mixture of methylene blue and methyl red indicators. The distillate was back titrated with 0.01 M HCl to a purple endpoint and the N content determined as described in section 3.4.1. and microbial biomass N determined as described in equation 12 above with K_{EC} = 0.40 (Vance et al., 1987).

3.4.2 Basal respiration

Forty grams (40 g) of < 2 mm sieved soil was weighed into incubation bottles in triplicates. The soil samples were moistened to 60% WHC and incubated at 27 ºC in the dark

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for 24 hr. A beaker containing 30 mL of 0.01 M NaOH solution was placed in the incubation bottles to trap the CO_2 evolved. At the end of the incubation period, the evolved CO_2 trapped in the NaOH was titrated with 0.05 M HCl after adding 5 mL of 0.05 M BaCl to precipitate carbonate. Carbon dioxide evolved was calculated as mg CO_2 g^{-1} soil. The basal respiration rate (BR) in units of µg CO_2-C g^{-1} dry weight per hour was then determined as follows:

$$BR = \frac{M_c \times V_b - V_s \times 0.05}{S_{dw} \times t \times 2} \quad [3.15]$$

where M_C is the molar weight of carbon (M_w = 12.01); V_b and V_s the volume, in ml, of 0.05 M HCl consumed in the titration of the blanks (mean of three replicates) and the sample, respectively; S_{dw} is dry weight of soil; and t is the incubation time in hours. Since two OH^- are consumed per CO_2 precipitated, a factor of 2 was included in the formula.

Furthermore, the metabolic quotient (qCO_2) was estimated as:

$$qCO_2 = \frac{basal\,respiration}{microbial\,biomass\,carbon} \quad [3.16]$$

and the microbial quotient (qMIC) was estimated as follows:

$$qMIC = \frac{microbial\,biomass\,carbon}{soil\,organic\,carbon} \quad [3.17]$$

3.4.3 Flush of carbon dioxide after rewetting dried soils

The flush of CO_2 evolved after rewetting of air-dried soils was determined as described by Franzluebbers (2016). One hundred grams (100 g) of dried soil was weighed into clean jars and moistened at 60% WHC. A vial containing 20 mL of 1 M NaOH was placed in the jar to trap CO_2, sealed, and incubated in the dark for 3 days. At the end of

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incubation, the excess NaOH was titrated with 0.5 M HCl after precipitation of carbonate with 2 M $BaCl_2$. Samples were incubated in triplicates, and 3 blanks were setup to correct for ambient CO_2. The CO_2 evolve was determined as follows:

$$CO_2 - C_{(mg\,kg^{-1}\,soil)} = \left(mL_{[blank]} - mL_{[sample]}\right) \times N \times \frac{M}{S} \qquad [3.18]$$

Where N = normality of acid (mol L^{-1})

M = mass conversion from $cmol_c$ to g C (6000),

S = weight of soil (g)

3.5 Carbon fractions in soils

3.5.1 Hot water extractable organic carbon (HWEOC)

The HWEOC was determined as described by Ghani et al. (2003). One gram (1 g) of the soil was weighed into 50 mL centrifuge bottles and 10 mL of distilled water added, capped, and placed in a water bath at 80 ºC for 16 hr. The tubes were then vortexed for 10 s and then centrifuged for 10 min at 4000 rpm. The C in the extract was oxidized with 2 mL of 0.4 N $K_2Cr_2O_7$ solution and the excess $K_2Cr_2O_7$ solution titrated with $Fe(NH_4)_2(SO_4)_2$.

3.5.2 Potassium permanganate extractable organic carbon (POX-C)

The POX-C of the soil samples was determined as described by Blair et al. (1995) and modified by Weil et al. (2003). A solution of 0.02 M $KMnO_4$ at a pH of 7.2 was made by dissolving 31.60 g of $KMnO_4$ in 1 L of 1 M $CaCl_2$ solution to stabilize the $KMnO_4$ solution. A standard stock solution was made by pipetting 0.25, 0.5, 0.75 and 1 mL into clean centrifuge tubes containing 9.75, 9.5, 9.25 and 9 mL of deionized water to obtain 0.005, 0.01, 0.015 and 0.02 M standards, respectively.

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Two and a half grams (2.5 g) of soil was weighed into 50 mL centrifuge tubes and 18 mL of deionized water was added. Two millilitres (2 mL) of the 0.2 M $KMnO_4$ solution were added, hand shaken for 2 s and then placed on a shaker and shaken at 240 oscillations per minute for 2 min. After shaking, the tube was swirled to remove any soil adhering to the sides. The cap was removed and tube with content placed in the dark for 10 min. A 0.5 mL aliquot of the supernatant was added to new centrifuge tubes containing 49.5 mL of deionized water, capped, and inverted to mix.

Four (4) working standard solutions were made by pipetting 0.5 mL of each standard solution into clean centrifuge tubes containing 49.5 mL of deionized water and use to calibrate the curve on the spectrophotometer at 550 nm. A blank was determined by adding 2 mL of the 0.2 M $KMnO_4$ stock solution to 50 mL centrifuge tubes containing 18 mL of deionized water without soil and treated as the samples. All experiments were done in triplicates. The absorbance (optical density) of the samples was read on spectrophotometer at 550 nm. The mass of $KMnO_4$ oxidizable C was calculated as

$$POX-C_{mg\,kg^{-1}\,soil}=¿ \qquad [3.19]$$

where 0.02 mol L^{-1}= initial concentration of $KMnO_4$ solution

a = intercept of the standard curve

b = slope of the standard curve

Abs = absorbance of the unknown soil sample

9000 mg = amount of C oxidized by 1 mol of MnO_4 changing Mn^{7+} to Mn^{4+}

0.02 L= volume of $KMnO_4$ solution reacted

Wt= weight of soil used (kg)

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3.6 Carbon management index (CMI)

The carbon management index for the soils was calculated according to the procedure used by Blair et al. (1995) with the forest (native) soil used as reference as follows:

$$CMI = CPI \times LI \times 100 \qquad [3.20]$$

where CMI = carbon management index

CPI = carbon pool index

$$CPI = \frac{total\,carbon\,(sample)}{total\,carbon\,(reference)} \qquad [3.21]$$

$$LI = \frac{lability\,of\,carbon\,(sample)}{lability\,of\,carbon\,(reference)} \qquad [3.22]$$

$$L = \frac{labile\,carbon}{non-labile\,carbon} \qquad [3.23]$$

3.6.1 Acid (6 M HCl) and Non-acid hydrolysable OC

Acid hydrolysis of the soil samples were carried out as described by Paul et al. (2006). One gram (1 g) soil samples were weighed into 50 mL centrifuge tubes and treated with 25 mL of 6N HCl. The samples were then stoppered and refluxed in a water bath for 16 hr at 80 °C. The suspension was centrifuged at 10000 rpm for 10 min and the supernatant decanted. The residue from the acid hydrolysis was washed with deionized water to rid it of excess chloride and the C content determined by dry combustion using LECO CNS Analyzer (LECO Corp., St Joseph, Michigan, USA) and labelled as non-(acid) hydrolysable C. The acid hydrolysable C fractions were then determined by the difference of the total C content and the C content of the non-hydrolysable fractions in the aggregate-size fractions.

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3.7 Soil C mineralization dynamics

3.7.1 Incubation studies

A long-term (365 day) carbon mineralization experiment was used to study C dynamics in the various soils. Seven hundred grams (700 g) of < 2 mm sieved soil was weighed into incubation bottles. Soils were moistened to 60% WHC and incubated in the dark at 25 °C for 1 year. Beakers containing 30 mL of 1 M NaOH were placed in the incubation bottles to capture CO_2 efflux. The NaOH solution was changed on 1, 3, 7, 14, 21, 28, 42, 56, 70, 84, 112, 140, 168, 244, 280 and 364 days of incubation. The CO_2 trapped in the 1 M NaOH solution was titrated with 0.5 M HCl after it was precipitated with 2 M $BaCl_2$. Samples were incubated in triplicates, and 3 blanks were setup to correct for ambient CO_2. The moisture content of the soil samples was maintained at 60% WHC throughout the incubation period by weighing and addition of water when needed. The amount of CO_2 evolved was calculated as described in section 3.4.3. Sub-samples were taken (every 3 months) and analysed for microbial biomass C and N using the chloroform fumigation extraction method described in section 3.4.1, total C using LECO CNS analyser (LECO Corp., St Joseph, Michigan. USA) as described in section 3.4.3 and available N as described in section 3.4.5 above.

Soils were also analysed for chemical fractions i.e., hot water extractable C, potassium permanganate extractable C and acid hydrolysable OC as described in section 3.5.1, 3.5.2 and 3.5.3, respectively.

The mineralization quotient (qM) was determined as:

$$qM = \frac{cumulative\, C\, mineralized}{soil\, organic\, C} \quad [3.24]$$

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3.7.2 Modelling of C mineralization in soils

The cumulative CO_2-C efflux was fitted to a single first order kinetic equation proposed by Bonde and Rosswall (1987) to estimate the potential mineralizable C pool as follows:

$$C_m = C_0\left(1 - e^{-kt}\right) \qquad [3.25]$$

or a double-exponential model which partitions SOC into labile and stable SOC pools, following equation by Molina et al. (1980), due to differences in susceptibility to mineralization.

$$\mathrm{C_m} = C_1\left(1 - e^{-k_1 t}\right) + C_2\left(1 - e^{-k_2 t}\right) \qquad [3.26]$$

where, C_m is the cumulative *C* mineralized at time *t*, C_0, C_1 and C_2 are the proportion of the potential mineralizable, labile, and stable SOC pools in SOC, respectively, and k, k_1 and k_2 ($\mathrm{day^{-1}}$) are the corresponding mineralization rate constants for each *C* pool. The rate constants of the C_0, C_1 and C_2 pools were used to calculate their respective half-life ($t_{½}$) using the following equation:

$$\mathrm{t}_{\frac{1}{2}} = \frac{\ln \backslash(2\backslash)}{\mathrm{k}}. \qquad [3.27]$$

3.8 Statistical analysis

The data obtained from the various experiments were subjected to normality test following the Shapiro-Wilk procedure. All normally distributed data were subjected to univariate two-way ANOVA and multivariate analyses and means separated by Tukey HSD test at 5% significant level using GenStat Procedure Library Release PL20.1 (12th Edition). Data from the C mineralization were subjected to the first order and double exponential models using SigmaPlot.14 to determine the kinetic parameters. The relationship among C pools, kinetic parameters of C mineralization, microbial activities,

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and soil parameters was determined using linear regression and Pearson's correlation. GraphPad Prism8 (GraphPad Software, San Diego, USA) was used to generate graphs for data presentation.

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CHAPTER FOUR

4 RESULTS

4.1 Physical, chemical, and biological properties of soils used

4.1.1 Soil physical characteristics

Physical properties of the soils are presented in Table. 4.1. Soil texture varied with location, with soils from the IS zone (Bawku, Walawale) recording very high sand content of more than 500 g kg^{-1}, high bulk density (e.g., Bawku UC 1.74 Mg m^{-3}) and a loamy sand texture. The low clay content resulted in high clay ratio values.

Soils from the forest-savannah transition (TZ) recorded the lowest mean bulk density values ranging from 0.65 to 1.06 Mg m^{-3} and the lowest sand content. The general textural class of the soils in the TZ zone was determined to be sandy loam (SL) and have lower sand content than the IS zone. The Clay Ratios were lower than those for the other locations.

The soils from the semi-deciduous (SD) zone bear similarities to those of the TZ, but have relatively higher silt + clay percent, and hence lower Clay Ratios. All the other soils in the SD recorded relatively lower sand contents, except for Asesewa that exhibited the highest sand content (829 g kg^{-1}), and hence the loamy sand texture.

Table 4.**1**: Some physical properties of the soils used

Ecological Zone	Site	Rainfall	Vegetation	Land-use	Bulk density	Sand	Silt	Clay	Clay ratio	Textural class
					Mg m^{-3}	----------------g kg^{-1}---------------				
IS	Bawku	1100	Grassland	UC	1.74	776	173	51	18.6	LS
				CT	1.40	798	155	48	20.0	LS
				WL	1.27	776	200	24	40.9	LS
	Walewale			UC	1.51	781	183	36	26.7	LS
				CT	1.68	742	222	36	26.5	LS
				WL	1.56	670	282	48	19.8	LS
TZ	Dormaa	1300	Woodlot	UC	1.06	540	340	120	7.3	SL
				CT	0.80	575	324	101	8.9	SL
				WL	0.95	559	358	84	11.0	SL
	Sunyani			UC	1.02	461	378	161	11.9	SL
				CT	0.65	439	483	78	5.2	SL
				WL	1.02	542	288	169	4.9	SL
SD	Asesewa	1500	Forest	UC	1.51	829	119	52	18.3	LS
				CT	1.54	772	167	61	15.5	LS
				WL	1.50	794	143	63	14.8	LS
	Kade			UC	1.12	584	356	61	15.5	SL
				CT	1.19	563	356	81	11.3	SL
				WL	1.01	529	396	75	12.4	SL
CS	Dodowa	800	Mixture of scrubs and grassland	UC	1.05	705	250	46	20.8	LS
				CT	1.36	723	232	45	21.1	LS
				WL	1.20	689	260	52	18.2	LS
	Legon			UC	1.16	621	262	117	7.5	SL
				CT	1.20	600	276	125	7.0	SL
				WL	1.18	632	240	129	6.8	SL

Interior savannah (IS); Forest-savannah transition (TZ); Semi-deciduous Forest (SD); Coastal savannah (CS) zones; Uncultivated (UC); Cultivated (CT); Woodlot (WL) lands

Sandy loam (SL); Loamy sand (LS); Clay ratio, (Sand + Silt)/Clay

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The soils from the CS zone bears similarities to those of the IS, except for Legon that exhibited higher clay content, lower Clay Ratio and a sandy loam (SL) texture.

With regard to land use type, the overall observation was that lower bulk densities were observed for either UC and WL systems.

4.1.2 Chemical properties of the soils

Chemical properties of the soils are presented in Table 4.2. The pH of soils from all the locations ranged between 4.3 and 7.1, with the most acidic soils found in the CS zone (Legon). Soils from the Interior savannah zone also exhibited relatively pH values of 5 to 6.

The highest total P was observed in the forest locations (TS and SD) and lowest in the savannah zones (IS and CS). In all locations, however, the available P was very low, often constituting not more than 15% of the TP. In the main, the lowest available P values were observed for the locations with the lowest pH (IS and CS) (see Table 4.2). The soils from TZ and SD had higher Available P compared to those of the other zones.

The TC and TN (4.12-47.27 and 0.2-4.23 g kg^{-1}) were strongly related to Land use type, the highest values generally observed for the UC and WL types.

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Table 4.2: Some chemical properties of the soils used

Ecolo-gical Zone	Site	Land-use	pH	TC	TN	Avail N	TP	Avail. P
				----g/kg----		----------mg/kg--------		
IS	Bawku	UC	5.5	6.79	0.42	23.53	113	5.8
		CT	5.8	4.12	0.20	23.48	154	26.2
		WL	7.0	35.86	2.27	23.28	618	41.7
	Walewale	UC	5.1	26.03	1.94	24.29	530	13.5
		CT	5.9	6.57	0.27	23.17	221	15.8
		WL	6.6	19.74	1.07	24.12	197	20.9
TZ	Dormaa	UC	6.6	23.85	3.08	24.82	314	16.4
		CT	6.7	23.38	2.65	24.22	163	20.9
		WL	6.0	29.25	3.40	24.18	376	3.1
	Sunyani	UC	7.1	37.44	4.43	24.81	412	18.8
		CT	6.3	22.22	2.67	23.94	244	8.2
		WL	6.1	18.89	2.37	24.01	213	3.7
SD	Asesewa	UC	6.2	20.66	2.44	24.63	244	24.3
		CT	6.4	15.47	1.86	23.80	216	8.5
		WL	6.7	36.32	3.49	24.17	364	29.8
	Kade	UC	6.3	36.76	2.80	24.18	489	16.2
		CT	5.7	20.94	1.95	24.17	233	12.7
		WL	5.5	16.79	1.26	24.07	280	11.8
CS	Dodowa	UC	7.0	47.27	3.55	25.96	549	22.5
		CT	6.7	13.78	1.00	23.83	611	115.7
		WL	6.5	12.77	1.00	25.33	180	14.6
	Legon	UC	5.0	13.23	1.02	23.19	299	6.5
		CT	4.4	11.12	0.88	23.34	383	7.7
		WL	4.3	12.09	0.89	24.47	393	8.4
		LSD	0.5	2.00	0.60	1.45	6.23	6.49

Interior Savannah zone (IS); Forest-savannah transition (TZ); Semi-deciduous Forest zone (SD); Coastal Savannah zone (CS); Cultivated land (CT); Woodlot (WL); Uncultivated land (UC); Organic carbon (OC); Total nitrogen (TN)

Table 4.3: Exchangeable cations in the soils

Ecological Zone	Site	Land-use	Ca	Mg	K	Na	CEC	Al_{ox}	Fe_{ox}	Al_d	Fe_d
				-------------------cmol$_c$ kg^{-1}--------------				------------------mg kg^{-1}------------------			
IS	Bawku	UC	2.36	0.23	0.075	0.298	5.82	0.036	0.082	0.806	1.327
		CT	2.72	0.23	0.169	0.342	6.47	0.145	0.034	0.595	0.530
		WL	12.68	1.30	0.220	0.327	9.43	0.082	0.053	0.945	0.310
	Walewale	UC	2.98	0.72	0.358	0.338	13.48	0.038	0.062	0.820	1.844
		CT	3.06	0.74	0.285	0.345	9.61	0.208	0.031	0.535	1.630
		WL	8.64	3.50	0.316	0.377	11.29	0.047	0.025	0.583	1.631
TZ	Dormaa	UC	4.98	1.76	0.392	0.455	17.69	0.090	0.149	0.863	1.272
		CT	8.38	1.67	0.508	0.472	15.51	0.131	0.078	1.351	1.955
		WL	4.52	1.79	0.675	0.489	21.07	0.043	0.078	2.254	2.001
	Sunyani	UC	17.62	2.06	0.338	0.518	28.77	0.033	0.174	0.763	1.297
		CT	7.77	1.91	0.473	0.437	25.95	0.020	0.168	0.356	0.544
		WL	6.12	1.39	0.376	0.392	23.06	0.031	0.102	0.503	1.620
SD	Asesewa	UC	9.25	1.61	0.461	0.495	8.54	0.160	0.061	0.599	2.781
		CT	5.23	1.15	0.530	0.407	9.68	0.014	0.047	5.317	1.039
		WL	10.22	4.39	1.031	0.462	14.23	0.125	0.159	4.912	1.245
	Kade	UC	15.44	3.40	0.750	0.505	19.68	0.224	0.140	4.760	1.327
		CT	5.09	1.45	0.314	0.388	14.76	0.203	0.034	1.537	0.530
		WL	5.10	0.83	0.158	0.424	13.81	0.147	0.052	4.981	0.310
CS	Dodowa	UC	9.63	4.31	1.111	0.433	18.04	0.016	0.129	5.301	0.484
		CT	5.85	1.46	0.989	0.396	7.88	0.029	0.128	4.725	0.489
		WL	5.20	1.27	0.534	0.530	8.51	0.027	0.023	0.808	0.367
	Legon	UC	2.50	1.24	0.674	0.571	12.10	0.007	0.055	1.270	0.269
		CT	3.01	0.96	0.541	0.466	20.83	0.012	0.065	5.173	0.919
		WL	2.65	0.88	0.644	0.498	15.93	0.006	0.085	5.027	0.348
		LSD	0.15	0.04	0.011	0.007	0.31	0.008	0.008	0.066	0.166

Fe_{ox} and Al_{ox} are oxalate extractable Fe and Al; Fe_d and Al_d are dithionate-citrate-bicarbonate extractable Fe_d and Al_d. Interior savannah (IS); Forest-savannah transition (TZ); Semi-deciduous Forest zone (SD); Guinea Savannah zone (GS); Coastal Savannah zone (CS); Uncultivated (UC); Cultivated (CT); Woodlot (WL)

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The lowest basic cations were observed in the IS zone, with Ca and Mg being the dominant exchangeable cations in the soils (Table 4.3). The soils from TZ and SD zones had the highest CEC. The lowest Fe_{ox} and Al_d were observed in the IS zone among the agro-ecological zones. The highest Al_{ox} and Fe_d were observed in the IS, TZ and SD zones compared to the CS that had the lowest.

With regards to land-use system, exchangeable cations were higher in the UC and WL soils compared to the CT soils at all locations. Exchangeable Ca ranged from 2.36 in Bawku UC to 17.62 $cmol_c$ kg^{-1} in Sunyani UC. Exchangeable Mg ranged from 0.23 in Bawku UC and CT to 4.31 $cmol_c$ kg^{-1} in Asesewa WL, exchangeable K ranged from 0.075 in Bawku UC to 1.111 $cmol_c$ kg^{-1} in Dodowa UC and exchangeable Na ranged from 0.298 in Bawku UC to 0.571 $cmol_c$ kg^{-1} in Legon UC. The cation exchange capacity (CEC) of soils ranged from 5.82 in Bawku UC to 28.77 $cmol_c$ kg^{-1} in Sunyani UC. With respect to land-use system, the highest Al_{ox} values were observed in the CT soils except for Sunyani and Asesewa CT where the lowest were recorded. The Al_{ox} and Fe_{ox} oxides contents of the soils ranged from 0.006 in Legon WL to 0.224 mg kg^{-1} in Kade UC and 0.023 mg kg^{-1} in Dodowa WL to 1.174 mg kg^{-1} in Sunyani UC, respectively. The CT soils within each sampling location recorded the lowest value for Fe_{ox}, except for Walewale and Dodowa where the WL soils recorded the lowest values. The Al_d and Fe_d contents ranged from 0.356 in Sunyani CT to 5.317 mg kg^{-1} in Asesewa CT, and from 0.269 in Legon UC to 2.781 mg kg^{-1} in Asesewa UC, respectively. Generally, the lowest Al_d values were observed in the UC soils at all sampling sites, except for Kade and Bawku CT and Dodowa WL which recorded the lowest. Higher Fe_d were observed in the UC soils at all sampling site, except for Dormaa and Legon UC where the lowest values were observed.

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4.1.3 Biological properties of the soils

The biological properties of the soils are presented in Table 4.4. The three parameters MBC, MBN and BR all follow the trend that lower values were recorded for the savannah locations than the TZ and SD locations. The basal respiration rate was also higher for the TZ and SD zones than the savannah zones.

