VARIATION IN SOIL CARBON STORAGE AND EMISSION IN DIFFERENT LAND USE TYPES OF THE LETABA CATCHMENT, LIMPOPO PROVINCE, SOUTH AFRICA

BY

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Declaration

I declare that the mini-dissertation hereby submitted to the University of Limpopo, for the degree of Master of Science in Agriculture (Soil Science) has not been submitted previously by me for a degree at this or any other university; that it is my work in design and in execution, and that all materials contained herein has been acknowledged accordingly.

Ntuli HI (Miss)

06/12/2022

Date

Dedication

I dedicate this mini-dissertation to God, my parents Selina and Paulos Ntuli, my siblings Trudy and Mxolisi Ntuli, my cousin Collen Skhosana and my niece Melokuhle Ntuli.

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First, I would like to thank God for the opportunity, strength and wisdom he has given me to carry out this research project. I wouldn’t have made it if it weren’t for his grace and favour upon me.

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LIST SYMBOLS, ACRONYMS AND ABBREVIATIONS

°C	Degrees Celsius
AFOLU	Agriculture, forestry and other land uses
ANOVA	Analysis of variance
C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
CO_{2eq}	Carbon dioxide equivalent
GDP	Gross domestic product
GHG	Greenhouse gas
N	Nitrogen
N_2O	Nitrous oxide
O_3	Ozone
OM	Organic matter

Abstract

The exponential growth in the world population has led to increased greenhouse gas emission. Carbon dioxide (CO_2) is one of the major greenhouse gases being emitted mainly through the burning of fossil fuels, solid waste and soil respiration, thus it's crucial to reduce its emission into the atmosphere. However, the emission of CO_2 from agricultural fields have long been overlooked. This study was aimed at attaining a better understanding of the effect of land use type on carbon (C) storage and emission from the soil. The objectives of the research were to (1) determine the variation and effect of season and land use on selected soil properties, soil CO_2 emission and soil C storage, to (2) characterise the microbial decomposer communities in the various land use types and determine their impact on CO_2 emission and to (3) determine the major soil factors driving the emission of CO_2 in the various land use types.

The study was conducted in the Letaba catchment in the Limpopo province under the banana plantation, *Eucalyptus grandis* (planted forest), bush, maize and forest (natural forest) land use types where in each, three plots were set up and C chambers were installed. The CO_2 and soil temperature data were measured by the GMP343 probe fitted with infra-red sensor (CO_2) and Pt1000 temperature sensor. While the volumetric moisture (measured in %) of the soil was measured using a soil moisture meter. The CO_2, soil moisture and soil surface temperature data were measured every two weeks for a whole year. Soil samples were also collected and analysed for chemical (exchangeable acidity, pH, macro and micro nutrients), physical (SOC stocks, MWD, bulk density, infiltration, clay % and SOC %) and biological properties (bacterial and fungal counts).

The results showed a significant ($p<0.001$) influence of season (temperature and moisture) on the emission rate of CO_2. The summer season resulted in the highest (0.11 tons/ha/day) emission rates of CO_2 as the soil temperature (30.2°C) and soil moisture (19.3%) increased during this season creating conditions which promote CO_2 emission. Thus, the winter season accounting for the lowest (0.03 tons/ha/day) soil CO_2 emission rates as temperatures (26.4°C) and moisture (7.5%) contents were lower. Higher (0.08 tons/ha/day) CO_2 emission rates were observed during autumn than that observed during spring (0.05 tons/ha/day) and winter (0.03 tons/ha/day). This is accounted for by the increased plant litter on the soil surfaces as plants shed their leaves during this season allowing for increased microbial decomposition.

The land use type also had a significant impact on the emission rate of CO_2 with the rates ranking from highest to lowest in the following order: forest > banana > maize > bush > eucalyptus. The high CO_2 emission rate under the forest land use type was due to the high amount of organic matter (OM) and the quality of the OM found on the forest floor as it is easily degradable than that found under the eucalyptus land use type. This was also due to higher root respiration as all areas without trees had standing grass biomass. The land use type affected the soil C storage significantly and the C stocks were ranked from highest to lowest in the following order: forest > eucalyptus > banana > maize > bush.