With regard to land use type, the UC soils had higher MBC_{mic} compared to the other land-use systems at all sampling sites except for Bawku and Dormaa, where the WL, and at Sunyani and Kade where CT soils recorded the highest MBC_{mic}. The MBC_{mic} ranged from 480 in Bawku CT to 7486 µg C g^{-1} in Dormaa WL, with soils from the interior savannah zone having lower values compared to other agro-ecological zones. Soil MBN_{mic} was also higher in UC lands, except for CT and WL lands of Bawku and Legon which had the highest values. The MBN_{mic} values ranged from 662 in Bawku UC to 5250 µg C g^{-1} soil in Kade UC. The SBR was lowest in CT soils compared to the other land-use systems at all sites, except for Kade where the lowest value was recorded in the WL soil. Basal respiration ranged from 2.49 in Bawku CT to 257.14 in Kade and Dodowa UC.

The TZ zone recorded higher MBC:MBN and qMIC values and lower qCO_2 values compared to the other zones except for Legon in the CS zone which also recorded lower qCO_2 values.

Table 4.4: Some biological characteristics of the soils

Ecological Zone	Site	Land-use	MBC	MBN	BR	qCO_2	Flush CO_2-C	MBC:MBN	qMIC
			--------μg g^{-1}--------		mg kg^{-1} h^{-1}		mg kg^{-1} 3 d^{-1}	---------%---------	
IS	Bawku	UC	891	662	25.32	0.033	222.36	1.346	14.6
		CT	480	677	2.49	0.006	108.29	0.709	15.2
		WL	1001	673	48.43	0.053	123.59	1.488	3.5
	Walewale	UC	1461	2515	97.88	0.067	346.58	0.581	4.7
		CT	699	733	39.56	0.057	172.44	0.954	9.6
		WL	1200	858	90.68	0.076	197.71	1.399	5.3
TZ	Dormaa	UC	6053	1090	141.90	0.026	208.69	5.554	25.9
		CT	3213	1164	103.26	0.033	66.02	2.760	15.8
		WL	7486	1269	176.16	0.024	231.55	5.899	26.7
	Sunyani	UC	6165	1213	234.12	0.040	360.25	5.084	18.1
		CT	3161	1259	194.04	0.066	89.75	2.510	14.8
		WL	3651	1122	87.54	0.024	214.71	3.254	21.6
SD	Asesewa	UC	3555	1846	237.70	0.067	221.71	1.925	17.7
		CT	3211	1779	95.98	0.037	104.11	1.805	20.9
		WL	2669	1693	110.28	0.046	144.22	1.576	8.8
	Kade	UC	1425	5250	257.14	0.181	347.23	0.271	3.8
		CT	1783	3582	150.07	0.085	176.62	0.497	8.6
		WL	1123	2824	137.11	0.122	177.08	0.398	6.7
CS	Dodowa	UC	5507	2224	257.14	0.049	484.12	2.476	14.6
		CT	1373	1804	106.14	0.078	190.16	0.761	9.5
		WL	2358	1800	113.93	0.05	221.99	1.310	18.8
	Legon	UC	3078	874	58.42	0.019	84.82	3.520	23.4
		CT	2115	1014	30.95	0.015	90.57	2.086	23.0
		WL	1367	1040	38.93	0.031	99.30	1.314	11.8
		LSD	1396.4	51.65	5.20	0.018	15.94	1.07	7.3

Interior Savannah zone (IS); Semi-deciduous Forest zone (SD); Forest-savannah transition (TZ); Coastal Savannah zone (CS); Uncultivated land (UC); Cultivated land (CT); Woodlot (WL); Microbial Biomass Carbon (MBC_{mic}); Microbial Biomass Nitrogen (MBN_{mic}); Basal Respiration (BR); Metabolic Quotient (qCO_2); Microbial Quotient (qMIC)

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The UC soils had higher qCO_2 compared to other land-use systems at all sites except for Dormaa and Dodowa where the highest values were recorded in the CT soils. The qCO_2 ranged from 0.006 in Bawku CT to 0.181 in Kade UC. The CT soils recorded the lowest flush of CO_2-C and highest was in the UC soils with values ranging from 66.0 mg kg^{-1} in Dormaa CT to 484.1 mg kg^{-1} in Dodowa UC. The UC soils recorded higher MBC:MBN ratio compared to the other land-use systems at all sampling sites, except for Walewale and Dormaa WL and Kade CT soils where the highest were recorded. The MBC:MBN ratio of the soils ranged from 0.271 in Kade UC to 5.899 in Dormaa WL. The UC soils recorded higher qMIC compared to other land-use systems at all sampling sites, except for Dormaa, Sunyani and Dodowa which had higher values in the WL soils. The qMIC of the soils ranged from 3.5 in Bawku WL to 26.7% in Dormaa WL across the land-use systems.

4.2 Land-use effect on carbon pools in the soils

4.2.1 Effect of land-use systems on soil carbon pools

Figure 4.1 shows the impact of land-use on the HWEOC, POX-C, HCl-C and Non HCl-C in soils at the time of sampling. The HWEOC, POX-C, HCl-C and Non HCl-C varied across ecological zone and land-use. The savannah zones (both Interior and Coastal) showed somewhat higher HWEOC and POX-C contents, with a land-use effect that followed the trend: CT > WL > UC and CT > UC > WL, respectively. The SD zone recorded the highest HCl-C, and the CS zone recorded the highest Non HCl-C values with a land-use effect following the trend: WD > UC > CT and CT > UC > WL, respectively.

In the IS zone, the carbon pools for all land-use systems ranged between 1.199 and 8.778, 2.290 and 4.041, 51.720 and 74.294 and 25.705 and 48.280 % TC for the HWEOC, POX-C, HCl-C and Non HCl-C, respectively in Bawku and between 2.859 and 8.333, 3.881 and 5.939, 36.996 and 51.080 and 49.864 and 63.003 g % TC for the HWEOC, POX-C, HCl-C and Non HCl-C, respectively in Walewale.

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In the TZ zone, the carbon pools for all land-use systems ranged between 1.393 and 2.843, 2.501 and 3.390, 46.981 and 60.762 and 39.237 and 53.158 % TC for the HWEOC, POX-C, HCl-C and Non HCl-C, respectively in Dormaa and between 1.360 and 3.560, 1.844 and 4.666, 35.869 and 60.017 and 39.982 and 63.329 % TC for the HWEOC, POX-C, HCl-C and Non HCl-C, respectively in Sunyani

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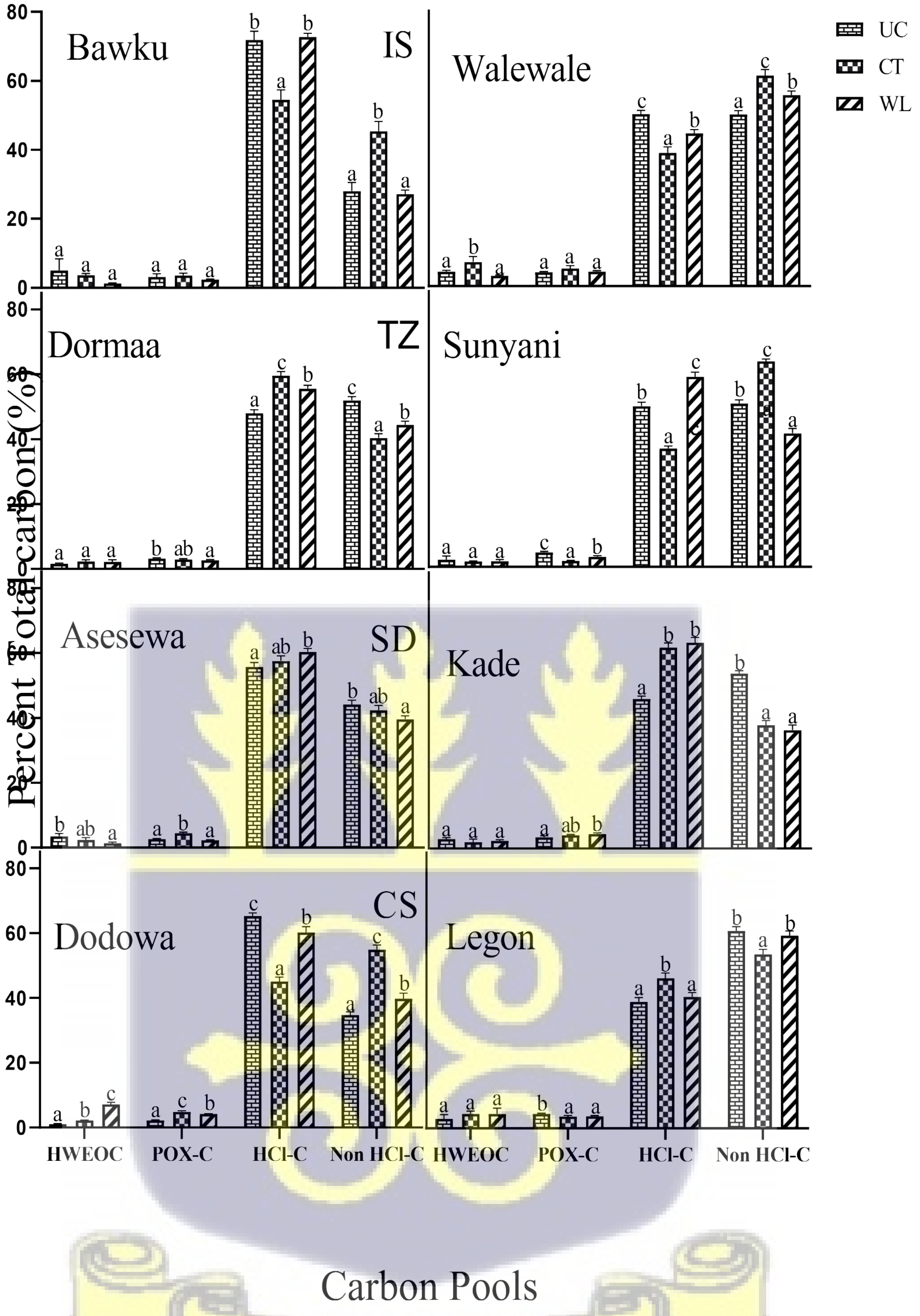

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Fig 4. 1: Carbon pools (HWEOC: hot water extractable OC; POX-C: potassium permanganate oxidizable C; HCl-C: HCl hydrolysable C; Non HCl-C: non HCl hydrolysable C) in g kg^{-1} of TC in soils under different land-use systems Interior savannah (IS); Forest-savannah transition (TZ); Semi-deciduous Forest zone (SD); Guinea Savannah zone (GS); Coastal Savannah zone (CS); Uncultivated land (UC); Cultivated land (CT); Woodlot (WL). Means with the same letters (within each pool) do not differ significantly among themselves

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In the SD zone, the carbon pools for all land-use systems ranged between 1.184 and 4.297, 2.296, 54.468 and 61.343 and 39.505 and 45.531 % TC for the HWEOC, POX-C, HCl-C and Non HCl-C, respectively in Asesewa and between 1.349 and 3.365, 3.172 and 4.748, 45.177 and 64.901 and 35.098 and 54.822 % TC for the HWEOC, POX-C, HCl-C and Non HCl-C, respectively in Kade

In the CS zone, the carbon pools for all land-use systems ranged between 0.956 and 7.820, 2.195 and 5.150, 43.671 and 66.139 and 33.860 and 56.328 % TC for the HWEOC, POX-C, HCl-C and Non HCl-C, respectively in Dodowa and between 2.106 and 5.873, 3.377 and 4.620, 37.810 and 47.748 and 52.251 and 62.189 % TC for the HWEOC, POX-C, HCl-C and Non HCl-C, respectively in Legon.

4.2.2 Relationship among soil texture on carbon pools

Figure 4.2 shows the relationship between soil textural attributes and carbon pools. The soil Clay/OC ratio had significant ($p \leq 0.0001$) inverse relationship with the HWEOC, POX-C, HCl-C and Non HCl-C. The Silt/OC and Clay + Silt/OC also had a significant inverse relationship with HWEOC. POX-C, HCl-C and Non HCl-C. The Clay + Silt/OC accounted for about 22, 64, 49 and 34% variations in the soils HWEOC, POX-C, HCl-C and Non HCl-C, respectively.

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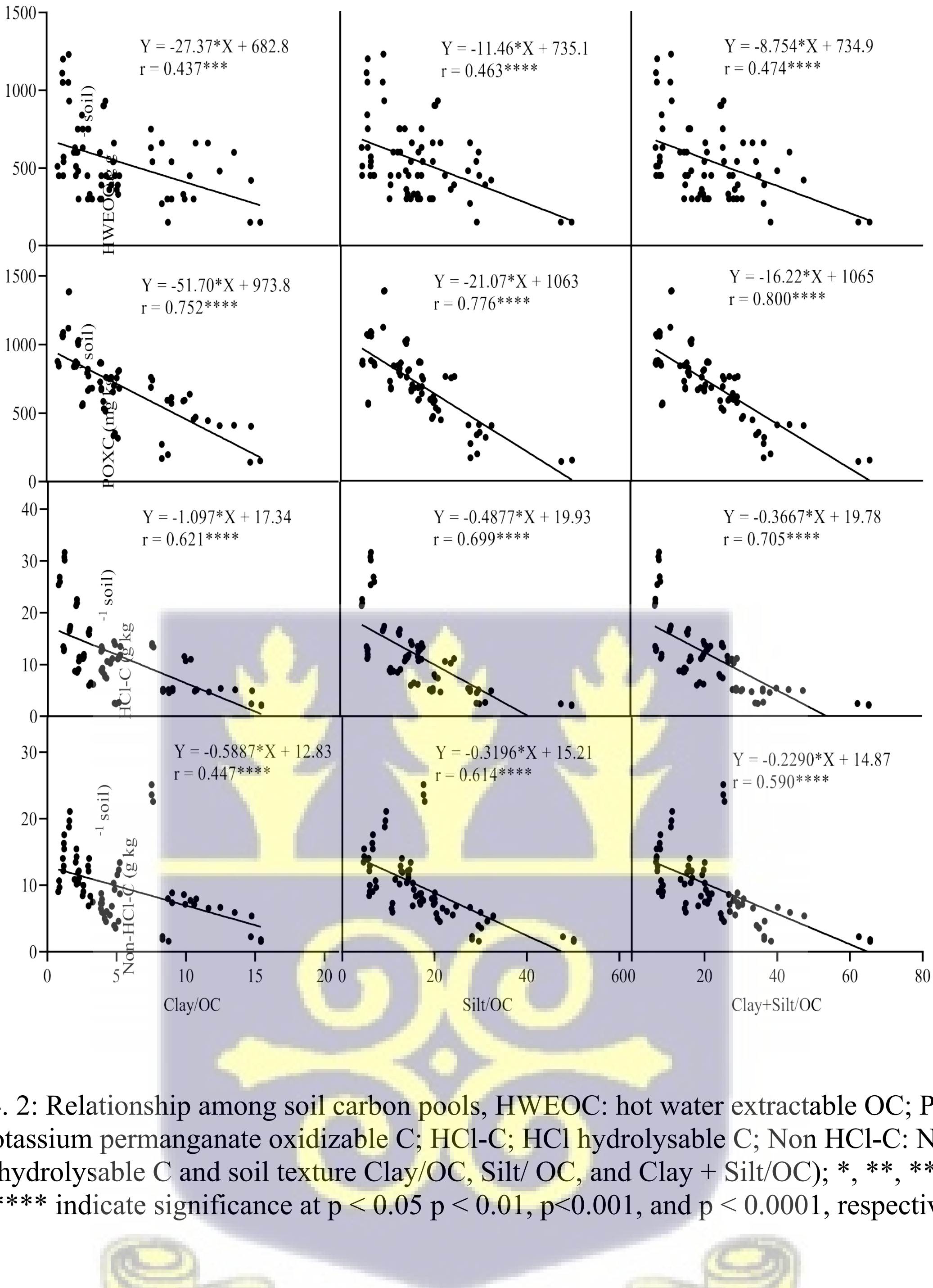

Fig 4. 2: Relationship among soil carbon pools, HWEOC: hot water extractable OC; POX-C: potassium permanganate oxidizable C; HCl-C; HCl hydrolysable C; Non HCl-C: Non HCl hydrolysable C and soil texture Clay/OC, Silt/ OC, and Clay + Silt/OC); *, **, *** and **** indicate significance at $p < 0.05$ $p < 0.01$, $p<0.001$, and $p < 0.0001$, respectively.

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4.2.3 Relationship among oxalate and dithionite extractable aluminium and iron and carbon pools

Figure 4.3 shows relationship among Al_{ox} and Al_d, and HWEOC, POX-C, HCl-C and Non HCl-C contents of the soils. The Al_{ox} and Al_d had a non-significant ($p > 0.05$) weak relationship with the HWEOC. POX-C. HCl-C and Non HCl-C in the soils.

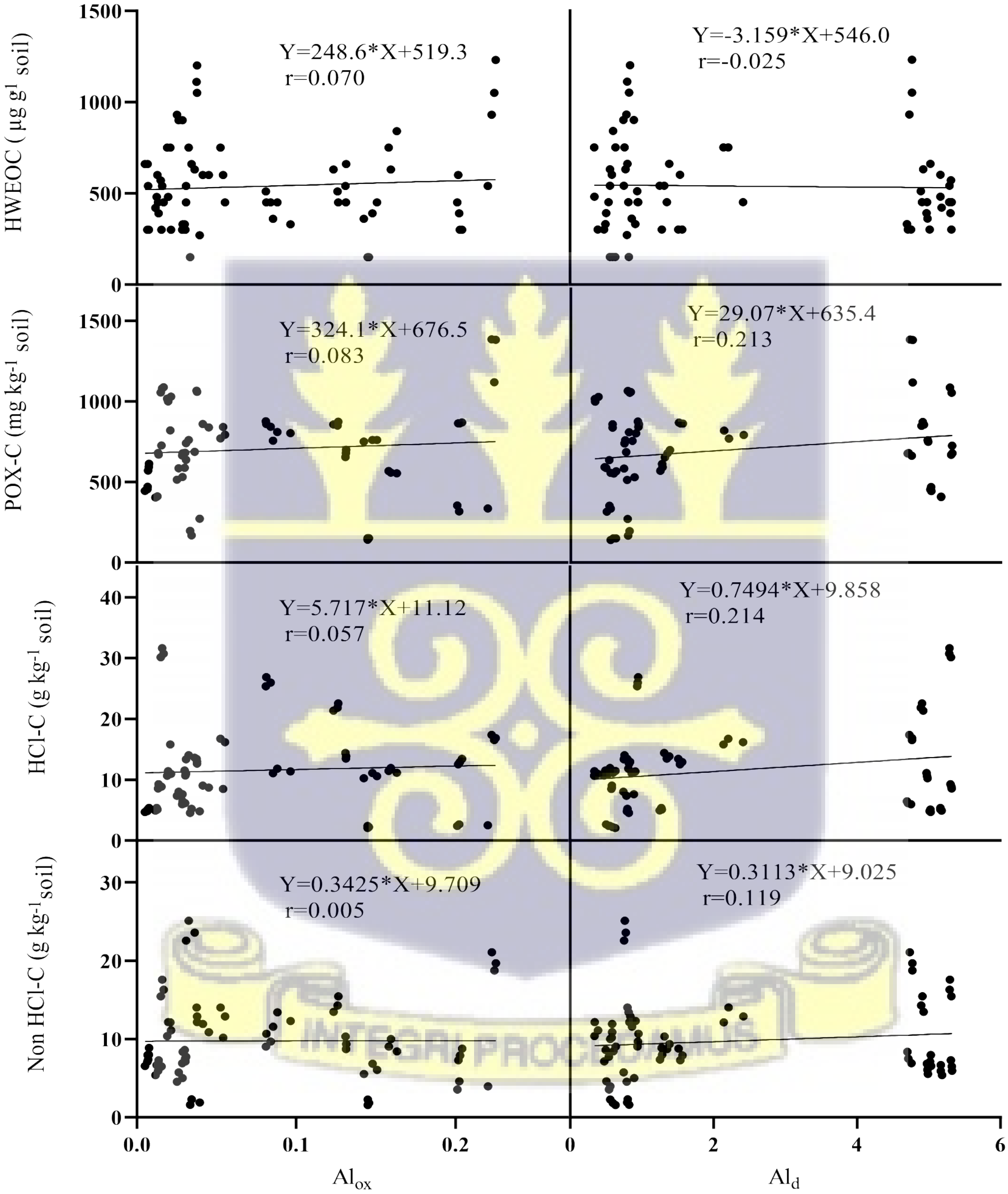

Fig 4. 3: Relationship among carbon pools (HWEOC, POX-C, HCl-C and Non HCl-C) and oxalate and dithionite extractable Al (Al_{ox}) and (Al_d).

The relationship between soil organic carbon fractions and Fe_{ox} and Fe_d is shown in Fig 4.4 below. The Fe_{ox} and Fe_d showed a significant ($p < 0.05$) moderate correlation with POX-C, HCl-C and Non HCl-C in the soils, except that of Fe_{ox} and HWEOC.

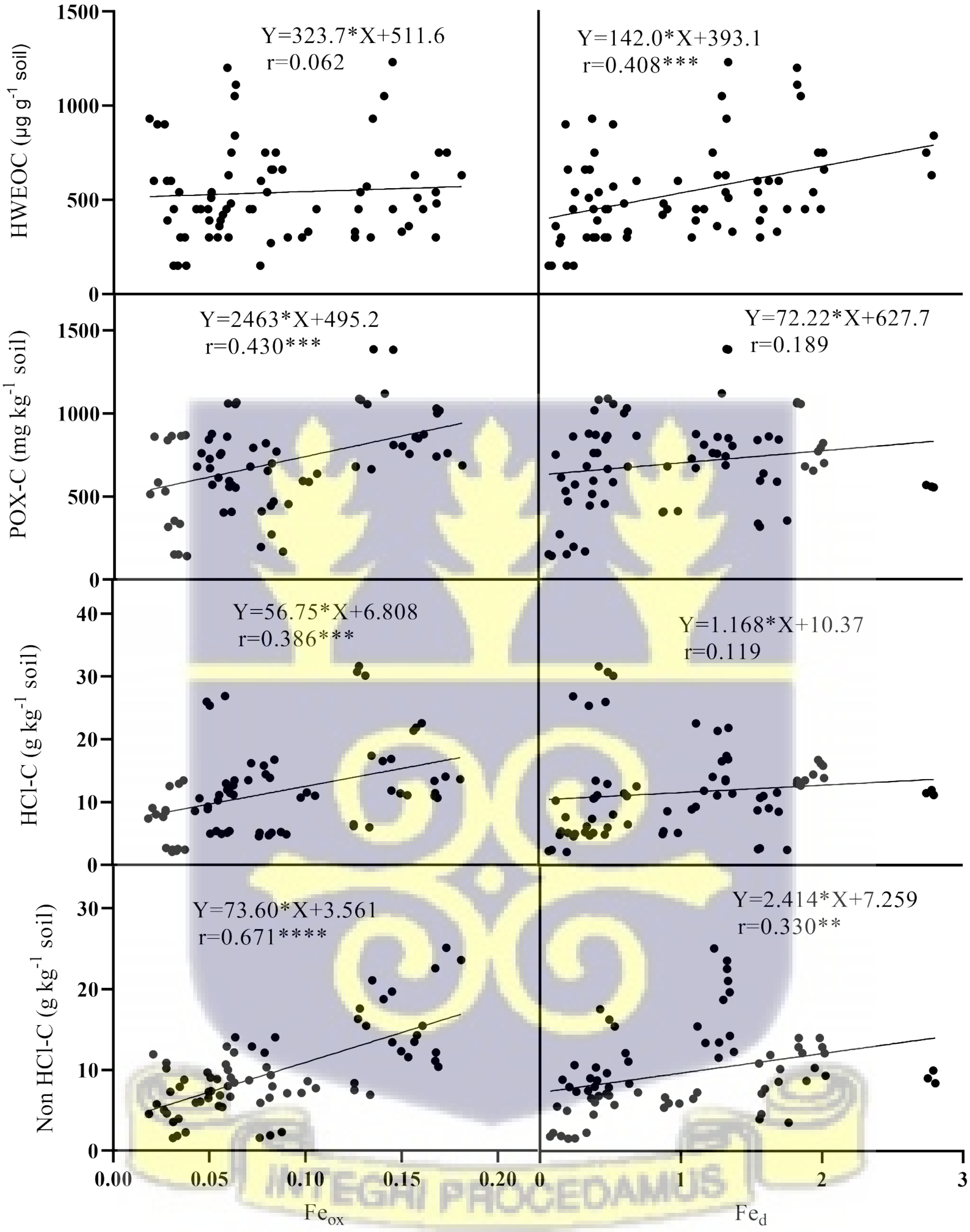

Fig 4. 4: Relationship among carbon pools (HWEOC, POX-C, HCl-C and Non HCl-C) and oxalate and dithionite extractable Fe (Fe_{ox}) and (Fe_d); *, **, *** and **** indicates significance at $p < 0.05$, $p < 0.01$, $p < 0.001$, and $p < 0.0001$, respectively.

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4.2.4 Variation in carbon during the incubation

The C content was highest in TZ and lowest in IS (Fig 4.5). The savannah zones (both IS and CS) showed somewhat lower C than TZ and SD zones. For the CS, Legon site had the lowest C, with values remaining at about 10 g kg^{-1} soil throughout the incubation period. Overall, on average, C content was highest under UC lands followed by the WL lands and then CT lands. Within the IS zone, the lowest C was observed in the CT soils, and highest in the WL and UC soils. Bawku WL showed an initial rapid drop in TC from 36 to 20 g kg^{-1} soil and remained study thereafter. For the UC and CT soils, the C content remained low at 10 g kg^{-1} soil. The C content in Walewale soils showed great impact of land-use where the UC soils had the highest C content of about 35 g kg^{-1} soil with no variation with time, whereas CT recorded 10 g kg^{-1} soil.

The TZ zone presented the highest C in the WL and UC soils of Dormaa and Sunyani among the land-use systems. Dormaa recorded C values in the range of 18.22 to 31.61 g kg^{-1} soil in the CT and UC soils, respectively. Sunyani recorded C values in the range of 14.51 in the WL to 37.44 g kg^{-1} soil in and UC soils.

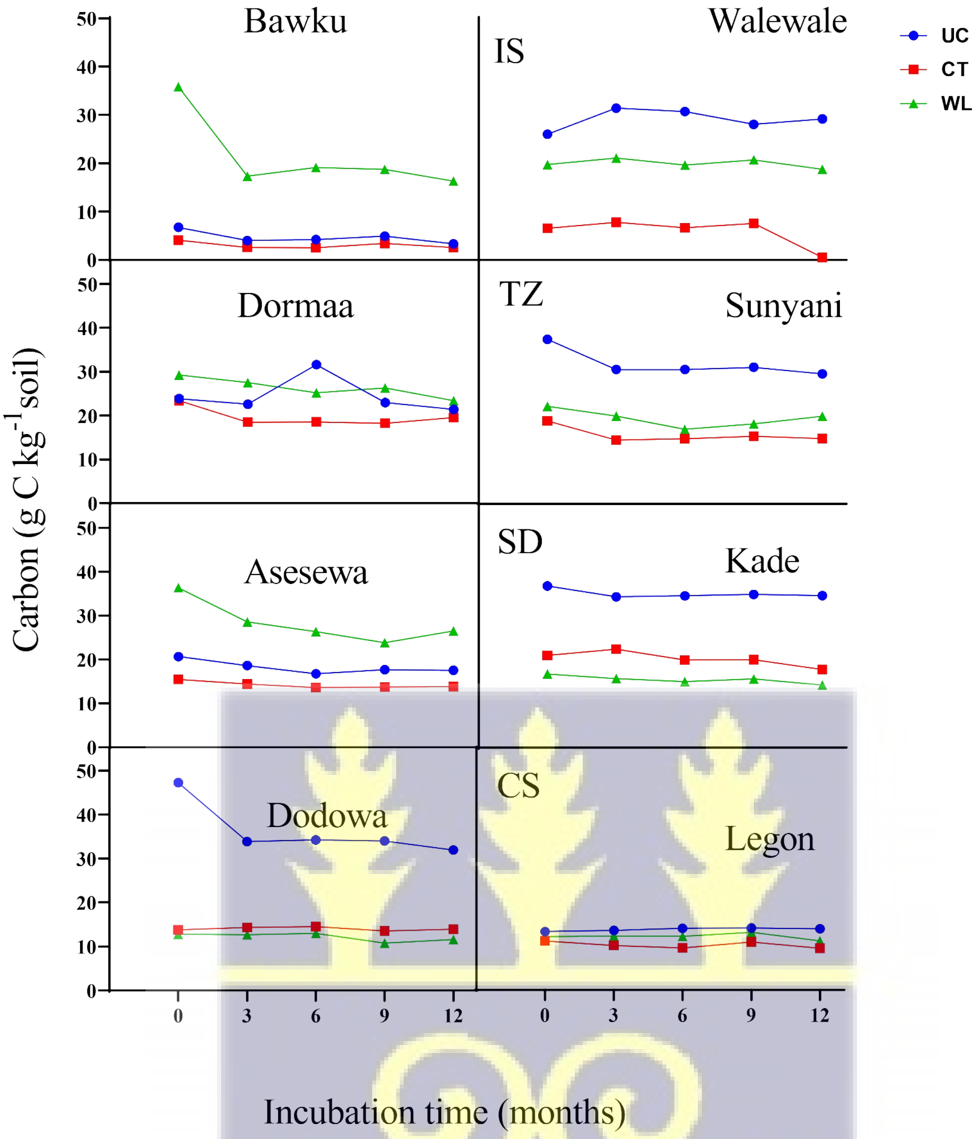

Fig 4. 5: Changes in the total carbon content of soils under different land-use systems during the year-long incubation study. Interior savannah (IS); Forest-savannah transition (TZ); Semi-deciduous Forest zone (SD); Guinea Savannah zone (GS); Coastal Savannah zone (CS); Uncultivated land (UC); Cultivated land (CT); Woodlot (WL).

In the SD zone, Asesewa recorded C values in the range of 13.65 in the CT to 36.32 g kg^{-1} soil in the WL respectively. Kade recorded C values in the range of 14.23 in the WL to 36.76 g kg^{-1} soil in the UC soils at the end and beginning the incubation study, respectively.

The CS zone presented the highest accumulated C values in the UC and lowest in the WL and CT soils of Dodowa and Legon, respectively among the land-use systems. Dodowa in

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the CS zone had high C of 10.77 in the WL to 47.27 g kg^{-1} soil in the UC soils.

4.2.5 Variation of carbon fractions during the incubation

4.2.5.1 Hot water extractable C (HWEOC)

Figure 4.6 shows the effect of land-use systems (UC, CT, and WL) on the HWEOC in soils from the different agro-ecological zones over one year incubation (Fig 4.2). except for Legon, there was a steep decline in the HWEOC content during the first quarter of incubation period, followed by a steady decline in the second quarter, and an upward adjustment to end of the incubation period. The soils from the savannah zones (Interior, Coastal) recorded the highest HWEOC. Soils from the TZ and SD zones showed a steady decline up to the first half of the incubation period, then increased gradually to the end of the incubation. They also recorded the lowest HWEOC in the soils.

Within the IS zone, HWEOC in Bawku ranged from 10.40 in the WL soil to 50.80 g kg^{-1} in the UC soils. Walewale on the other hand recorded HWEOC that ranged from 11.62 in the UC soil to 43.07 g kg^{-1} in the UC soil. By the end of the second quarter to the end of the incubation period, the UC soil recorded the lowest HWEOC of 18.68 g kg^{-1} among the land-use systems.

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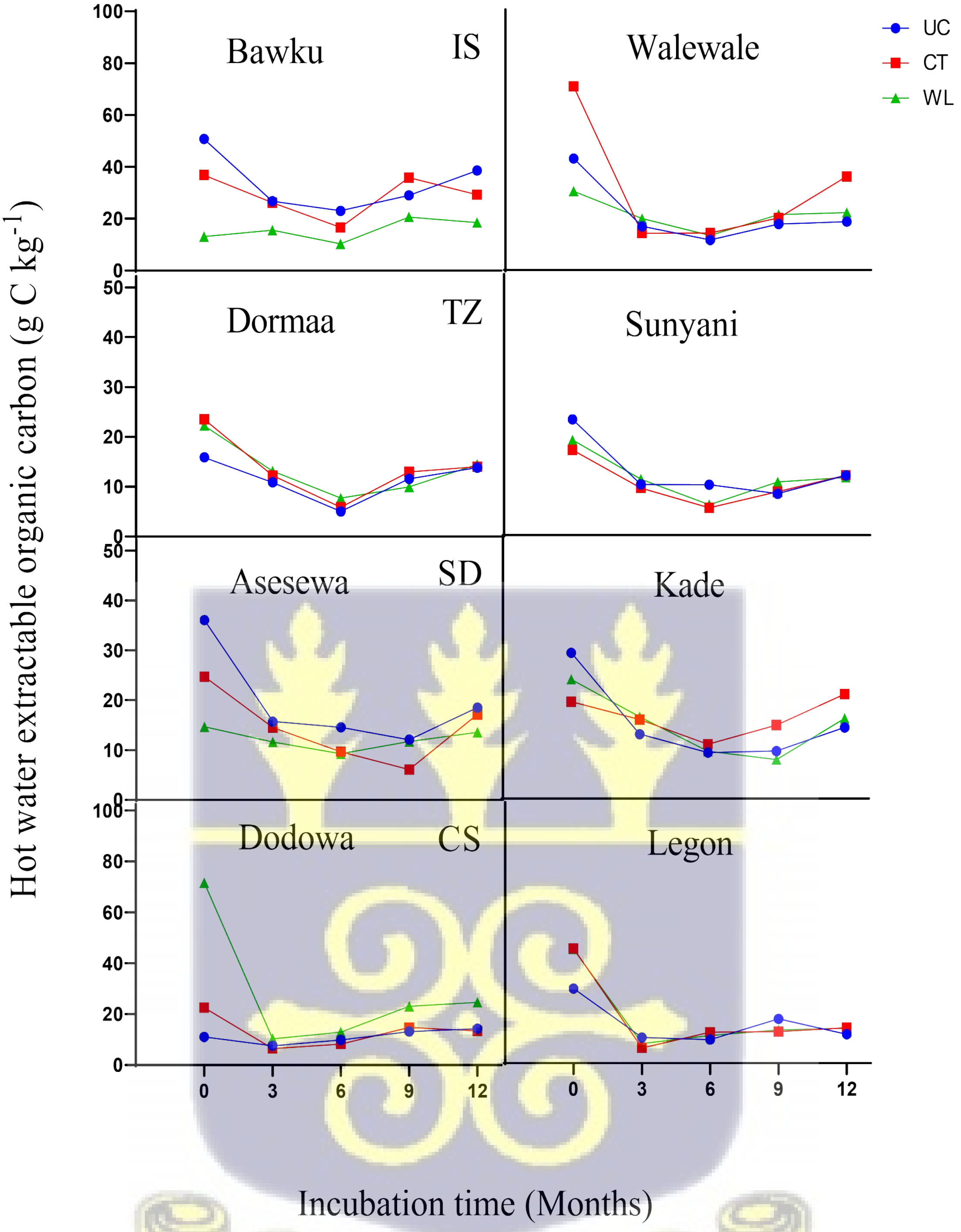

Fig 4. 6: Changes in the hot water extractable carbon (HWEOC) in soils under different land-use systems during the year-long incubation study. Interior savannah (IS); Forest-savannah transition (TZ); Semi-deciduous Forest zone (SD); Guinea Savannah zone (GS); Coastal Savannah zone (CS); Uncultivated land (UC); Cultivated land (CT); Woodlot (WL). Values are means and bars standard error of three replicates.

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The TZ showed land-use effect on HWEOC in Dormaa and Sunyani, with values ranging from 5.0 to 23.5 g kg^{-1} TC. The HWEOC dropped from 15.89 to 5, from 22.24 to 7.69 and from 23.52 to 5.87 g kg^{-1} at the end of the first half of incubation period and then increased to 13.78, 14.47 and 13.96 g kg^{-1} by the end of the incubation, in the UC, WL and CT respectively in Dormaa. Sunyani, on the other hand recorded a land-use effect that followed the trend: UC > WL > CT. The HWEOC dropped from 23.2 to 8.3, 19.09 to 6.12 and 17.04 to 5.5 g kg^{-1} at the end of the first half of the incubation period and then increased to 11.98, 11.57 and 12.01 g kg^{-1} by the end of the incubation, in the UC, WL and CT, respectively.

Among the land-use systems the highest HWEOC was recorded in the UC soil in Asesewa in the SD zone, with values ranging from 6.09 in the CT to 36.09 g kg^{-1} in the UC. The HWEOC of the CT soils dropped from 24.7 g kg^{-1} to an all-time low of 6.09 g kg^{-1} TC by the 3rd quarter, then rose to 17.15 g kg^{-1} by the end of the incubation period. The initial HWEOC in g kg^{-1} followed the trend: UC > WL > CT soil at Kade. The end of the first quarter showed an opposite trend with UC soil recording the lowest and the CT soil the highest HWEOC. The HWEOC ranged from 7.81 in the WL to 29.2 g kg^{-1} in the UC.

Among the land-use system in the CS zone, the Dodowa and Legon WL soils recorded the highest HWEOC, whereas their UC soils recorded the lowest HWEOC values. Dodowa recorded HWEOC ranging from 6.45 in the CT to 71.59 g kg^{-1} in the WL, and Legon recorded a range from 5.99 in the CT to 45.04g kg^{-1} in the CT.

4.2.5.2 Potassium permanganate oxidizable carbon (POX-C)

The effect of land-use systems (UC, CT, and WL) on POX-C in soils is shown in Fig 4.7. Overall, the first quarter of the incubation period witnessed a steep decline in POX-C values followed by a steady increase which peaked at the last quarter of the incubation. Agro-ecolo-

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gical zones had significant effect ($p < 0.05$) on the POX-C content of the soils, with the savannah zones (Interior, Coastal) recording fluctuation throughout the incubation period. The highest POX-C were recorded in the IS zone and the lowest in the TZ zones.

Within the IS zone, the mean POX-C fluctuated between 53.52 g kg^{-1} in the WL to 1.05 g kg^{-1} in the CT in Bawku during the entire incubation period. Among the land-use systems, the CT soil recorded the highest POX-C (36.39 g kg^{-1}) while WL recorded the lowest (24.01 g kg^{-1}) at the initial stage of the incubation. By the end of the first quarter of the incubation, a reverse was observed with WL recording the highest (53.52 g kg^{-1}). The POX-C for all Land-use recorded the lowest mean POX-C values in the 1st and 3rd quarter of the incubation period. The POX-C recorded in Walewale ranged from 71.56 in the CT to 3.79 g kg^{-1} in the UC. Among the land-use, the CT soils recorded the highest mean value while the UC soils recorded the lowest.

There was an effect of land-use on POX-C in the TZ zone. The UC soils recorded the highest POX-C in g kg^{-1} and the CT soils, the lowest. Though UC recorded the highest POX-C (33.13 g kg^{-1}) at the initial stage of incubation in Dormaa, a reverse was observed by the 1st quarter (4.26 g kg^{-1}) through to the 3rd quarter (21.97 g kg^{-1}) and then back to the original trend by the end of the incubation period. The POX-C ranged from 4.17 g kg^{-1} in the CT to 45.78 g kg^{-1} TC in the UC in Sunyani. The CT initially dropped from 19.48 to 4.17 g kg^{-1} by the end of the first quarter, then increased to 32.01 g kg^{-1} TC by the 3rd quarter, then to 28.47 g kg^{-1} at the end. Sunyani by the 3rd quarter recorded the higher POX-C (41.61 g kg^{-1}) in the WL compared to the UC soils (39.75 g kg^{-1}) and this continued to the end of the incubation period.

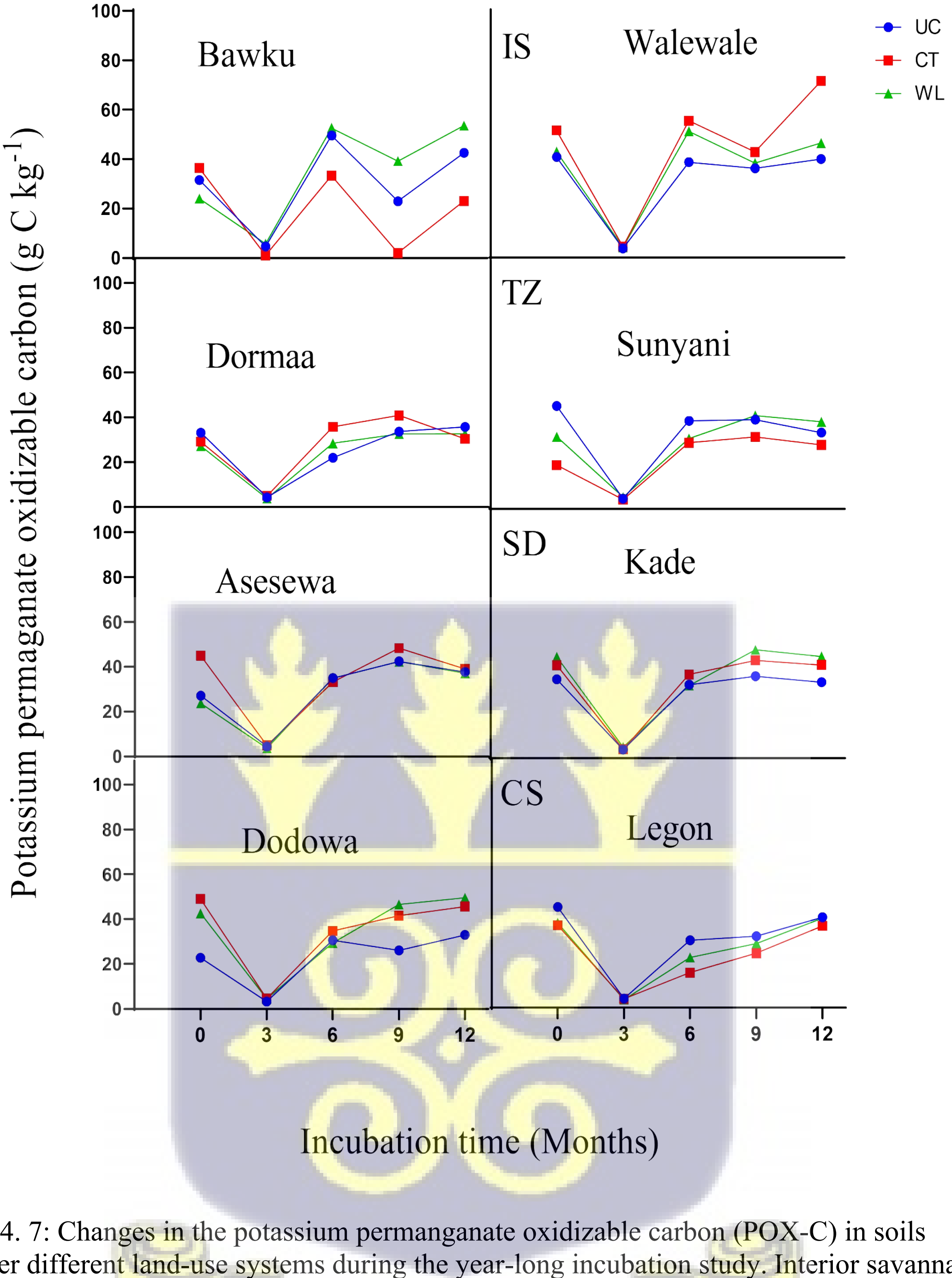

Fig 4. 7: Changes in the potassium permanganate oxidizable carbon (POX-C) in soils under different land-use systems during the year-long incubation study. Interior savannah (IS); Forest-savannah transition (TZ); Semi-deciduous Forest zone (SD); Guinea Savannah zone (GS); Coastal Savannah zone (CS); Uncultivated land (UC); Cultivated land (CT); Woodlot (WL). Values are means and bars standard error of three replicates.

The SD zone showed a land-use effect on POX-C, with the CT lands recording the highest POX-C compared to the WL and UC soils in Asesewa. The POX-C values in Asesewa fluctuated in the 1st half of the incubation period from 44.89 g kg^{-1} in the CT to 4.89 g kg^{-1}, then

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plateaued by the 3rd quarter at about 48.28 g kg^{-1} TC, before slowly declining to about 39.01 g kg^{-1} by the last quarter. However, though CT land at Asesewa recorded the highest POX-C at the initial stage, by the end of the 2nd quarter, the UC land recorded the highest (34.97 g kg^{-1}) then reverted to the CT (39.01 g kg^{-1}) for the rest of the incubation period. Kade on the other hand recorded the highest POX-C of 45.16 g kg^{-1} in WL soil at the initial stage, 5.04 g kg^{-1} at the 2nd, 48.30 g kg^{-1} at the 3rd and 45.32 g kg^{-1} 4th quarter of the incubation period. The CS zone witnessed the lowest POX-C of 3.24 g kg^{-1} in Dodowa UC at the 1st quarter of incubation. The CT soil in Dodowa recorded the highest POX-C value (49.02 g kg^{-1}) at the initial stage. By the 3rd and last quarter, the WL recorded the highest POX-C content, with mean values ranging from 46.52 and 49.50 g kg^{-1}, respectively. The land-use effect observed at Legon showed the UC soils recording the highest POX-C whiles the CT soils recorded the lowest ranging from 44.84 g kg^{-1} in the UC at the initial stage to 3.99 g kg^{-1} in the CT by the end of the 1st quarter. There was an initial drop from 36.75 to 3.99 g kg^{-1} at the end of the 1st quarter, then a steady increase to 36.45 g kg^{-1} by the end of the incubation period in the CT.