The interaction between the season and land use type displayed significant ($p<0.001$) impacts on the emission rate of CO_2. The eucalyptus land use type had the lowest CO_2 emission rate in the autumn and summer while the bush land use type had lower CO_2 rates in winter and spring. The highest CO_2 emission rates during the spring and summer season was under the forest land use type, while autumn and winter had the highest emission rates under the banana land use type. The results displayed insignificant negative relationships between all soil physical properties (except C stocks and fungal count), with both the C emission and the C storage. In contrast, the C stocks and the fungal count of the soils were the only properties which had significant ($p<0.05$) relationships with both the storage and the emission of soil C. The main driver of CO_2 emission was the soil moisture content under all the land use types, with exception of the banana land use type where soil surface temperature drove CO_2 emission.

In conclusion, the land use type and season have significant impacts on the storage and emission of C and are largely influenced by the soil surface temperature and moisture content. Also, land use type and seasons interacted to influence soil CO_2 emission rates. Thus, an improved understanding of the dynamic relationship between the land use type and C storage and emission as affected by season, soil properties and land management practices can subsequently aid in the mitigation of CO_2 emission and thus enhance soil C sequestration, to help reduce climate change.

Keywords: Carbon dioxide, emission, land use type, season

Mini-dissertation layout

The mini-dissertation consists of the introduction (Chapter 1) which provides a general outline of the study and description of the research problem. This chapter is followed by the literature review (Chapter 2) which provides a theoretical and practical overview of variation in soil C storage and emission as affected by different land use types. Chapter 3 focuses on investigating and discussing the objectives of this study by providing insight of how land use and season affected soil C storage and emission and which soil properties affected soil C storage and emission under each land use type. The final chapter (4) provides a brief summary and general conclusion of the findings and further suggest recommendations for future studies.

CHAPTER 1

GENERAL INTRODUCTION

1.1. Background

Carbon dioxide (CO_2) is one of the main greenhouse gases and thus, it is of paramount importance to monitor it and curtail its emission into the atmosphere. Although the highest CO_2 emissions are reported by industrial activities, agriculture also contributes towards emissions (Asner *et al*., 2010). Soil CO_2 release results from the respiration of roots and the decomposition of soil organic C by soil microorganisms. Although agriculture accounts for 10–14% of global greenhouse gas (GHG) emissions, it is also responsible for its sequestration (Jantke *et al.*, 2020). The soil represents the chief and most vital long term organic C reservoir in the terrestrial environment. It contains about twice the quantity of C found in the atmosphere and three times the C that is found in the plant biomass (Anokye *et al*., 2021). The storage and emissions of C under various land use types vary and conversion of one land use type to another affects CO_2 emissions. C is the main component of soil OM and helps improve the soil's water holding capacity, structure and fertility (Ray *et al*., 2020). The study conducted by Iqbal *et al.* (2008) stated that CO_2 forecasting is one of the major aspects in trying to attenuate the emission of CO_2 into the atmosphere. With the implied importance of C and the exponential growth in its emission, an improved understanding of its dynamic in relation to the plant, soil and atmosphere has become crucial for the development of attenuation strategies (Krull *et al*., 2003). This can be attained through CO_2 forecasting. The study conducted by Meng and Noman (2022) stated that CO_2 forecasting can help in the identification of major CO_2 contributors, development of greener cities, to compensate for losses caused by CO_2 emission, to increase understating of the emission foot print, asses the effect of CO_2 emission on the gross domestic product (GDP) reduction, air pollution, disease outbreaks and last and most importantly to quantify and setback irreversible climate change.