4.2.5.3 6 M HCl hydrolysable carbon

Figure 4.8 shows the effect of Land-use (UC, CT, and WL) on the acid (6M HCl) hydrolysable C in the soils after a year of incubation. Overall, there were fluctuations of the mean HCl-C throughout the incubation period, leading to a gentle decline in HCl-C at the end of the incubation period. Agro-ecological zones show significant difference ($p < 0.05$), with the savannah zones (Interior, Coastal) recording UC > WL > CT with a few fluctuations along the incubation period.

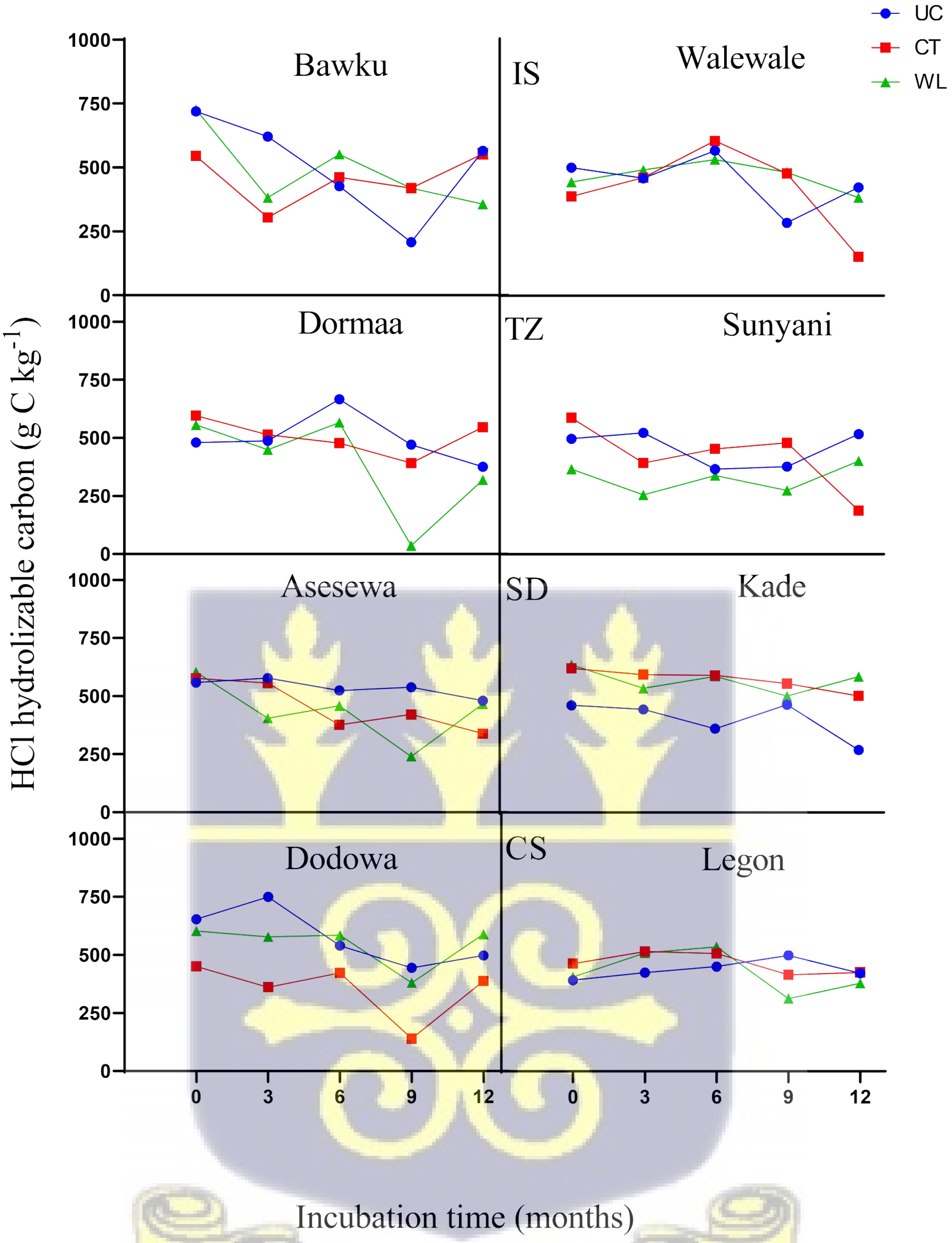

Fig 4. 8: Changes in the acid (6M HCl) hydrolysable C in soils under different land-use systems during the 365 days incubation study. Interior savannah (IS); Forest-savannah transition (TZ); Semi-deciduous Forest zone (SD); Guinea Savannah zone (GS); Coastal Savannah zone (CS); Uncultivated land (UC); Cultivated land (CT); Woodlot (WL). Values are means and bars standard error of three replicates.

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The IS zone presented the lowest HCl-C in the CT soil of Bawku and Walewale. Bawku recorded a decline in HCl-C from about 727 in the WL to 208 g kg^{-1} in the UC throughout the incubation period. The UC soil recorded a decline from the initial stage (719 g kg^{-1}) to the 3rd quarter (208 g kg^{-1}), the lowest HCl-C, followed by a steep increase to 565.6 g kg^{-1} TC in the last quarter. On the other hand, the CT soils recorded an increase from 304.8 to 554 g kg^{-1} during the 1st to the last quarters, with the 3rd quarter recording the highest HCl-C among the Land-uses. Among the Land-use in Walewale, the HCl-C showed a fluctuation from about 388 to 604 g kg^{-1} by the end of the 2nd quarter in the CT, followed by a decline to about 152 g kg^{-1} by the end of the incubation.

The CT soil at Dormaa in the TZ zone showed a steady decline in the HCl-C from an initial high value of about 596 g kg^{-1} to about 391 g kg^{-1} by the 3rd quarter, followed by a rise to 546 g kg^{-1} at the end of the incubation period. The WL fluctuated between 555 to 566 g kg^{-1} by the 2nd quarter, and then a decline to about 36 g kg^{-1} by the 3rd quarter before steeply increasing to 319 g kg^{-1} TC towards the end. Among the Land-use at Sunyani, the WL soils recorded the lowest HCl-C during the entire incubation period. The CT soil started with the highest HCl-C (587 g kg^{-1}), then dropped to about 393 g kg^{-1} by the 1st quarter before increasing to about 478 g kg^{-1} by the 3rd quarter of the incubation period. This was followed by a drop in value to about 188 g kg^{-1} by the end of the incubation period.

The SD zone showed a typical Land-use effect on the HCl-C observed at Asesewa, where the UC soil recorded the highest HCl-C the entire incubation period with values ranging from about 558 to 480 g kg^{-1}. Although the WL soils started with a higher HCl-C value (604 g kg^{-1}), it dropped to 466 g kg^{-1} by the end of the incubation. Kade showed an inverse of what was observed at Asesewa, with the UC soil recording the lowest HCl-C, with a steady decline from about 461 to 269 g kg^{-1} whiles the CT recorded the highest values the entire incubation period.

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Among the Land-uses in the CS zone, Dodowa, showed the highest HCl-C in the UC soils and the lowest in the CT soils. The HCl-C in UC soils rose from about 653 to 750 g kg^{-1} by the 1st quarter, followed by a steady decline to about 444 g kg^{-1} by the 3rd quarter and then rose again to 497 by the end of the incubation period. At Legon, it was observed that the CT soils recorded the highest HCl-C among the Land-uses. It rose from 462 to 514 g kg^{-1} by the 1st quarter, followed by a slow decline to about 415 g kg^{-1} by the 3rd quarter, then a slight increase to about 425 g kg^{-1} by the end of the incubation period. The UC soils on the other hand witnessed a steady rise in the HCl-C values from about 391 to 498 g kg^{-1} by the 3rd quarter where it peaked, then slowly declined to about 421 g kg^{-1} at the end of the incubation.

4.2.5.4 Non-HCl hydrolysable carbon

Figure 4.9 shows the effect of land-uses (UC, CT, and WL) on the non-hydrolysable C (non HCl-C) in soils. The non HCl-C in the soils also fluctuated throughout the entire incubation period, though it exhibited an upward trend generally. Among the agro-ecological zones, the TZ zone recorded the highest non HCl-C values, followed by the savanna zone and then the SD forest zone.

The IS zone showed the highest non HCl-C in the CT soils of Bawku and Walewale. Although the UC soils started with a lower non HCl-C in Bawku, it rose steadily from 280 to 792 g kg^{-1} by the 3rd quarter (9th month) of the incubation period. Thereafter, the values declined to about 434 g kg^{-1} at the end of the incubation. The CT and WL soils recorded fluctuations in non HCl-C values during the entire incubation period, with values ranging between 272 to 642 in the WL and 446 to 695 g kg^{-1} in the CT. Walewale recorded fluctuations in non HCl-C among the Land-uses, with values between in 396 in the CT to 716 g kg^{-1} in the UC during the entire incubation period.

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The TZ showed the CT soils in Dormaa recording the highest non HCl-C and the lowest in the CT soil at the initial stage of incubation. The non HCl-C in the CT soil rose steadily from 404 to 609 g kg^{-1} by the 3rd quarter, the dropped to 454 g kg^{-1} by the end of incubation. The UC and WL soils dropped to about 400 g kg^{-1} by the 2nd quarter, then rose steadily to about 680 g kg^{-1} by the end of the incubation. Sunyani recorded the highest non HCl-C in the WL soil ranging from 634 to 745 g kg^{-1}. The CT and UC soils recorded fluctuations in non HCl-C values between 412 to 726 g kg^{-1}.

The SD zone presented the lowest non HCl-C in UC soils at Asesewa, even though it started as the highest (442 g kg^{-1} TC) at the initial stage of the incubation. The non HCl-C value of WL soils, increased between 396 to 759 g kg^{1} by the 3rd quarter then dropped to 533 g kg^{1} at the end of the incubation. All the Land-uses showed an upward trend in the non HCl-C values, with the UC soils recording the highest and the CT soils the lowest values at Kade. The non HCl-C content of the Kade soils ranged from 365 in the WL to 730 g kg^{-1} in the UC.

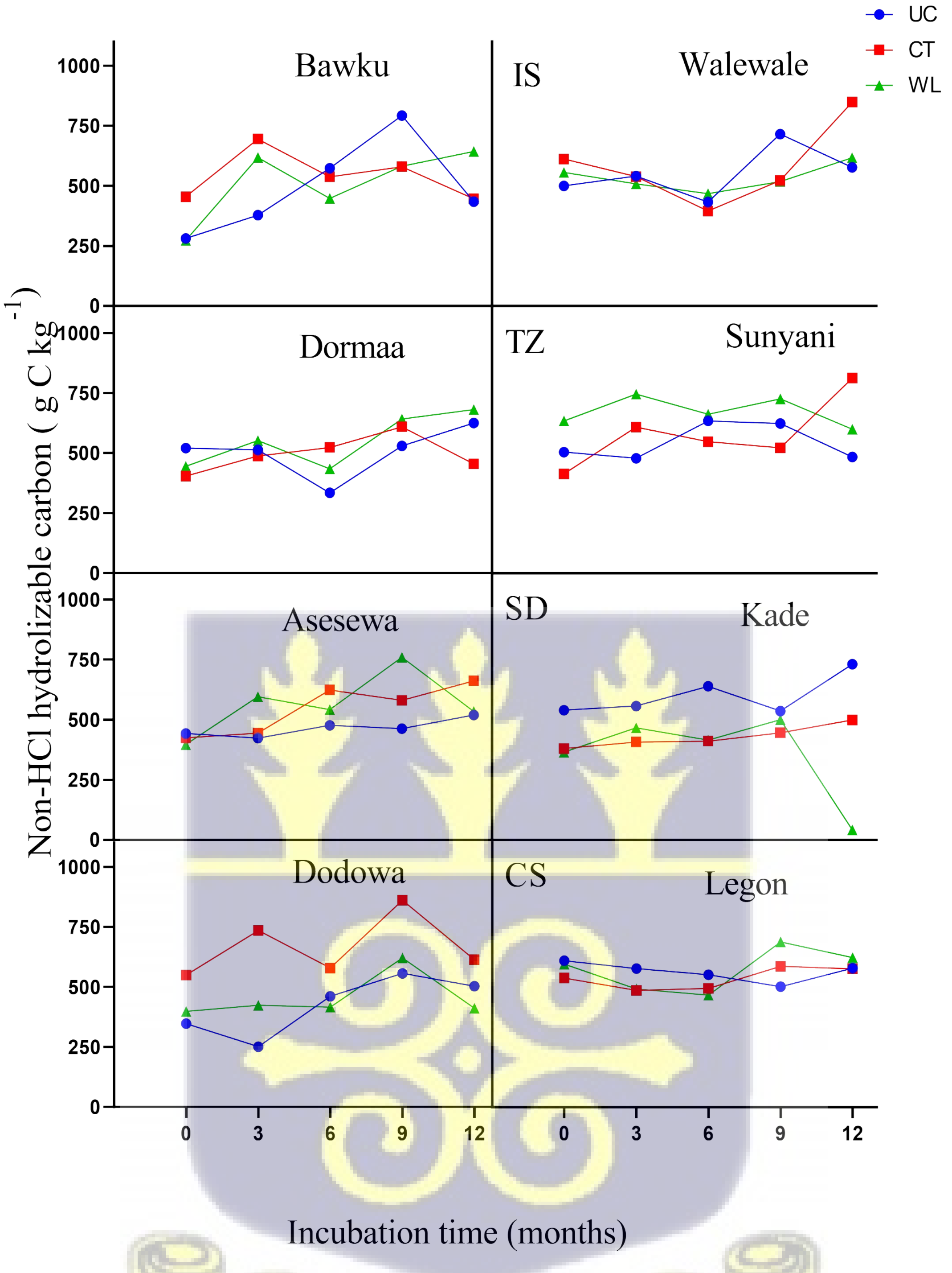

Fig 4. 9: Changes in the total carbon in soils under different land-use systems after HCl hydrolysis during the year-long incubation study. Interior savannah (IS); Forest-savannah transition (TZ); Semi-deciduous Forest zone (SD); Guinea Savannah zone (GS); Coastal Savannah zone (CS); Uncultivated land (UC); Cultivated land (CT); Woodlot (WL). Values are means and bars standard error of three replicates.

The CT zone presented the highest non HCl-C in the CT soils of Dodowa. The CT soils showed fluctuations in non HCl-C values between 549 to 735 g kg^{-1} TC the entire incubation

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period. The WL, and UC soils also showed fluctuations in values between 250 to 620 g kg^{-1} TC throughout the incubation period. The effect of the Land-use systems at Legon showed the UC soil recording the highest non HCl-C and the CT soils recording the lowest. The non HCl-C content of UC soils slowly declined from 609 to 501 g kg^{-1} TC by the 3rd quarter, then rose to 578 g kg^{-1} TC by the end of the incubation period.

4.3 Land-use effect on microbial activities

4.3.1 Dynamics of microbial biomass carbon (MBC$_{mic}$)

The effect of different land-uses (UC, CT, and WL) on the changes in MBC$_{mic}$ of soils from the various agro-ecological zones are shown in Fig. 4.10. There was a sharp drop in MBC$_{mic}$ by the end of the 1st quarter, followed by fluctuations until the end of the incubation period. Among the land-uses MBC$_{mic}$ followed the trend UC > WL > CT. The highest MBC$_{mic}$ was observed in the TZ zone, whiles the IS recorded the lowest MBC$_{mic}$.

The IS zone showed a fluctuation in the MBC$_{mic}$ values from the initial stage to the 3rd quarter of the incubation period. During this period the MBC$_{mic}$ values in the WL soils of Bawku were between 1000 and 85 µg g^{-1} soil. Thereafter, the value increased to about 700 µg g^{-1} soil in the WL soils of Bawku. The MBC$_{mic}$ in the CT soil and dropped from 480 and 79 µg g^{-1} by the 1st quarter, after which it rose steadily to 245 µg g^{-1} by the 3rd quarter, then dropped to 154 µg g^{-1} soil at the end of the incubation period. The UC soils in Walewale recorded a drop in the MBC$_{mic}$ from 1461 and 534 µg g^{-1} soil. The CT soil recorded fluctuation in the MBC$_{mic}$ between 699 and 433 µg g^{-1} soil the entire incubation period.

In the TZ, WL soils of Dormaa showed the highest MBC$_{mic}$ values. The MBC$_{mic}$ in the WL soils decreased from 7486 and 929 µg g^{-1} soil by the 1st quarter, after which it fluctuated between 929 and 758 µg g^{-1} soil up to the end of the incubation period. The MBC$_{mic}$ values of CT soils also dropped from 3213 to 368 µg g^{-1} soil by the 1st quarter, followed by fluctuations

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between 368 to 446 μg g^{-1} soil by the end of the incubation. The UC soils at Sunyani recorded a drop in the MBC_{mic} values from 6165 to 788 μg g^{-1} soil by the 1st quarter, by the 3rd quarter, it experienced a rise from 609 to 813 μg g^{-1} soil. The MBC_{mic} values CT soils started as the lowest at 3161 μg g^{-1}, then rose to 4410 μg g^{-1} by the 1st quarter. Thereafter, it declined to 260 μg g^{-1} soil by the 3rd quarter and then increased to 885 μg g^{-1} at the end of the incubation.

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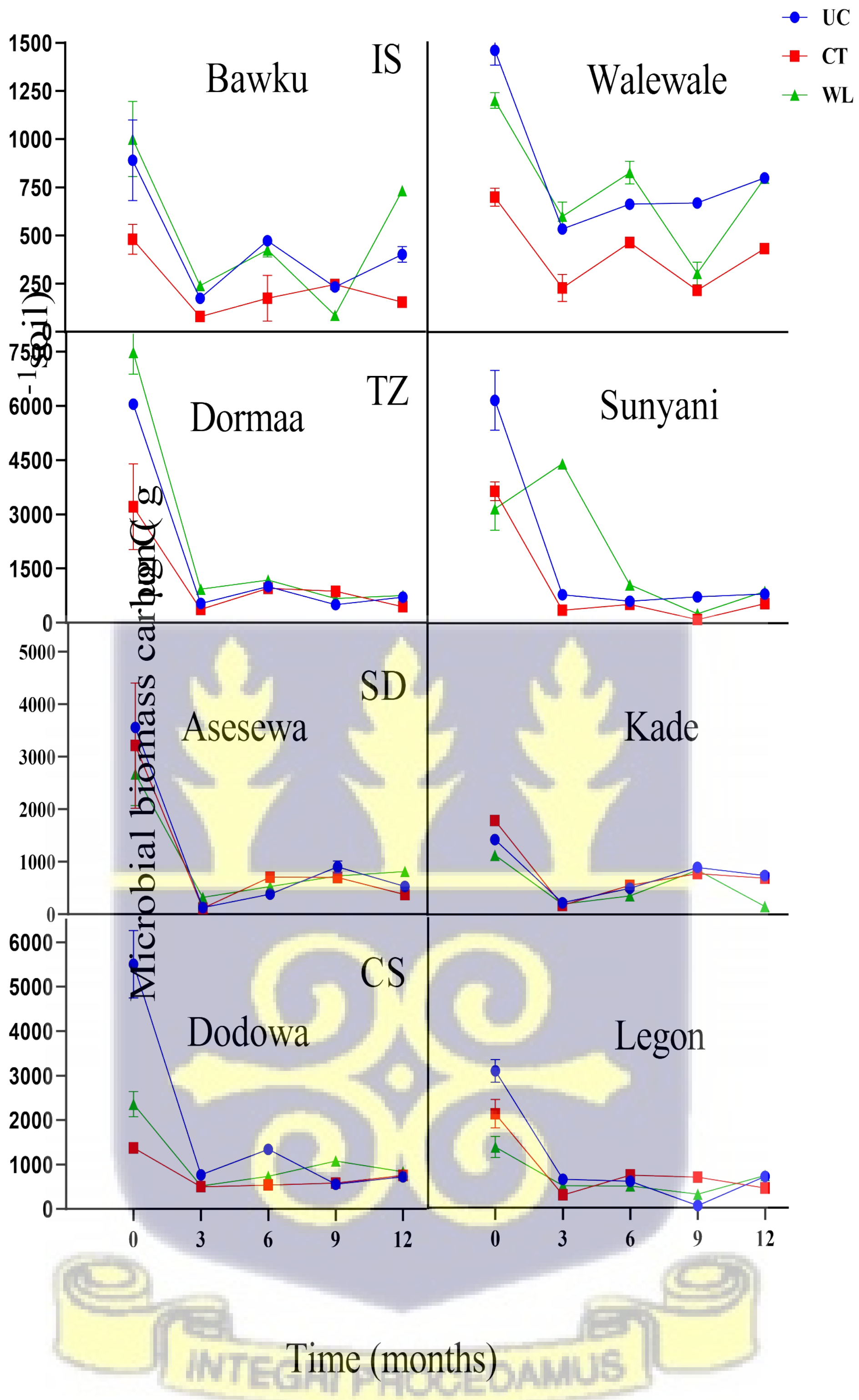

Fig 4. 10: Dynamics of microbial biomass carbon (MBC_{mic}) under different land-use systems after 365-day incubation study. Interior savannah (IS); Forest-savannah transition (TZ); Semi-deciduous Forest zone (SD); Guinea Savannah zone (GS); Coastal Savannah zone (CS); Uncultivated land (UC); Cultivated land (CT); Woodlot (WL). Values are means and bars standard error of three replicates.

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In the SD zone, the UC soils of Asesewa showed the highest MBC_{mic}. The MBC_{mic} in the UC soils decreased from 3555 to 124 µg g^{-1} soil by the 1st quarter, after which it increased to 900 µg g^{-1} soil by the 3rd quarter, and then dropped to 531 µg g^{-1} soil by the end of the incubation period. The CT soils also dropped from 3211 to 111 µg g^{-1} soil by the 1st quarter, followed by a steady rise to 704 by the 2nd quarter, then decreased to 375 µg g^{-1} soil by the end of the incubation. The UC soil at Kade recorded a drop in the MBC_{mic} from 1425 to 222 µg g^{-1} soil by the 1st quarter, at the 3rd quarter, it rose to 898 µg g^{-1} soil, then a declined to 741 µg g^{-1} soil at the end of the incubation period. The CT soil started as the highest value of 1783 µg g^{-1} soil, the dropped to174 µg g^{-1} soil by the 1st quarter. Thereafter, it increased to 778 µg g^{-1} soil by the 3rd quarter and then dropped to 692 µg g^{-1} soil by the end of incubation.

Within the CS zone, UC soils of Dodowa and Legon showed the highest MBC_{mic}. The MBC_{mic} in the UC soil at Dodowa decreased from 5507 to 766 µg g^{-1} soil by the 1st quarter, after which it fluctuated between 554 to 1339 µg g^{-1} soil by the end of incubation period. The CT soil also dropped from 1373 to 499 µg g^{-1} soil by the 1st quarter, followed by an increase to 755 µg g^{-1} soil by the end of the incubation. The CT soils at Legon recorded a drop in the MBC_{mic} value from 2115 to 289 µg g^{-1} soil, followed by an increase to 738 µg g^{-1} soil by the 2nd quarter, then a steady drop to 445 µg g^{-1} soil by the end of the incubation.

4.3.2 The dynamics of microbial biomass nitrogen

The effect of different Land-uses (UC, CT, and WL) on the changes in microbial biomass N (MBN_{mic}) of soils from various agro-ecological zones was a significant ($p < 0.05$). There was a decline in MBN_{mic} by the end of the 1st quarter. Thereafter, the MBN_{mic} remained stable till the end of 2nd quarter, then increased by the 3rd quarter, and then decreased by the end of the incubation period. Among the land-uses, MBN_{mic} followed the trend: UC > WL > CT. The

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highest MBN_{mic} was observed in the Semi-deciduous forest zone, whiles the lowest was recorded in the Interior savannah zone.

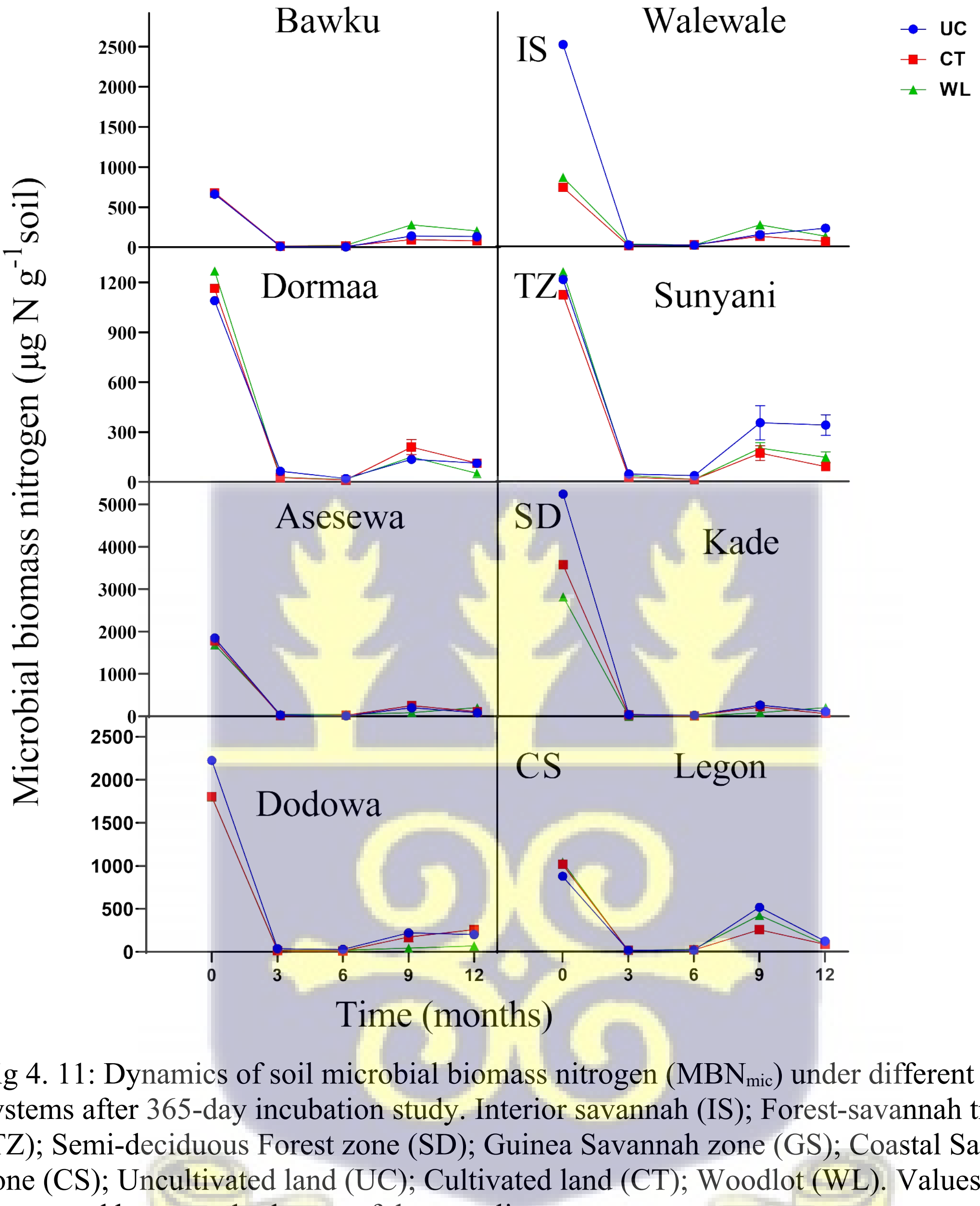

Fig 4. 11: Dynamics of soil microbial biomass nitrogen (MBN_{mic}) under different land-use systems after 365-day incubation study. Interior savannah (IS); Forest-savannah transition (TZ); Semi-deciduous Forest zone (SD); Guinea Savannah zone (GS); Coastal Savannah zone (CS); Uncultivated land (UC); Cultivated land (CT); Woodlot (WL). Values are means and bars standard error of three replicates.

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In the Interior savannah zone Bawku UC and WL had the lowest and highest MBN_{mic}, respectively. The Land-uses showed high MBN_{mic} values being 662, 677 and 673 μg g^{-1} soil for the UC, CT, and WL soils respectively at the initial stage of incubation. Following this, the MBN_{mic} declined significantly ($p > 0.05$) drop to about 9 μg g^{-1} soil, after which it remained

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stable by the 2nd quarter. Thereafter, the MBN_{mic}, fluctuated between 4.7 to 204 µg g^{-1} soil up to the end of the incubation period. The UC soil in Walewale recorded the highest MBN_{mic}, but this declined significantly from 2115 to 17.4 µg g^{-1} soil by the 1st quarter. By the end of the incubation, the values increased from about 16 to 225 µg g^{-1} soil. The CT soil dropped significantly from 733 to 6.5 µg g^{-1} soil by the 1st quarter and fluctuated between 6.5 to 125 µg g^{-1} soil from the 2nd quarter to the end of incubation study.

In the Forest-savannah transition zone, CT soils of Dormaa and Sunyani showed the highest MBN_{mic} than the other two land-use. The MBN_{mic} in the UC soil at Dormaa recorded a significant drop from 1090 to 64 µg g^{-1} soil by the 1st quarter, after which it fluctuated between 19.9 and 136.5 µg g^{-1} soil by the end of the incubation study. The CT soil also showed a significant decline in MBN_{mic} from 11164 to 24.7 µg g^{-1} soil, after which it fluctuated between 11.3 to 209.4 µg g^{-1} soil by the end of the incubation. Sunyani recorded the lowest MBN_{mic} in the CT. For the Sunyani UC there was a significant drop in the MBN_{mic} from 1213 to 44.2 µg g^{-1} soil by the 1st quarter, after which values fluctuated between 34.2 to 337 µg g^{-1} soil by the end of the incubation study. The WL soil showed a significant drop in the MBN_{mic} from 1259 to 34.8 µg g^{-1} soil by the 1st quarter, after which it fluctuated between 12.6 to 200.6 µg g^{-1} soil by the end of the incubation studies.

In the Semi-deciduous forest zone, the WL of Asesewa showed the highest MBN_{mic} values. The MBN_{mic} in the UC dropped significantly from 1846 to 29 µg g^{-1} soil by the 1st quarter at Asesewa, after which it fluctuated between from 8 to 199 µg g^{-1} soil by the end of the incubation. The MBN_{mic} values in the CT decreased from 1779 to 12.3 µg g^{-1} soil by the 1st quarter, after which it fluctuated between 23.7 to 247.8 µg g^{-1} soil by the end of incubation study. In the Kade soils, the UC soils showed the highest MBN_{mic}. Kade recorded MBN_{mic} values in the range of 6.5 to 304.1 µg g^{-1} soil in the woodlot soil at the 3rd and before the incubation study respectively.

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The Coastal savannah zone showed UC soils of Dodowa recording the highest MBN_{mic} values in the among the land-uses. The MBN_{mic} in the UC soil dropped significantly ($p>0.05$) from 2224 to 38.4 μg g^{-1} soil by the 1st quarter at Dodowa, after which it fluctuated between 29.3 to 222.3 μg g^{-1} soil by the end of the incubation. The MBN_{mic} values of CT decreased from about 1800 to 13.8 μg g^{-1} soil by the 1st quarter, then slowly increased from 9.3 to 259.3 μg g^{-1} soil by the end. The WL at Legon recorded the highest MBN_{mic} means among the Land-uses. The MBN_{mic} in the WL soil significantly dropped from 1040 to 13.1μg g^{-1} soil by the 1st quarter, after which it fluctuated between 30.6 to 422.3 μg g^{-1} soil by the end of the study. The UC soil also showed a significant drop from 874 to 13.8 μg g^{-1} soil by the 1st quarter, then fluctuated between 16.3 to 514.1 μg g^{-1} soil from the 2nd quarter to the end of the study.

4.3.3 The dynamics of mineralized nitrogen of soils

Figure 4.12 indicated that with regard to different Land-uses (UC, CT, and WL) on the changes in the mineralized N of soils from various agro-ecological zones, a sharp drop in the 1st quarter was observed in the savannah zones (Interior, Coastal), which was followed by a slow fall by the 2nd quarter. Thereafter, there was a sharp rise in N by the end of the incubation period. The mineralized N in the Forest savannah transition and Semi-deciduous forest zones witnessed a downward trend up to the 3rd quarter, after which it rose to the end of the incubation period. The highest N was observed in the Forest savannah transitional zone (TZ), whiles the lowest was recorded in the Interior savannah zone (IS). Among the land-uses, the UC had highest mineral N followed by WL then CT.

In the Interior savannah zone, the WL of Bawku, and UC soils of Walewale showed the highest mineralized N. Although initially the highest (23.53 mg kg^{-1} soil) at the beginning of the incubation studies, the UC soil at Bawku fluctuated between 1.53 and 10.95 mg kg^{-1} soil

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by the 3rd quarter. Following this, it rose to 4.15 mg kg^{-1} soil by the end of the incubation. The mineral N in CT soil declined towards the 3rd quarter of the incubation period from 23.48 to 1.36 mg kg^{-1} soil. The UC soil in Walewale recorded a drop in the mineralize N from 24.29 to 12.83 mg kg^{-1} soil by the 1st quarter, it then remained relatively stable in the 2nd quarter. Following this, it fluctuated between 12.67 and 24.24 mg kg^{-1} soil at the incubation study. The CT soil also showed a significant drop in the mineralized N from 23.17 to 1.96 mg kg^{-1} soil by the 3rd quarter, then rose to 7.39 mg kg^{-1} soil by the end of the study.

In the Forest-savannah transition zone, the WL of Dormaa and UC soils of Sunyani showed the highest mineral N. Dormaa recorded a rise in mineralize N in the UC soil from 24.82 to 27.01 mg kg^{-1} soil by the 1st quarter. This was followed by a drop to 2.35 mg kg^{-1} soil by the 3rd quarter, then an increase to 10.64 mg kg^{-1} soil at the end of the incubation. The CT soil showed a rise from 24.22 to 26.87 mg kg^{-1} soil by the 1st quarter, then fluctuated between 3.54 and 9.29 mg kg^{-1} soil from the 2nd quarter to the end of the incubation. Sunyani observed close range differences among the Land-uses within the 3 quarters of the incubation studies. The UC soil showed a decline from 24.81 to 4 mg kg^{-1} soil by the 3rd quarter, then increased to 15.41 mg kg^{-1} soil by the end. The CT soil also presented a significant ($p>0.05$) drop from 23.94 to 3 mg kg^{-1} soil by the 3rd quarter, then rose to 9.14 mg kg^{-1} soil at the end of the incubation.

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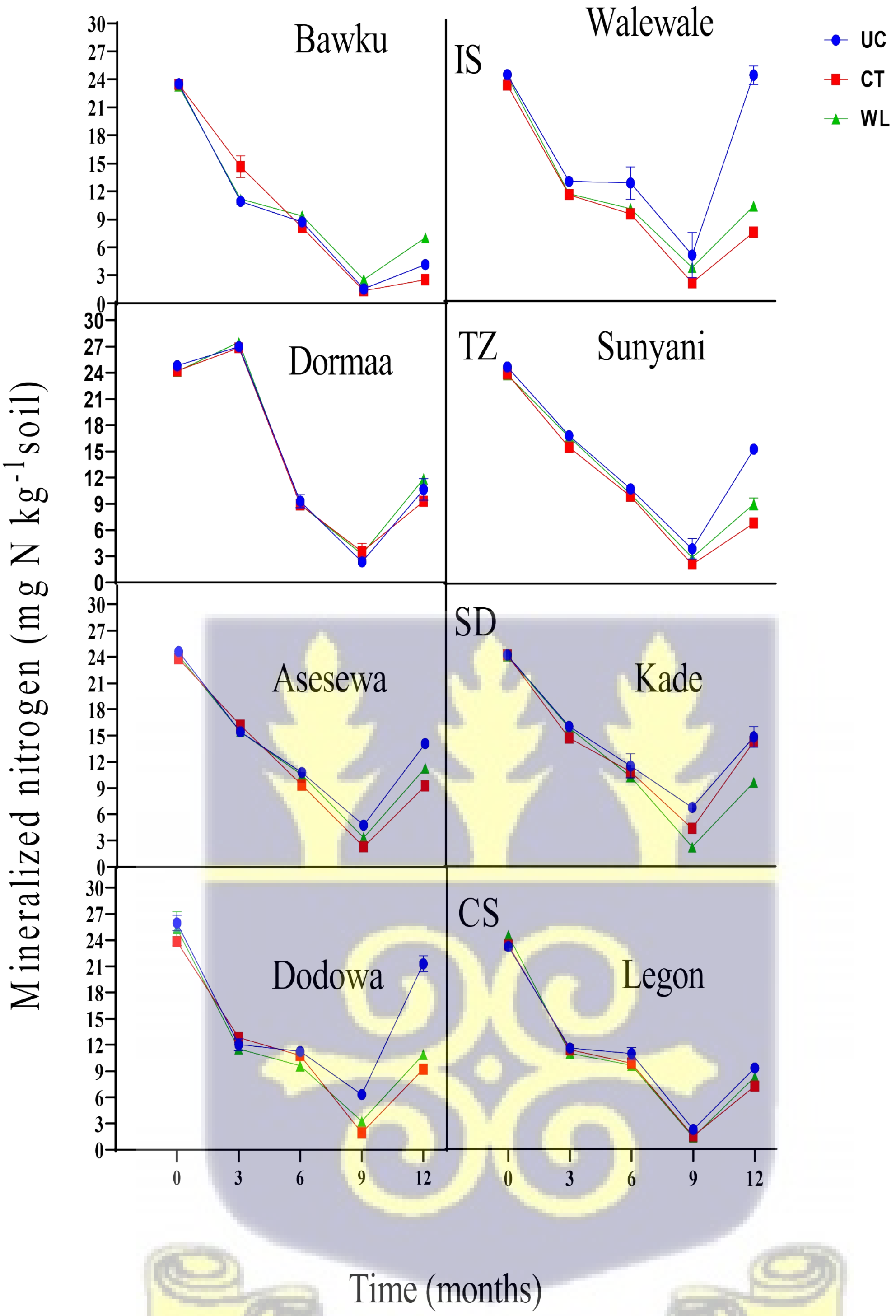

Fig 4. 12: Dynamics of mineralized nitrogen in soils under different land-use systems after 365-day incubation study. Interior savannah (IS); Forest-savannah transition (TZ); Semi-deciduous Forest zone (SD); Guinea Savannah zone (GS); Coastal Savannah zone (CS); Uncultivated land (UC); Cultivated land (CT); Woodlot (WL). Values are means and bars standard error of three replicates.

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In the Semi-deciduous forest zone, the UC soils of Asesewa and Kade showed the highest mineralized N values. The UC at Asesewa recorded a significant drop in mineralized N from 24.63 to 4.76 mg kg^{-1} soil by the 3rd quarter, then increased to 14.09 mg kg^{-1} soil by the end of the incubation. The WL recorded a significant drop in mineralized N from 24.17 to 3.31 mg kg^{-1} soil by the 3rd quarter, then increased to 11.30 mg kg^{-1} soil by the end of the incubation. The CT recorded a significant drop in mineralized N from 23.80 to 2.31 mg kg^{-1} soil by the 3rd quarter, then increased to 9.24 mg kg^{-1} soil by the end of the incubation. The UC at Kade recorded a significant drop in mineralized N from 24.18 to 6.73, then increased to 14.82 mg kg^{-1} soil by the end of the incubation. The WL also showed a significant drop in mineralized N from 24.07 to 2.19 and then increased to 9.62 mg kg^{-1} soil by the end of the incubation. The CT also showed a significant drop in mineralized N from 24.17 to 4.34 mg kg^{-1} soil by the 3rd quarter, then increased to 14.29 mg kg^{-1} soil by the end of the incubation.

In the Coastal savannah zone, the UC soils of Dodowa and Legon showed the highest mineralized N values among the land-uses. The UC at Dodowa recorded a significant decrease in the mineralized N from 25.96 to 6.33 mg kg^{-1} soil by the 3rd quarter, and then a rise to 21.28 mg kg^{-1} by the end of the incubation. The WL also recorded a significant decrease in the mineralized N from 25.33 to 3.26 mg kg^{-1} soil by the 3rd quarter, and then a rise to 10.92 mg kg^{-1} soil by the end of the incubation. The CT also recorded a significant decrease in the mineralized N from 23.83 to 1.96 mg kg^{-1} soil by the 3rd quarter, and then a rise to 9.24 mg kg^{-1} soil by the end of the incubation study. The UC at Legon recorded a significant decrease in the mineralized N from 23.19 to 2.26 mg kg^{-1} soil by the 3rd quarter, and then a rise to 9.29 mg kg^{-1} soil by the end of the incubation. The WL also showed a significant decreased in the mineralized N from 24.47 to 1.38 mg kg^{-1} soil by the 3rd quarter, then a rise to 8.28 mg kg^{-1} soil by the end of the incubation. The CT also showed a significant decreased in the mineralized N from

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23.34 to 1.47 mg kg^{-1} soil by the 3rd quarter, then a rise to 9 7.22 mg kg^{-1} soil by the end of the incubation.

4.3.4 Correlation among organic C fractions and microbiological indices

Fig. 4.13 show the correlation between MBC$_{mic}$ and POX-C and HWEOC. The POX-C had a significant ($p < 0.05$) positive relationship with MBC$_{mic}$ $r = 0.245^*$ and a non-significant ($p > 0.05$) relationship with HWEOC ($r = 0.055$).

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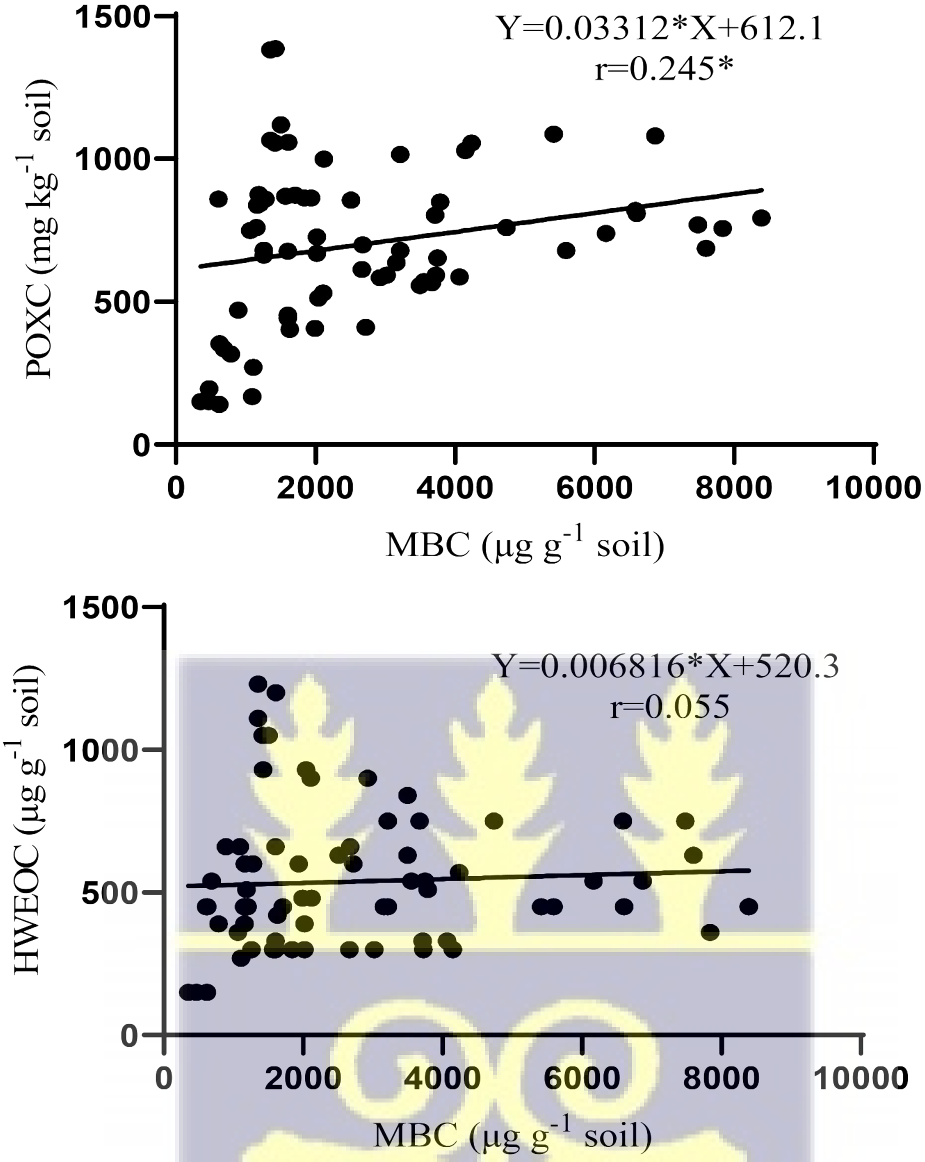

Fig 4.**13**: Pearson correlation between MBC_{mic} and POX-C and HWEOC in soils; *, **, *** and **** correlation significant at $p < 0.05$ $p < 0.01$, $p < 0.001$ and $p < 0.0001$ respectively

Table 4.5: Correlation among organic carbon fractions and some microbiological indices of the soils

	MBC_{mic}	MBN_{mic}	*POX-C*	*HWEOC*	*HCl-C*	*Non HCl-C*	*TC*	*BR*	qCO_2	C_{min}	*MBC:MBN*	*qMIC*	*qM*
MBC_{mic}	1												
MBN_{mic}	-0.083	1											
POX-C		0.634***	1										
HWEOC		0.472***	0.494***	1									
HCl-C	0.368**	0.309**	0.709***	0.231*	1								
Non HCl-C	0.515***	0.393***	0.848***	0.399***	0.638***	1							
TC	0.475***	0.380***	0.847***	0.333**	0.932***	0.874***	1						
BR	0.541***	0.587***	0.699***	0.408***	0.559***	0.750***	0.706***	1					
qCO_2	-0.352**	0.808***	0.561***	0.430***	0.211	0.320**	0.284*	0.484***	1				
C_{min}	0.316**	0.541***	0.806***	0.529***	0.688***	0.751***	0.788***	0.775***	0.460***	1			
MBC:MBN	0.908***	-0.366**	0.107	-0.124	0.153	0.370**	0.271*	0.256*	-0.524***	0.025	1		
qMIC	0.715***	-0.367**	-0.301**	-0.204	-0.202	-0.091	-0.170	0.012	-0.660***	-0.264*	0.773***	1	
qM	-0.200	0.074	-0.132	0.236*	-0.227	-0.201	-0.238*	0.059	0.196	0.278*	-0.297*	-0.127	1

MBC_{mic}: microbial biomass C, MBN_{mic}: microbial biomass N, MBC:MBN:, qMIC: microbial quotient, qM: mineralization quotient, C_{min}: cumulative C mineralized, POX-C: potassium permanganate oxidizable organic C, HWEOC: hot water extractable organic C, HCl-C: HCl hydrolysable organic C, Non HCl-C: Non-HCl hydrolysable organic C. *, ** and *** correlation significant at $p < 0.05$ $p < 0.01$and $p < 0.001$ respectively

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Table 4.8 summarizes results for all correlations among the different soil properties measured. The highest correlation coefficient of r = 0.932*** was observed between HCl-C and TC across the study. Generally, OC fractions and the microbiological characteristics were significantly and positively correlated, except for correlation between MBC and MBN, MBC and SOC and qM, which were negatively correlated. These correlations ranged from very weak to very strong. Among the microbiological indices, the highest correlation of r = 0.908*** was recorded between MBC_{mic} and MBC:MBN and the lowest was between BR and qMIC (r = 0.012). A negative correlation was recorded between MBC, MBN, qCO_2 and qM; MBC: MBN, MBN, qCO_2 and qM; qMIC, MBN, qCO_2, C_{min} and qM.

4.4 Land-use effect on the C mineralization dynamics

4.4.1 CO_2 fluxes

The cumulative carbon dioxide-C (CO_2-C) evolved under the different land-use systems during the 365 days incubation is presented in Fig.4.14. Generally, the effect of ecological zone was significant, with the savannah zone showing lower CO_2-C evolution compared to the Forest-transition and Semi-deciduous zones. Bawku soils recorded the lowest CO_2-C. The land-use significantly ($p < 0.05$) influenced the CO_2-C evolved during the incubation period. The CT soils recorded the lowest whilst UC soils recorded the highest values in all sites. The trend observed in CO_2-C evolution was as follows: UC > WL> CT.

In the Interior savannah zones (Bawku, Walewale), Bawku had cumulative CO_2-C values ranging from 139.50 to 1525.53 mg CO_2-C kg^{-1} soil and Walewale recorded the highest cumulative CO_2-C in the UC in a range from 1225.06 to 3055.80 mg CO_2-C kg^{-1} soil.

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For the Forest-savannah transition soils (Dormaa, Sunyani), the highest cumulative CO_2-C values were for the UC soils with values ranging from 1228.29 to 1978.084 and 1021.816 to 2786.18 mg CO_2-C kg^{-1} soil in Dormaa and Sunyani, respectively. Semi-deciduous forest zone presented the highest cumulative CO_2-C values in the WL and UC soils of Asesewa and Kade, respectively compared to the other land-use systems. The CO_2-C evolved at Asesewa ranged from 1453.258 to 2601.875 mg CO_2-C kg^{-1} soil with the lowest in the CT soils. Kade recorded the lowest CO_2-C value in the WL soil, with values ranging from 1675.342 to 3400.229 mg CO_2-C kg^{-1} soil.

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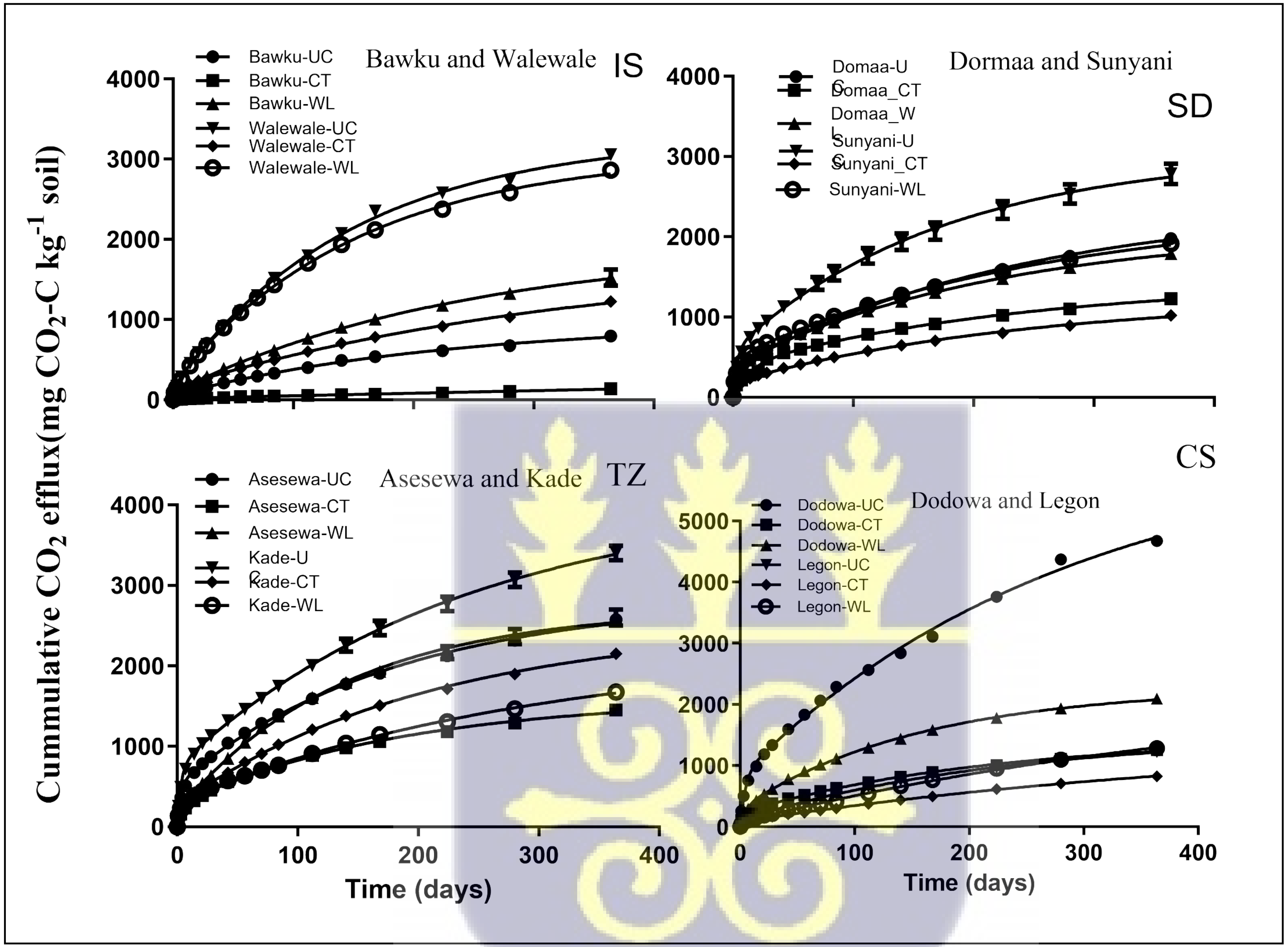

Fig 4. 14: Carbon mineralized (mg CO_2-C kg^{-1}) in soils under different land-use systems during the 365 days incubation study. Interior savannah (IS); Forest-savannah transition (TZ); Semi-deciduous Forest zone (SD); Guinea Savannah zone (GS); Coastal Savannah zone (CS); Uncultivated land (UC); Cultivated land (CT); Woodlot (WL).

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The Coastal savannah zone showed the lowest cumulative CO_2-C value in the cultivated soils of Dodowa and Legon compared to the other land-use systems. Dodowa had the highest CO_2-C in the UC soil, values ranging from 1256.072 to 4672.875 mg CO_2-C kg^{-1} soil. Legon recorded the highest CO_2-C value in the WL compared to the UC and CT soils and ranged from 823.526 to 1280.378 mg CO_2-C kg^{-1} soil.

4.4.2 Kinetic parameters of carbon mineralization

The effect of land-use systems on the kinetic parameters (C_0, C_1, C_2, k, k_1, k_2 and $t_{1/2}$ (half-lives)) of C mineralization in the soils from the different agro-ecological zones of Ghana are presented in Table 4.5. Overall, there was a significant ($p < 0.05$) effect of the land-uses on the C_0 (potential mineralizable C), C_1 (labile pool) and C_2 (stable pool) values, with the UC soils recording the highest compared to other land-uses.

The potential mineralizable C (C_0) values varied significantly ($p < 0.05$) from 200 to 4606 mg C kg^{-1} soil across the different land-uses, with the highest C_0 values were recorded in the UC soils of Walewale, Dormaa, Sunyani, Kade and Dodowa and the WL soils of Bawku, Asesewa and Legon, respectively.

The rate constant k varied from 0.003-0.014 day^{-1}, with Bawku, Walewale, Sunyani, Asesewa, Kade and Legon recording the highest k value (0.006, 0.008, 0.013, 0.013, 0.011 and 0.007 day^{-1}) in the UC soils, whereas the Dormaa and Dodowa recorded the lowest (0.010 and 0.008 day^{-1}).

The initial potential rate of C mineralized (C_0*k) values varied significantly ($p < 0.05$) from 0.59 to 38.77 mg kg^{-1} soil day^{-1}. The highest C_0*k value was recorded in the uncultivated soils of Walewale, Sunyani, Asesewa, Kade, Dodowa and Legon but in the woodlot soils of Bawku and Dormaa, respectively.

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The half-live ($t_{1/2}$) values ranged from 50.7 to 240.8 days. Bawku, Asesewa, Kade and Legon recorded the lowest values in the UC soils, Walewale and Dodowa in the wood-lot soils and Dormaa and Sunyani in the CT soils.

Table 4.6: Size, decomposition rates and half-lives of potentially mineralizable, labile, and stable C pools (C_o, k, C_l, k_l, C_s, and k_s, respectively) estimated by the first and double exponential models in soils under different land-use systems, Interior savannah (IS); Forest-savannah transition (TZ); Semi-deciduous Forest zone (SD); Guinea Savannah zone (GS); Coastal Savannah zone (CS); uncultivated land (UC), cultivated land (CT), and woodlot (WL) during the 365-days of incubation period.

Ecological Zone	Site	Land-use	First-order equation					Double-exponential equation						
			C_o	k	C_o*k	$t_{1/2}$	R^2	C_l	k_l	$t_{1/2}$	C_2	k_2 ($x10^{-4}$)	$t_{1/2}$	R^2
			(mg kg^{-1})	(day^{-1})	mg/kg/d	(day)		(mg kg^{-1})	(day^{-1})	(day)	(mg kg^{-1})	(day^{-1})	(day)	
IS	Bawku	UC	861b	0.006b	5.22b	115.1a	0.988	312b	0.017a	41.6b	5993b	2.34b	3214a	0.993
		CT	200a	0.003a	0.59a	240.9b	0.971	22a	0.046b	15.8a	3981a	0.79a	8770b	0.995
		WL	1737c	0.006b	9.40c	128.4ab	0.993	613c	0.015a	48.6b	34334c	0.76a	9194b	0.997
	Walewale	UC	3138c	0.008b	24.94b	87.2a	0.995	2066c	0.012a	58.42c	22974c	1.25a	5611c	0.996
		CT	1307a	0.006a	7.72a	117.6b	0.981	273a	0.047b	15.16a	5345a	5.56c	1250a	0.997
		WL	2887b	0.008b	23.98b	83.5a	0.995	1605b	0.015a	45.45b	16879b	2.17b	3189b	0.998
TZ	Dormaa	UC	1877c	0.010a	17.90a	73.2b	0.949	619a	0.072a	9.60ab	21872a	1.91c	3636a	0.988
		CT	1098a	0.014b	15.44a	50.7a	0.949	564a	0.052a	14.9b	22152b	0.88a	7967c	0.989
		WL	1622b	0.012ab	19.58a	57.4ab	0.917	616a	0.109b	6.40a	27462c	1.32b	5243b	0.984
	Sunyani	UC	2532c	0.013b	32.37c	54.3a	0.940	1117c	0.062a	11.29c	34653c	1.48b	4686b	0.984
		CT	946a	0.010a	9.34a	70.3b	0.938	319a	0.081b	8.64b	17868a	1.18a	5893c	0.988
		WL	1699b	0.013b	21.85b	54.0a	0.903	659b	0.129c	5.38a	20306b	1.92c	3621a	0.987
SD	Asesewa	UC	2331b	0.013c	29.17c	55.4a	0.936	977b	0.068c	10.16a	18086b	2.76c	2513a	0.984
		CT	1336a	0.011b	15.01a	61.8a	0.960	585a	0.043b	16.28b	14017a	1.85b	3747b	0.991
		WL	2564b	0.009a	23.61b	75.2b	0.991	1457c	0.018a	39.94c	33718c	0.97a	7155c	0.997
	Kade	UC	3118c	0.011b	35.33b	61.4a	0.924	1112c	0.116b	6.10a	33360c	2.15a	3225b	0.986
		CT	2122b	0.008a	17.42a	84.4b	0.968	731b	0.042a	18.90b	18789b	2.29ab	3039ab	0.987
		WL	1597a	0.009a	13.96a	79.4b	0.936	443a	0.128b	5.40a	15115a	2.52b	2754a	0.989
CS	Dodowa	UC	4606c	0.008a	38.77c	82.7b	0.952	1356c	0.071c	9.76a	42597c	2.44a	2841b	0.991
		CT	1165a	0.010b	11.94a	67.7a	0.948	427a	0.061b	11.50a	12524b	2.00a	3469c	0.988
		WL	2014b	0.010b	20.88b	67.0a	0.977	945b	0.029a	23.77b	10678a	3.35b	2092a	0.992
	Legon	UC	1301b	0.007b	8.44c	107.4a	0.984	458.7b	0.020a	35.40b	12007b	1.87b	3727b	0.990
		CT	1002a	0.004a	4.41a	157.7b	0.981	135.7a	0.079ab	9.16a	46446c	0.44a	15930c	0.995
		WL	1806c	0.003a	6.05b	207.8c	0.991	132.3a	0.135b	5.55a	10859a	3.12c	2229a	0.995

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According to the double exponential model (Table 4.5), the estimated labile pool (C_1) ranged from 22 to 2066 mg C kg^{-1} soil across the land-uses in all sites. The highest C_1 values were recorded in the UC soils of Walewale, Dormaa, Sunyani, Kade, Dodowa and Legon, whilst the highest was recorded in the WL soils of Bawku and Asesewa, respectively.

The rate constant (k_1) of the labile pool ranged from 0.012-0.135 day^{-1}. In Bawku, Asesewa and Dodowa WL soils recorded the lowest estimated k_1 values, whereas in Walewale, Legon and Sunyani, and in Dormaa and Kade, the UC and CT soils, respectively had the lowest values.

The estimated half-lives ($t_{1/2}$) of the labile pool ranged from 5.38 to 58.42 days. In the IS zone (Bawku, Walewale) and Sunyani, CT soils recorded the lowest $t_{1/2}$ values, whereas Dormaa, Kade and Legon, and Asesewa and Dodowa the WL and UC soils recorded the lowest $t_{1/2}$ values, respectively.

The estimated stable pool (C_2) values of soils ranged from 3981 to 46446 mg kg^{-1} soil. The IS zone (Bawku, Walewale) and Asesewa, CT soils recorded the lowest C_2 values, whereas Sunyani, Kade, Dodowa and Legon, and in Dormaa the WL and UC soils had the lowest values, respectively.

The rate constant (k_2) ranged from 0.44-5.56 x 10^{-4} day^{-1}. In Bawku, Sunyani and Asesewa, the WL recorded the highest k_2 values, whereas in Walewale and Kade, and in Dormaa, Dodowa and Legon, the UC and CT soils, respectively recorded the highest values. The estimated half-lives ($t_{1/2}$) ranged from 2092 to 9194 days. In Bawku, Dormaa, and Asesewa, the UC soil recorded the lowest estimated $t_{1/2}$ values, whereas in Walewale and Sunyani in and Kade, Dodowa and Legon the CT, and WL soils, respectively had the lowest values.

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4.4.3 Correlation among parameters of first order model and the different organic carbon fractions in the soils

The correlation coefficients among the parameters of the first order model and the different OC fractions in the soils are shown in Fig 4.15 and Table 4.7. The highest correlation coefficient value of r = 0.984*** was observed between C_0 and C_{min} across the study. Generally, a significant ($p < 0.001$) positive correlation was found for all kinetic parameter and OC fractions, except between k and C_0, HWEOC, HCl-C and C_{min} which were weakly correlated. The kinetic parameters were also significantly and strongly correlated amongst each other, except for k and C_0. Among all the OC fractions, HWEOC showed weak to moderate correlation with POX-C, HCl-C, Non-HCl-C, C_{min} and TC. The OC fraction (POX-C, HCl-C, Non-HCl-C and C_{min}) showed a strong correlation with TC, and a moderate to very strong correlation amongst each other.

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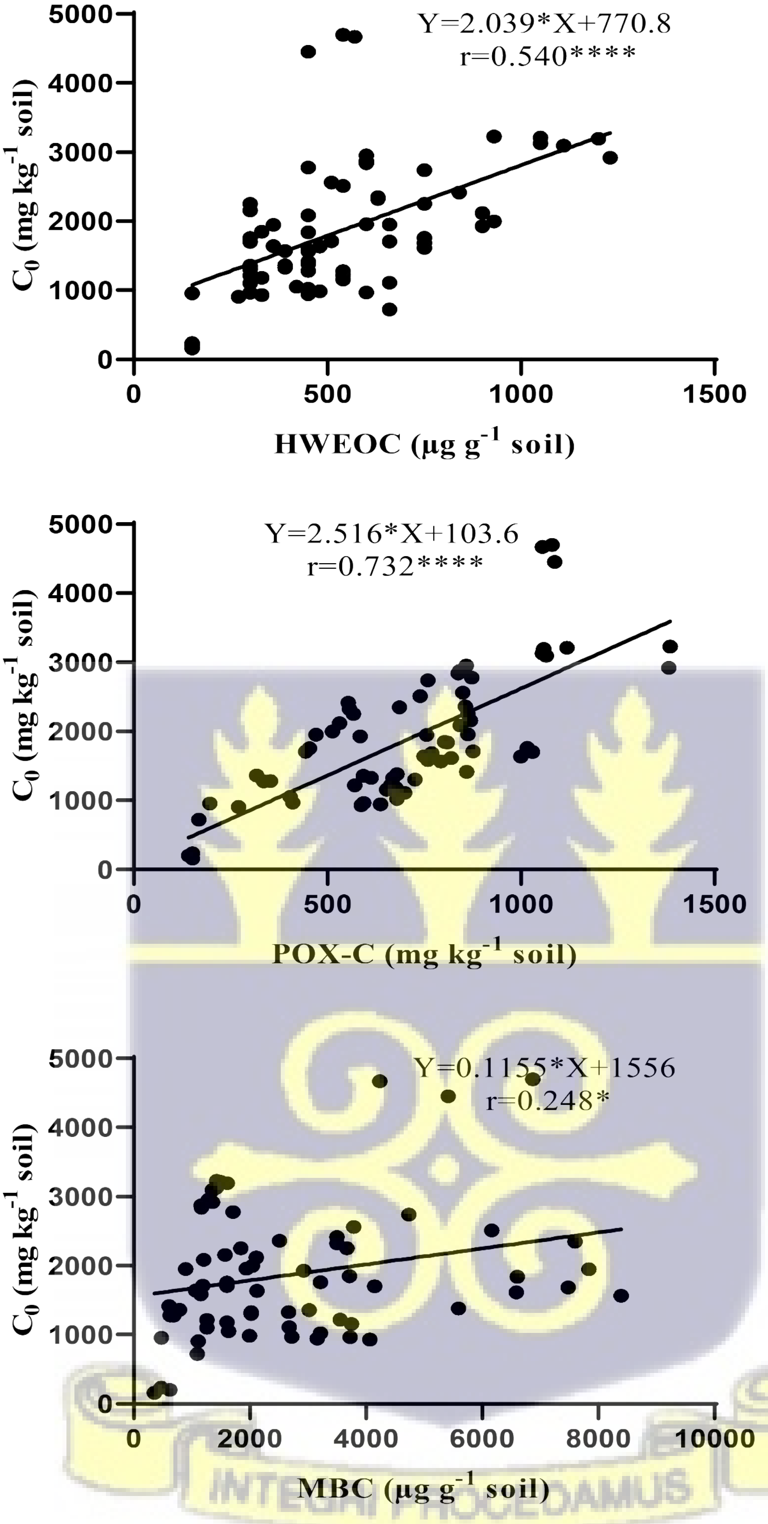

Fig 4. 15: Pearson correlation between potential mineralizable carbon (C_0) and microbiochemical properties, *, **, *** and **** correlation significant at $p < 0.05$ $p < 0.01$, $p < 0.001$and $p < 0.0001$ respectively

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Table 4.7: Correlation coefficient (r) between parameters of first order model and the different organic carbon fractions in the soils

	C_0	k	C_0*k	*HCl-C*	*Non HCl-C*
C_0	1.000				
k	0.226	1.000			
C_0*k	0.871***	0.626***	1.000		
HCl-C	0.663***	0.299*	0.614***	1.000	
Non HCl-C	0.614***	0.504***	0.706***	0.638***	1.000
C_{min}	0.984***	0.369**	0.939***	0.674***	0.661***
TC	0.708***	0.426***	0.720***	0.932***	0.874***

C_0: potential mineralizable C, k: rate constant, C_0*k: initial potential rate of C mineralization, HCl-C: HCl hydrolysable organic C, Non-HCl-C: Non-HCl hydrolysable organic C. *, ** and *** correlation significant at $p < 0.05$ $p < 0.01$and $p < 0.001$ respectively

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4.5 The effect of land-use systems on the carbon pools and carbon management index of soils used

Table 4.8 summarises the effect of land-use on the carbon stored in the soil and the CMI. The lability index (LI) for all locations ranged from 0.674 and 2.216 with the highest values found in the CS zone (Dodowa) The trend in the LI followed the order: CS > SD > TZ > IS.

Ecological zone and land-use effect was significant ($p < 0.05$). Generally, the highest was recorded in the among all the ecological zones. The trend recorded for carbon pool index (CPI) and carbon management index (CMI) followed the order: IS > SD >TZ > CS. Across the land-use systems, a trend of CT > WL > UC was recorded for LI and WL > UC > CT for CPI and CMI.

In the Interior savannah zone, the carbon indices for all land-use systems ranged between 0.674 and 1.0, 1.606 and 5.280 and 40 and 432 for LI, CPI and CMI, respectively in Dormaa and between 1.0 and 1.280, 0.2524 and 1.0 and 32 and 100 for LI, CPI and CMI, respectively in Sunyani.

In the Forest-savannah transition, carbon indices for all land-use systems ranged between 0.8168 and 1.0, 0.980 and 1.226 and 85 and 100 in Dormaa and between 1.0 and 1.178, 0.5046 and 1.0 and 57 and 100 in Sunyani for LI, CPI and CMI, respectively. In the semi-deciduous forest zone, carbon indices for all land-use systems ranged between 0.919 and 1.736, 0.749 and 1.758 and 100 and 161 in Asesewa and between 1.0 and 1.238, 0.457 and 56 and 100 in Kade for LI, CPI and CMI, respectively.

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In the Coastal savannah zone, carbon indices for all land-use system ranged between 1.0 and 2.216, 0.270 and 1.0 and 52 and 100 in Dodowa and between 0.813 and 1.0, 0.841 and 1.0 and 68 and 100 in Legon for LI, CPI and CMI, respectively.

Table 4.8: Carbon indices of soils used

Ecological Zone	Site	Land-use	LI	CPI	CMI
IS	Bawku	UC	1.000b	1.000b	100b
		CT	0.674a	0.606a	40a
		WL	0.819ab	5.280c	432c
	Walewale	UC	1.000a	1.000c	100c
		CT	1.280a	0.252a	32a
		WL	1.055a	0.758b	80b
TZ	Dormaa	UC	1.000b	1.000a	100b
		CT	0.874ab	0.980a	85a
		WL	0.817a	1.227b	100b
	Sunyani	UC	1.000a	1.000c	100c
		CT	1.178a	0.594b	70b
		WL	1.125a	0.505a	57a
SD	Asesewa	UC	1.000a	1.000b	100a
		CT	1.736b	0.749a	130b
		WL	0.919a	1.758c	161c
	Kade	UC	1.000a	1.000c	100c
		CT	1.147b	0.570b	65b
		WL	1.238b	0.457a	56a
CS	Dodowa	UC	1.000a	1.000b	100c
		CT	2.216c	0.292a	64b
		WL	1.910b	0.270a	52a
	Legon	UC	1.000b	1.000b	100c
		CT	0.813a	0.841a	68a
		WL	0.837a	0.914ab	76b
		LSD	0.129	0.105	5

Interior savannah (IS); Forest-savannah transition (TZ); Semi-deciduous Forest zone (SD); Guinea Savannah zone (GS); Coastal Savannah zone (CS); Cultivated land (CT); Woodlot (WL); Uncultivated land (UC) Lability Index (LI); Carbon Pool Index (CPI); Carbon Management Index (CMI). Means with the same letters (within each location) do not differ significantly among themselves.

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CHAPTER FIVE

5 DISCUSSION

5.1 Soil properties

5.1.1 Agro-ecological effect on texture, bulk density, pH, TC, CEC

The soil properties varied with agro-ecological zone, even though they could be generally classified as loamy sands and sandy loams (Table 4.1). The very high bulk density of soils from the IS zone, especially that of Bawku, is presumably due to the high sand content. Most agricultural soils in the IS zone are known to be shallow (< 40 cm) (Tetteh et al., 2016), with low cover from the savannah vegetation and show high Fe concretions (Abekoe & Tiessen, 1998; Nartey et al., 1997) and exposed Fe pan outcrops (Asiamah & Dedzoe, 1999). The lower values recorded for bulk density in the TZ zone (Dormaa, Sunyani), is due to the lower sand content.

The susceptibility of soils to erosion as measured by clay ratio was based on the soil factors only. The high sand and low clay content, coupled with the lower rainfall and less vegetation leading to more unprotected soils, resulted in the high clay ratio observed in the soils of the IS zone (Bawku, Walewale). The higher the clay ratio value (Table 4.1), the more susceptible the soil is to erosion, hence soils from the interior savannah zone were more susceptible to erosion (Bouyoucos, 1935). The low Clay Ratios observed in the TZ zone soils is due to the high clay content or a higher proportion of the fine soil fractions (silt + clay). The soils of the TZ are generally known to be deep with high litter cover from forest litter that prevents erosion despite the relatively high rainfall. The higher rainfall and temperature of the TZ zone leads to increase mineralization of soil mineral, leading to more clay particles production (Zhong et al., 2018), and thus the low clay ratio. The soils from the SD forest zone bear similarities to those of the TZ,

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but have relatively higher silt + clay percent, and hence lower Clay Ratios. The location receives higher rainfall and except cleared, has both high forest and litter cover that prevents erosion. The soils are deep, and Fe content is relatively lower than the IS locations.

The pH of the soils (Table 4.2) varied with agro-ecological zones ranging from strongly acidic (4) to neutral (7). The strongly acidic reaction of soils from the savannah zones (Interior and Coastal), especially Legon, could be attributed to parent material, land-use, and management. Though the coastal savannah zone received the lowest rainfall, the cultivated soils often received fertilizer application regularly, which may affect soil pH. Though the TZ zone received higher rainfall than the savannah zones (Interior and Coastal) and would have been expected to lose much of the basic cations via leaching, the denser vegetation cover could have played some tempering roles in soil acidity development. The shade from tree canopy reduces the temperature creating a microclimate that slows the rate of decomposition, hence the high C content.

The low TC in the IS soils is characteristic of soils (Adu, 1995) found in this area (semi-arid region). The high temperatures increase the decomposition rate of organic matter, reducing the accumulation of C in the soil. These soils are also susceptible to erosion which further decreases their C content (Dowuona et al., 2012). Soils from the transitional and semi-deciduous zones had relatively high organic carbon. The medium temperature and high rainfall observed in these areas improve biomass production which translate into the accumulation of organic carbon in the topsoil. Carbon input from the high forest biomass and the generally low soil disturbance would enhance C accumulation in these zones (Owusu-Bennoah et al., 2000).

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The P levels in Ghanaian soils are generally low due to the characteristics of the parent materials (Abekoe & Tiessen, 1998; Nartey et al., 1997). Though total P levels (Table 4.2) may be high, the amount available for plant uptake is mostly low. For the IS zone (Bawku, Walewale), the low available P status of the soils could be attributed to the relatively high presence of Fe and Al ions which fix P making it less available in the soil solution (Nartey et al., 1997). The high P levels recorded for Dormaa, Sunyani and Dodowa CT may be due to application of P fertilizer. Secondly, the pH of these soils is close to neutral, which makes P more available compared to acidic soils. It is generally known that Fe_d is effective in complexing P and reduce P availability. Our observation seems to point to the contrary, as the Fe_d was lowest for CS (Table 4.3), which also had the lowest pH and lowest Available P. thus, the lower P recorded in the CS soil may be as a result of clay activity. The soils from TZ and SD had the highest Fe_d but also showed higher Available P. The impact of Land use type cannot be totally disregarded in this case.

Cation exchange capacity (CEC) at pH 7 of soils ranged from low to high. The high CEC (Table 4.2) values of soils with higher clay (Table 4.1) and organic matter content shows they have high negative charges on their surface and hence higher ability to retain positive plant nutrient such as K^+ and NH_4^+ cations. The soils with higher sand content and low clay activity showed lower values of CEC except for the UC soils can be attributed to organic matter accumulated in the topsoil. As discussed in the Literature Review (Chapter 2), high SOM can also contribute to CEC via the dissociation of carboxylic and phenolic functional groups.

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5.1.2 Land-use differences on bulk density and TC

Conversion of forest to cultivated land affects physical, chemical, and biological properties of the soil. The lower bulk density (Table 4.1) of UC soils reflects the effect on land-use which increase the SOC (Awoonor, 2012) and the decrease in bulk density. Furthermore, the frequent disturbance of soils under constant cultivation, especially with heavy forms of machinery would lead to increases in bulk density over time (Aina et al., 2019; Neina & Adolph, 2022; Osunbitan et al., 2005)

The low TC content in the CT soils in the study may be attributed to increased decomposition rate in the soils as the cultivation process also increases soil aeration and microbial activity. The medium TC (Table 4.1) recorded in the WL of both Bawku and Walewale may be attributed to litter accumulation, little disturbance and improved microclimate created by the tree canopies. Generally, woodlots mimic natural uncultivated forests over time and tend to have properties close to uncultivated soils (Awoonor, 2012).

Using the classification scheme defined by Landon (2014), on rating of N levels in soils as: >10 g/kg very high; 5 - 10 g/kg high; 2 - 5 g/kg medium; 1 - 2 g/kg low and <1 g/kg very low, the soils could be classified as having N levels ranging from very low to medium. The low N levels in the CT soil could be due to crop uptake and nutrient mining, and high mineralization of organic matter. The medium N level (Table 4.2) recorded for Sunyani CT soil may be due to fertilizer application. The high levels N in the WL of Bawku and Walewale may be due to accumulation or organic matter in the topsoil, slower decomposition rate because of the microclimate created by the canopy though it is found in the semi-arid region. Though low N levels are characteristic of soils in the sub-Saharan Africa, land-use and management practices influence the amount and availability of N in soils.

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The higher MBC_{mic} and MBN_{mic} (Table 4.4) recorded in Bawku, Walewale, Dormaa, Sunyani, Asesewa, Dodowa and Legon UC and WL compared to CT soils could be attributed to the dense tree canopies and absence of soil disturbance in these land-use systems (UC, and WL), aggregate formation and enhanced stability which may have provided favorable environmental conditions that protect microbial biomass against soil water and temperature (Awale et al., 2017; Balota et al., 2004; Purakayastha et al., 2009) . The low MBC_{mic} and MBN_{mic} (Table 4.4) recorded for the CT soil can be due to the increased mineralization of SOM when soil is disturbed during cultivation, increasing soil aeration, and breaking down aggregates, exposing hitherto protected organic matter (Owoade et al., 2021). The higher MBC_{mic} values recorded for Kade cultivated soil may be as a result of fertilizer application and management practices observed in these soils. High MBN_{mic} may be as a result of greater assimilation of N by microbe during the mineralization process of organic sources.

The high steady BR rate (Table 4.4) in the UC and WL soils could be attributed to the high OC content of these soils which served as an energy source for microbial survival and proliferation, whiles the low BR in the cultivated soils may be due low MBC_{mic} and C availability.

Microbial metabolic quotient (qCO_2) is used as an index of ecosystem development to determine the efficiency of microbial activity in soil. The low qCO_2 (Table 4.4) in the UC and WL soils compared to the CT soils observed in Dormaa, Sunyani and Dodowa this study, confirms the view that qCO_2 decreases in more stable systems (Balota et al., 2004). The higher diversity of organic substrates and absence of soil disturbance found in the WL and UC (forest) soils, may have resulted in a more efficient utilization of OC

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by the microbial biomass (Maia et al., 2007). This result is consistent with other researchers who reported that high qCO_2 indicates low C use efficiency of microbe whiles low qCO_2 show a relatively good efficiency during the metabolism of OC and a more stable system (Cao et al., 2019; Wardle & Ghani, 1995). This is due to the lower SOC and MBC mostly found in CT soils compared to UC or forest soils as a result of differences in the accessibility of microorganisms to C substrates, microbial community and metabolic rates (Balota et al., 2004).

Generally, increase in MBC_{mic} leads to a relative decrease in the qCO_2 of soils. From Table 4.4, soils with high MBC_{mic} recorded a relatively low values of qCO_2, which is similar to that reported by Balota et al. (2004), who observed an 83% increase in MBC_{mic} and 32% decrease in qCO_2 in tropical/subtropical agroecosystem in Brazil. The high qCO_2 observed in the UC and WL soils in Bawku, Walewale, Asesewa, Kade and Legon confirms the findings of Toh et al. (2020), who observed a high qCO_2 in forest/fallow soils compared to other land-use management systems.

The CO_2 flush following rewetting of dried soil observed in this study was influenced by ecological zones and land-use across all the sampling sites. The variation observed (Table 4.4) among the agro-ecological zones may partly be attributed to the mean annual precipitation and temperature differences among these zones (Franzluebbers et al., 2000). The high CO_2 efflux observed in the UC and WL soils of Bawku, Walewale, Dormaa, Sunyani, Asesewa, and Dodowa may be due to the high substrate availability (Laffely et al., 2020) from the varied C input (vegetation) and precipitation in these land-uses (UC and WL) compared to the CT soils. The absence of soil disturbance and increased aggregation also improves the accumulation of OC in these soils. The drying accumulates lysed cells content in soil, whiles rewetting releases these accumulated OC, including the protected ones from aggregates. Furthermore, higher depolymerized

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and extracellular soluble C are found in soils after drying and re-wetting (Fraser et al., 2016; Laffely et al., 2020; Rey et al., 2017; Warren, 2016). The reduced C input due to crop removal and cropping system, and the quality of C found in the cultivated lands affected soil respiration (Sainju et al., 2021) which led to the decreased amount of CO_2 efflux obtained in the CT in Bawku, Walewale, Dormaa, Sunyani, Asesewa, and Dodowa.

The MBC:MBN ratio is often used to describe the state and structure of the microbial community in soil. Since microbial biomass consist mostly of fungi and bacteria, a high MBC:MBN (Table 4.4) ratio in the microbial biomass indicates a high proportion of fungi whilst bacteria dominated microbial population has a low MBC:MBN ratio (Moore et al., 2000). Thus, the observed lower MBC:MBN (Table 4.4) ratio in the CT, compared to the UC and WL soils may suggest a shift from fungi dominated biomass to a bacterial dominated one when native land was converted to cultivated land. This is because fungi have a higher C demand, are present at near carrying capacity and their growth rate and reproduction are tuned to the limited available resource. Bacterial in an attempt to occupy a niche as quickly as possible, place large percentage of their available energy into reproduction and as a result become wasteful and C lost as CO_2 (Awale et al., 2017; Cleveland & Liptzin, 2007). Fungi dominated soils, such as the UC and WL soils from the study, lead to improved soil aggregation, accumulation, and stability of SOC (Cookson et al., 2008). Balota et al. (2004) and Awale et al. (2017) also reported high MBC:MBN values in no-till or undisturbed soils than disturbed (tilled) soils when they studied the effect of different tillage practices on the dynamics of SOC in a Typic Haplorthox and a Typic Haploxerol in Brazil and Columbia, respectively.

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The wide variations in the qMIC of the soils reported in literature (Alvarez et al., 1995; Anderson & Domsch, 1989; Insam & Domsch, 1988; Novak et al., 2017; Sousa et al., 2015) may serve as an indicator of the state of C in the soil i.e., decreasing, increasing (accumulating) or at equilibrium. Secondly, the differences in the vegetative cover, soils, management, sampling time as well as analytical methodology influence these wide variations (Anderson & Domsch, 1989). The low qMIC values (Table 4.4) of some land-use systems may be due to the degree of OC stabilization in soil, reduced nutrient availability to microbes and the soil management history (Novak et al., 2017). Thus, the ability of microbes to convert OC into biomass is reduced under stress conditions. The low qMIC observed in the CT of Dormaa, Sunyani and Dodowa, may be due to decreased ability of the microbes to convert OC to microbial biomass. An appropriate microbial growth condition is reflected by higher qMIC values (Novak et al., 2017; Sousa et al., 2015), as recorded in the UC soils of all sites except Kade. This may be due to the efficient conversion of OC into MBC_{mic} and the stabilization of OC by the soil mineral fractions (Sousa et al., 2015), as result of increase litter input and quality (Anderson & Domsch, 1989).

5.2 Carbon pools in soils

Due to its influence on soil physical, chemical, and biological characteristics, SOC is crucial for enhancing soil fertility and maintaining soil productivity. Conversion of native land to agriculture leads to the depletion of SOC through crop removal, exposure of hitherto protected SOC to microbial attack, increased aeration, and temperature and the loss of water content (Awale et al., 2017; Six et al., 2000; Zhao et al., 2014).

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The low initial HWEOC (Fig. 4.1) obtained in this study probably suggests that though it is very little, yet significant and extremely labile soil organic C components (Gregorich et al., 2003; Xue et al., 2013). The HWEOC values reported in this study are similar to those reported by Curtin et al. (2006) for some New Zealand soils. The range of HWEOC recorded in the SD and TZ zones are similar to those reported by Xue et al. (2013), for soils of the Loess Plateau of China, but lower than those of the savannah zones (interior and coastal). The conversion of native lands to cultivated lands significantly increased the percentage ratio of HWEOC to TC in soils and this is consistent with the observations made by Xu and Xu (2003) who reported a higher HWEOC in the cultivated land compared to the native land in China.

The ratio of SOC oxidized by 0.333 M $KMnO_4$ according to Haynes (2005) is between 15 to 30%. The proportion observed in this study was lower (2.195 to 5.939%), but slightly higher than the 1 to 4% reported by Hurisso et al. (2016) in the United States. This could be the effect of land-use, ecological zones which determines the amount and quality of organic input ant the rate of decomposition, and soil type. The higher POX-C as a percent of TC in the CT in the savannah zones (interior and coastal) may indicate that POX-C represents a more stable form of OC (Tirol-Padre & Ladha, 2004). This is because cultivation increases C decomposition which may promote relative enrichment of mineralizable C (Hurisso et al., 2016). The higher OM input via higher precipitation and diversity of vegetation, coupled with the absence of soil disturbance found in the UC and WL, which leads to the accumulation of labile C in soils resulted in the higher POX-C proportion of TC observed in the UC and WL of the TZ and SD zones, respectively.

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The initial 35.87 to 74.29% HCl-C observed in this study from the various soils is similar to the 23-70% reported by Paul et al. (2001) for some USA soils, but higher than the 18 to 25% reported by Silveira et al. (2008) for some USA soils. The differences in the quality of OM coupled with the effect of land-use and agro-ecological zones (Silveira et al., 2008) may have resulted in the variation in the amount of HCl-C and Non HCl-C observed in this study.

5.2.1 Relationship among soil texture and organic carbon pools

Soil texture plays an important role in the stabilization of carbon and the rate of SOC sequestration in soils (Lal, 2004b). Although the TC influences the C contents of soils, clay and silt particles interaction with OC is very significant. The clay and silt aggregates physically protect SOC due to their fine texture, which increases aggregation and slows decomposition rate by inhibiting the aerobic activities of microbes with low O_2 (Ramesh et al., 2019; Tirol-Padre & Ladha, 2004). Chemically, the minerals associated with clay and silt aggregates have reactive surfaces which reacts with SOC, increasing its binding capacity (Zacháry et al., 2018). Thus, as clay and silt contents increase, SOC become more stable and less available to microbes. From the results (Fig 4.2), it is apparent that the silt component of soil texture had a stronger effect on the soil OC pools than clay. Secondly, the inverse relationship between soil texture and C pools indicates that, as clay and silt aggregates increase in the soils, the amount of HWEOC, POX-C, HCl-C and Non HCl-C decreased. From Fig 4.2, soil texture may have little or no effect on soils with very low or high OC.

The high correlation between POX-C and the soil texture (Clay/OC, Silt/ OC, and Clay + Silt/OC) ratios, is consistent with the results of Tirol-Padre and Ladha (2004), who

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also reported significant correlation among POX-C and Clay/OC, Silt/ OC, and Clay + Silt/OC.

5.2.2 Relationship among oxalate and dithionite extractable aluminium and iron

The positive correlation between the POX-C and Fe_{ox} and Fe_d (Fig 4.4) indicates that the POX-C which consists of particulate organic matter, may be occluded in aggregates made up of clay minerals and Fe oxide which may not have yet reacted to form complexes (Culman et al., 2012; Rennert et al., 2017), and may thus be oxidizable by potassium permanganate. The positive correlation between POX-C and Fe_{ox} and Fe_d is consistent with the results of Rennert et al. (2017) who studied POX-C in 18 profiles of floodplain soils in Germany and found that the POX-C as soil decomposition indicator may be limited by the amount of clay present and degree of aggregation.

5.3 Land-use effects on C fractions

The high C (Fig 4.5) content observed under WL in Bawku compared to the CT, and UC could be due the accumulation of organic matter over time as this type of land-use system does not disturb the land and influences the storage of C in soil. Secondly, the litter from tree leaves and root exudates add to the C in the soil. The shade from tree canopy reduces the temperature creating a microclimate that slows the rate of decomposition, hence the high C content. The low C content of the CT, and UC soil in Bawku could be attributed to the high coarse sand and low clay content (Owoade et al., 2021) of the soil (Table 4.1) which inhibits the soil capacity to protect C in the long term. The high temperature observed in this area also increase the rate of decomposition of SOM. Whilst cultivation reduces the amount of C stored in the soil by increasing decomposition rate and the harvesting of crops, the UC soil is bare, with patches of grass hence the low C content (Bongiorno et al., 2018; Bongiorno et al., 2019; Six et al., 1999).

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The high C content (Fig 4.5) in the UC soils of Walewale, Dormaa, Sunyani, Asesewa, Kade, Dodowa and Legon can be attributed to higher C input through litter fall from leaves and root exudates annually. Furthermore, the high clay content (Owoade et al., 2021) in Legon soil preserves the C within the aggregates making it unavailable for microbial attack, hence the high C content observed. The changes observed in the total C (Fig 4.5) content of soils under different land-use systems across the year could be as a result of changes in the microbial biomass observed during the incubation period (Liddle et al., 2020; Rakhsh et al., 2020).

5.3.1 Influence of different land-use system on hot water extractable C

The high HWEOC (Fig 4.6) in the UC and WL soils compared to the CT can be attributed to the higher biodiversity, higher biomass and larger stock which leads to the accumulation of different organic residues (litter biomass) with varying chemical composition and rate of decomposition found in these land-uses (Choudhary et al., 2013). As HWEOC represents readily decomposable SOC in the bulk soil (Choudhary et al., 2013), the conversion of WL and native UC land to cultivation decreases the amount of HWEOC in the soil. This could be explained by high non-humified organic material such as lignocellulose, lignin and other carbohydrates, or high microbial biomass content in forest (native UC) and WL soils that may be partly extracted with hot water (Hamkalo & Bedernichek, 2014). Cultivation of soil may lead to a rapid decomposition of the labile pool of SOC, which leads to a relative enrichment of more stable SOC. The HWEOC is one of the most labile and dynamic fractions of organic C (Fan et al., 2013) and is easily lost through cultivation, thus the low HWEOC in the cultivated soils. Fan et al. (2013) and Hamkalo and Bedernichek (2014) also found that HWEOC was lower

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in CT than the UC soils. Huang and Song (2010) also reported a low HWEOC content in CT soils compared to that of forest land when they investigated the effect of land-use and depth on water soluble organic C.

The variation observed in the HWEOC value (Fig 4.6) during the year-long incubation confirms the observation by Heller and Weiß (2015) that HWEOC is seemingly less dependent on seasonal variation.

5.3.2 Influence of land-use systems on the potassium permanganate oxidizable C

The high POX-C of soil (Fig. 4.7) recorded at the beginning of the year-long incubation could be associated with the accumulation of recently decomposed organic substances and microbial biomass at the time of sampling. The higher POX-C values (Fig. 4.7) in WL, and UC compared to CT soils across ecological zones and location can be attributed to the effect of the different land-use systems, as reported by other researchers (Blair, 2000; Geraei et al., 2016; Mandal et al., 2011). This is because cultivation reduces the amount of SOC due to crop removal, lack of biomass addition (Geraei et al., 2016), and soil disturbance, which leads to increased decomposition via aggregate disruption, increased soil aeration (Choudhary et al., 2013), and microbial activities. Thus, as noted by Hurisso et al. (2016) and Culman et al. (2012), the POX-C reflects a more relatively stable SOC than the HWEOC. Furthermore, the quality and type of organic compounds added to the UC and WL soils through litter fall and root exudation differ from that of the CT soils (Geraei et al., 2016).

The sharp decline in POX-C (Fig 4.7) at the third month of incubation can be attributed to the exhaustion of the easily mineralized organic C pools, probably resulting in decreased MBC_{mic} and positive relationship between the two variables, as has been reported previously (Awale et al., 2017; Morrow et al., 2016). The results (Fig 4.7) indicate

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that POX-C extracted C pool that are closely related to the biological functions of soil compared to the TC (Weil et al., 2003).

5.3.3 Influence of land-use systems on the HCl and non-HCl hydrolysable C in soils

The relatively higher fraction of TC as Non-HCl-C (Fig 4.9) observed in the cultivated soils of Bawku, Walewale, Dormaa, Sunyani, Asesewa and Dodowa is probably due to the higher mineralization of SOC as soil disturbance increases with cultivation. This agrees with Rovira and Vallejo (2002) that HCl-C represents a more labile fraction whilst Non-HCl-C represents a recalcitrant fraction of SOC. However, this may not always be the case as lower fractions of Non-HCl-C was observed in the CT at Kade and Legon. Morrow et al. (2016) reported a higher fraction of SOC as Non HCl-C in undisturbed soils compared to CT soil and concluded that HCl-C and Non-HCl-C provide a biochemical framework in which to understand SOM pools.

Multiple studies (Martel & Paul, 1974; Paul et al., 2001; Paul et al., 1997; Paul et al., 2006) have shown that Non-HCl-C was much older than SOC, supporting the association of Non-HCl-C to a more recalcitrant pool. Paul et al. (1997) observed a preferential hydrolysis of nucleic acids, proteins, and polysaccharides by HCl whilst alkyl, cellulose and aromatic components are unaffected. The changes observed in both HCl and Non-HCl hydrolysable C (Fig 4.9) throughout the incubation study and those reported from other studies can help elucidate the effect of land-use on SOM. Change in land-used i.e. cultivation or agroforestry, can lead to a rapid increase or decrease of the amount of HCl-C and Non-HCl-C in soil.

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5.3.4 Soil microbial activities response to different land use systems

The low MBC_{mic} and MBN_{mic} (Fig 4.10 and Fig 4.11) in the IS zone, may be due to high temperatures which increase decomposition rates, the low C input resulting from lower rainfall received in these areas, the high sand content of the soils, which further influence the microbial activities (Dowuona et al., 2012; Owoade et al., 2021). The higher MBC_{mic} recorded in the TZ, and SD zones may be attributed to the high rainfall, diverse vegetation and high C input, and the high TC recorded in this zone.

The high MBC_{mic} and MBN_{mic} (Fig 4.10 and Fig 4.11) observed in the UC soils in Bawku, Walewale, Sunyani, Asesewa, Kade, Dodowa and Legon compared to the CT soils could be attributed to high litter fall, varied root type and root exudates, and the absence of soils disturbance, which may lead to reduced soil temperature, increased aggregation, water retention and C content and thus influencing the pool size and activities of soil microbes (Chen et al., 2005; Feng et al., 2009).

The low microbial biomass recorded in the CT soils of in Bawku, Walewale, Sunyani, Asesewa, Kade, Dodowa and Legon may be due to the shift in plant community and chemical composition of plant residues (Jin et al., 2010) after cultivation. Loss of SOM through crop removal, low quantity and quality of crop residue, and crop residue removal during land preparation leads to starvation of the microbes hence the low amount of MBC_{mic} and MBN_{mic} recorded (Balota et al., 2004; Kasel & Bennett, 2007; Yang et al., 2010). As land is prepared for cultivation, there is an increase in SOM decomposition rate which reduces the amount of substrate available and hence affecting the microbial biomass and activity (Bongiorno et al., 2019; Six et al., 1999). This confirms the statements made by Carter et al. (1999) and Moore et al. (2000) that microbial biomass gives an indication of the soils microbiota response to environmental changes, site disturbance and management.

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The fluctuations observed in the MBC_{mic} and MBN_{mic} (Fig 4.10 and Fig 4.11) in the 3rd, 6th, 9th, and the 12th month could be a reflection of the availability of readily decomposable organic C to microorganisms, which may have caused the shift in the type and number of microorganisms present at the time of sampling. Moore et al. (2000) and Yang et al. (2010) concluded that soils C is immobilized when microbial biomass increases and mineralized when microbial biomass decreases, when they studied the effect of season variation of microbial biomass

5.3.5 Nitrogen mineralization

The low mineralized N (Fig 4.12) recorded in this study reflects the inherently low N in sub-Saharan Africa soils. The relative high N values recorded at the beginning compared to the rest of the incubation period may be attributed to the presence of already decomposed organic matter at the time of sampling (Ali et al., 2021).

The lower N (Fig 4.12) content observed in soils at the 9th month of the incubation could be attributed to increased microbial biomass (Saetre & Stark, 2005) leading to the assimilation (immobilization) of mineralized N by microbes which is reflected in the increased in the MBN_{mic} in the same month. The C:N ratio of substrate decreases as decomposition proceeds thus, the increase in the mineralized N observed may be attributed to release of N in the decomposed SOM and lysed microorganisms in soil.

The effect of land-use on N is observed, as the UC soils in all sites recorded the highest mineralized N whereas the CT soils recorded the lowest. This is because of the high-quality SOM that is accumulated in UC soils from a variety of vegetation found in this land-use type.

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5.4 Relationship among organic carbon fractions and microbial indices

The low correlation between MBC and POX-C (r = 0.245*) and other labile C fractions (Table 4.5) (HCl-C and C_{min}), respectively may suggest that POX-C may represent a more stable fraction of the total C in soils (Tirol-Padre & Ladha, 2004). Secondly, it also implies that the MBC_{mic} is composed of limited set of substances and biomolecules such as microbial necromass and enzyme (Kästner et al., 2021) compared to the other labile fractions which may have plant residues and other constituents in them (de Souza et al., 2016). Awale et al. (2017) also reported a significant correlation between MBC_{mic} and POX-C, but Tirol-Padre and Ladha (2004) reported a no correlation between MBC_{mic} and POX-C in their study.

The insignificant correlation between MBC_{mic} and MBN_{mic} (r = -0.083) agrees with the results of Awale et al. (2017) but contradicts Moore et al. (2000), who reported close relationship between the two variables. This could be due to differences in land-use, soil properties and nutrient availability. The C:N ratio of microbial biomass i.e. MBC:MBN can also vary based on environmental conditions and curtain nutrient limitations. The significant positive correlation between MBC_{mic} and TC (r = 0.475***) confirms that MBC_{mic} is influenced by the SOM present in different ecosystems (Lepcha & Devi, 2020; Liddle et al., 2020). Soils with high SOC content have high microbial biomass.

The moderate to highly significant correlation between MBC_{mic} and Non HCl-C (r = 0.515***), BR (r = 0.541***), MBC:MBN (r = 0.908***) and qMIC (r = 0.715***) suggest that these soil biological functions plays a significant role in the MBC_{mic} (Wang et al., 2017) and as these functions increases, MBC_{mic} also increases. The negative correlation between MBC_{mic} and qCO_2 (r =-0.316**) and qM (r = -0.200) indicates that these microbial indices are influenced by other factors other than MBC, such as quality of organic substrates, soil pH, moisture content, temperature, and soil type.

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The positive correlation of POX-C with BR (r =0.699***), qCO_2 (r = 0.561***) and C_{min} (r = 0.806***) agree with the observation by Weil et al. (2003) that POX-C oxidation mimics SOM decomposition by microorganisms. Bongiorno et al. (2018), also reported a positive correlation between POX-C and BR (r =0.46***) and qMIC (r = 0.26**) when they studied labile C fractions as soil quality indicators in different soils within different seasons in Wageningen. The HWEOC is reported to comprise largely of soil microorganism derived amides, carbohydrates, root exudates, enzymes, and lysates (Bongiorno et al., 2018; Ghani et al., 2003). This explains the moderate correlation between HWEOC and BR (r = 0.408***), qCO_2 (r = 0.430***), and C_{min} (r = 0.529***) and the low correlation with qM (r = 0.236*).

The significant and positive correlation between qCO_2 and C_{min} (r = 0.484***), and the negative correlation between qCO_2 and MBC:MBN (r = 0.524***) indicate that an increase in the MBC:MBN ratio leads to a decrease in the qCO_2. High MBC:MBN ratio implies higher fungi population of biomass (Moore et al., 2000), which leads to an efficient use of C resources in soil, reducing the qCO_2 (Cao et al., 2019; Cookson et al., 2008; Maia et al., 2007). The negative correlation between qCO_2 and qMIC (r = -0.660***) shows that an increase in the qCO_2 reflects the difficulties of microorganisms to utilize organic substrates during microbial activities due to low levels of OC in the soil leading to lower qMIC values (Toh et al., 2020).

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5.5 Land-use effect on kinetic parameters of C mineralization

5.5.1 Response of carbon mineralization to different land-use systems

The large initial (Fig 4.14) CO_2 efflux from the soils is as a result of rapid utilization of the easily mineralizable or labile C fractions present in SOC at the beginning of the incubation studies (Ramesh et al., 2019). The rewetting of soils led to changes in temperature and humidity, aggregate disruption, and the release of protected organic C to microbial degradation (Dodor et al., 2019).

As incubation proceeded, the slower linear increase in CO_2 efflux could be due to the decline in the amount of labile C available for microbial activity a true reflection of their direct relationship. Thus, an increase in labile C would lead to increased CO_2 efflux and vice versa.

The high CO_2 efflux (Fig 4.14) in uncultivated and woodlot compared to the CT soils across the different soil types could be due the vegetation type and the absence of soil disturbance in the uncultivated and woodlot soils leading to an accumulation of organic C. This is consistent with the high SOC content of the WL, and UC soils which was mineralized by the microbes, resulting in the higher CO_2 efflux compared to the CT soils (Ramesh et al., 2019). Cultivation alters the amount of organic input from both above and below ground plant litter through the wide spacing of plants, removal of harvested produce and burning and removal of crop residues. It also influences the rate of decomposition of these inputs and the release of CO_2 into the atmosphere by decomposer communities annually, through increased soil aeration, temperature, and the exposure of protected physically SOM (Bongiorno et al., 2019; Haynes, 2005; Six et al., 1999)

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The observed trends in CO_2 efflux (Fig 4.14) from soils sampled from Walewale, Asesewa, Kade, Dormaa, Dodowa and Legon agrees with the reported 31% higher cumulative CO_2 efflux in agroforestry compared to agricultural and fallow lands in a 150-days incubation study in the northeast India on four major land-uses i.e., agriculture, horticulture, agroforestry, and fallow (Ramesh et al., 2019).

Sandy and sandy loam soils tend to contain low amount of organic carbon due to their low clay content and hence low capacity to protect SOC for a long period of time. Thus, the low SOC (Table 4.2) content in Bawku soils is as a result of its high sand and low clay content (Table 4.1). Also, the high CO_2 efflux observed in the WL compared to the UC, and CT soil may be due to SOC accumulation in the WL through litter from the trees found here.

5.5.2 Kinetics of carbon mineralization under three different land-use systems

The high regression coefficient (R^2) values (0.903-0.998) obtained when CO_2 evolution was fitted to the double exponential model indicates that the model is a useful approximation of C mineralization in soils under different land-use systems. From Table 4.6, the R^2 values of the double exponential model ranged from 0.984-0.998 which exceeded the 0.903-0.995 of the first order model, thus making it a better representation C dynamic across land-use systems and agro-ecological zones. Parameter differentiation such as the labile (C_1, K_1) and the stable (C_2, K_2) pools show quick turnover of easily decomposable OC and the slow turnover of the sable OC. All agro-ecological zones exhibit this two-phase kinetic behavior, from the drier Interior and coastal savannah zones, where low k_2 values suggest longer carbon stabilization, to the semi-deciduous and transition zones, where high C_1 and k_1 values indicate rapid C cycling. Additionally,

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land-use effects are more evident: uncultivated (UC) sites exhibit intermediate dynamics, whereas woodlots (WL) often preserve higher total C and longer half-lives than cultivated (CT) soils.

The lower potential mineralizable C (C_0) recorded in the CT and WL soils of Sunyani and Kade suggest lower microbial activities or slower mineralization rate due to differences in the chemical compositions of organic residues (Desalegn et al., 2019; Riffaldi et al., 1996), whilst the higher C_0, recorded in the UC soils suggests an easily decomposable organic residue (Toh et al., 2020). The narrow range observed for k (Table 4.6) for CT and WL in coastal savanna zone and at Kade, implies similarity in the metabolized organic material and microbial respiration or in their degree of availability. The higher potential rate of C mineralized (C_0*k) observed in the UC, and WL soils in this study in all sites can be attributed to the higher MBC and TC (Desalegn et al., 2019; Shiny & Byju, 2021). The longer half-life ($t_{1/2}$) of C mineralization in the CT, and some WL soils indicates slow mineralization can be attributed to the abundance of the stable SOC pools (Table 4.6) (Toh et al., 2020).

The varied labile pool (C_l) values are an indication of the effect of the different soil types and land-use systems on C mineralization (Riffaldi et al., 1996). The low C_l in the CT soils compared to the WL and UC soils is attributable to the quantity and quality, and high decomposition rate of organic residues associated with cultivation, leading to a low amount of SOC and for that matter labile C (Wiesmeier et al., 2019).

The significant difference in k_l and k_2 among the land-use systems can be attributed to the relative size of the C pools. The low k_2 suggest a slower decomposition rate of the stable or recalcitrant pool whilst the relatively high k_l is indicates faster rate of decomposition of the labile pool, explaining the initial higher rate of mineralization during the

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first week of incubation compared to the latter stage (Zacháry et al., 2018). Dodor et al. (2019) and Zacháry et al. (2018) also reported a similar trend in their studies.

The shorter half-lives of C_1 and the longer half-lives of C_2 reflects how fast the labile pool is degraded leaving behind a large amount of stable pool with long turnover time. The variations in the half-lives of both the C_1 and C_2 pools can be attributed to the type, quality, and quantity of organic residues in the different land-use systems (Dodor et al., 2019). The difference in the physical, chemical, and biological properties of soils affect the decomposition rate, accumulation, and stabilization of organic C (Bolan et al., 2011). Soil texture plays an important role in the stabilization of carbon and the rate of SOC sequestration in soils (Lal, 2004b).

5.5.3 Relationship among first order kinetic parameters and organic carbon fractions in soils

The strong correlation between C_0 and the different organic carbon fractions suggest that the labile *C* fractions serve as an important C source for microorganisms in the soils (Dodor et al., 2019). The insignificant correlation between C_0 and *k* indicates that the differences in *k* values among soils cannot be attributed to differences in the relative sizes of the C pools (Desalegn et al., 2019; Riffaldi et al., 1996).

The positive correlation among the labile C fractions and TOC (Table 4.7) is an indication that the TOC is a major determinant of both labile and non-labile *C* (non-HCl-C) in soils (Bongiorno et al., 2018; Geraei et al., 2016). This also suggests that these various C fractions represent definite parts of the TOC. The significant and positive correlation between POX-C and HWEOC, HCl-C and Non HCl-C may be indicative of their representation of similar *C* pools. This also suggests that POX-C oxidation reaction does

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not target only labile but also complex form of SOM which are recalcitrant (Bongiorno et al., 2018). Morrow et al. (2016) also reported a moderate correlation between POX-C and HWEOC. They also reported a strong correlation between POX-C and HCl and non-HCl hydrolysable C (r = 0.84) which is within the range observed in this study (r = 0.709***, 0.848***), respectively.

5.6 Carbon management indices (CMI)

The carbon management index (CMI) has been used to measure the response and dynamics of SOC to land use and management changes and an integrated measure of the quantity and quality of SOC. Though the numerical value of CMI is not significant, the difference shows how management and land-use influenced the lability, stability, and amount of C, with soils having higher value considered as better managed (Zhang et al., 2020; Zhao et al., 2014).

The 100 CMI value recorded in the UC land in Walewale, Dormaa, Sunyani, Kade, Dodowa and Legon indicating and ideal situation is because the UC soils were used as a reference with which the other land-use systems were compared. The maximum CMI values observed in the WL soils of Bawku 432, Dormaa 100, and Asesewa 161 can be attributed to the high labile and total C content found in these soils as a result to the accumulation of litter on the soil surface and root exudates within the rhizosphere. Also, these soils are woodlot lands with trees and natural grasses which are undisturbed for many years, resulting in increased C inputs and lower losses (Kalambukattu et al., 2013).

The low CMI (< 100) values observed in the CT soils of Bawku, Dormaa, Sunyani, Kade, Dodowa and Legon compared to the UT soils 100 within these locations is an indication that the cultivation of these lands led to the loss of C. the high CMI (130) value

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observed in the CT of Asesewa compared to the other locations could be a result of management practices used here. Since management history was not effectively captured in this study, the interpretation of CMI results must the made with causion.

These findings corroborate the study of Kalambukattu et al. (2013), who reported forest showing the highest CMI when they studied soil carbon pools and carbon management index under different land use systems in the central Himalayan region.

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CHAPTER SIX

6 SUMMARY, CONCLUSION AND RECOMMENDATION

6.1 Summary and conclusion

This study investigated the impact of three land-use systems under four different agro-ecological zones on the dynamics of SOC and microbial activities in some Ghanaian soils.

Results indicate that the amount of C content of the soils were significantly affected by agro-ecological and land-use. And the conversion of native vegetation into agricultural lands resulted in significant increase in the amount of HWEOC in soils. In general, soils from the savannah zones recorded higher amount of POX-C in the CT whereas the TZ and SD zones recorded higher POX-C in the UC and WL soils. The soil texture had little or no effect on soils with high or very low OC content.

Generally, ecological zones influenced vegetation type and C biomass input, with the soils of the savannah zones apparently receiving less vegetation than those of the forest zones. Also, CT soils had lower TOC than uncultivated soils. Conversion of native (UC) and WL to CT lands reduced the TOC in soil. The diverse vegetation in the UC lands, coupled with the lack of disturbance in the WL increased the TOC of the soils.

Various chemical methods were used to fractionate the soil organic carbon from the different land use systems. These findings of this study indicated that the conversion of woodlot and native uncultivated land to cultivation decreased the amount of HWEOC and POX-C in the soil during the incubation. Cultivation increased the non-HCl C in soils of Bawku, Walewale, Dormaa, Sunyani, Asesewa and Dodowa but decreased in Kade and Legon, and the HCl-C in Dodowa and Sunyani soils.

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The soil microbial biomass was influenced by the land-use and organic carbon content of the soil. The highest MBC_{mic} and MBN_{mic} values were recorded in the Forest -savannah transition and the lowest in the Interior savannah zones.

The strength of the relationship between labile organic carbon fractions and other soil properties, such as TOC, suggests that these fractions quantify separate sections of the TOC with different functional features. The MBC_{mic} was poorly correlated with POX-C and other labile C fractions (HCl-C and C_{min}), suggesting the MBC_{mic} may have a limited composition of compounds and substances compared to the other labile fractions.

Labile fractions of SOC such as HWEOC, POX-C show a rapid response to land-use changes and can thus be used as a sensitive indicator of changes in SOC. The chemical (POX-C, HWEOC, HCl-C and non-HCl-C) and biological (MBC_{mic}, MBN_{mic}, C_{min}, BR, and qCO_2) fractions are relatively more sensitive to land-use changes than the TOC.

The conversion of forest to CT lands reduces the amount of C stored in soil and decreased the CO_2 efflux from cultivated soils. The high CO_2 efflux observed in the UC, and WL soils suggest a high accumulation of SOC in these land-use systems over time. The positive correlation between C_0 of the first order model and C fractions (POX-C, HWEOC, HCl-C), and the cumulative C (C_{min}), suggest that the availability of these fractions influence the mineralization of C in soils.

Across agro-ecological zones and land-use system, the double exponential equation was a better representation of decomposition dynamics than to the first order equation. Soil C is mainly stored in the stable pool form. Generally, the kinetic parameters of C mineralization (namely C pool size and *k*) were affected by an interaction of land use, and ecological zones.

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However, this remains a research challenge. The important issue brought to the fore in this study was that the mineralization parameters relate more to various C fractions than to the TOC. Many previous studies have not explored this issue adequately.

The LI was highest in the cultivated soils. This suggests that cultivation increased the rate of mineralization of C compounds. The CMI was higher in the UC, and WL soils than the CT soils. This suggests that the cultivation of soils reduces the organic C pool by rapid mineralization of SOC, whilst management systems that include the regular addition of organic inputs increase it.

6.2 Recommendation

The following recommendations were based on the results obtained from this study, the made.

- Research on SOC dynamics should be lean towards the understanding of the molecular structure and composition of SOC and the mechanism of its stabilization under specific climatic conditions. This would go a long way to further explain the effect of land-use and ecological zone on the kinetic parameters from this study.
- The study, due to limited time and lack of resources could not be expanded to consider physical fractionation of soil C to explore soil aggregation of C protection, and the manner in which this would affect the mineralization parameters. This would help better explain the land-use effect on SOC mineralization. This is an area of research that requires further research.

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