1.2. Problem statement

There is growing evidence showing that agriculture has led to reductions in the soil C stocks as found in the studies conducted by Ashagrie *et al*., (2007), Girmay *et al*., (2008), Haddaway *et al*. (2015) and Lemenih *et al.* (2005). Although agriculture is linked with the release of C it is also associated with its sequestration (Kane and Solutions, 2015). Higher C emissions are associated with warmer and rainy seasons than colder and dryer seasons as determined by Brito *et al*. (2015), Fernandes *et al*. (2002) and Huang *et al.* (2019). However, the response of these processes to seasonal variation under different land use types is not well known. In addition, the factors that drive CO_2 release in the different land use types have not been well elucidated. While it is commonly recognized that the atmospheric concentrations of CO_2 have risen evidently as a result of human activities, there is however less appreciation that natural and managed soils are also vital sources and sinks for C found in the atmosphere (Gougoulias *et al.*, 2014). Although CO_2 emitted from soils is in smaller quantities, small fluctuations in the soil C cycle could cause huge impacts on the atmospheric CO_2 concentrations (Gougoulias *et al.*, 2014). Therefore, it is vital to accurately measure the amount of C released or stored in various land use types for better management of soil organic C.

1.3. Rationale

The emission of greenhouse gases is increasing at an alarming rate thus demanding attention in terms of reducing the rate and amount being emitted into the atmosphere to sustain the environment (Yoro and Daramola, 2020). Agriculture has had an impact on the overall C emission contributing 10–14% of GHG emissions (Jantke *et al.*, 2020). Reducing its emission under the different agricultural types can help mitigate atmospheric CO_2 concentrations and subsequently help mitigate climate change (Rosenzweig and Tubiello, 2007). The different land use types may affect the storage and emissions of C. However, the quantity of C stored or emitted in these land use types is not well established. Most studies conducted such as those conducted by Anokye *et al*. (2021), Lai *et al*. (2016), Rajput *et al.* (2017), Sharma *et al.* (2019) and Shiferaw *et al.* (2019) showed that conversion of natural land types into cultivated land leads to great releases of C into the atmosphere due to the subsequent reduction in storage capacities. Hence an understanding of the relationship between land use type, C stock and emission is crucial and can be used efficiently to mitigate the emission of CO_2 into the atmosphere. Although much consideration has been given to the anthropogenic causes and impacts of these gases, the importance and inferences of microorganisms have remained unknown (Dutta and Dutta, 2016). The effect of microbial biomass and diversity on C storage and emission is not fully understood thus this study aims at bringing light to this overlooked aspect. The emission and storage of C vary with change in seasons (temperature and moisture) and there is little knowledge on how it affects the emission and storage of C as well as the microbial decomposer community under various land use types (Brito *et al*., 2015). The changes in season not only brings about changes in temperature and moisture which affect soil respiration, but also has an impact on the population and the activity of the soil microbes. Therefore, it is crucial to understand the relationship between the change in season and the microbial diversity and biomass as microbes also have an important role in the emission of C as well as its sequestration. Although C storage is of importance with regards to soil health for agricultural activities, pastures and forest, its emission is also as crucial as it influences climate change which in turn affects crop production (Girmay *et al.*, 2008). With the threat of climate change, the data on emission and sequestration of C is crucial for establishing approaches that will improve output by improving sequestration and storage of C and reducing its emission (Lai *et al*., 2016). An ultimate understanding of the relationship between C storage and emission as affected by climatic variation due to changes in the seasons and the microbial biomass and diversity is essential to develop mitigation strategies to counteract the imminent threat of climate change.

1.4. Purpose of the study

1.4.1. Aim

This study aims at attaining a better understanding of the effect of land use type on the storage and emission of soil C under seasonally arid tropical conditions.

1.4.2. Objectives

The objectives of this study are to:

i) Determine the variation of selected soil properties, soil CO_2 emission and soil C storage across various land use types.
ii) Determine the effect of season and land use on soil CO_2 emission and storage.
iii) Characterise the microbial decomposer communities in the various land use types and determine their impact on CO_2 emission.
iv) Determine the major soil factors driving CO_2 release in the various land use types.

1.4.3. Hypotheses

i) There is no variation in selected soil properties, soil CO_2 emission and soil C storage across various land use types.

ii) Season and land use have no effect on soil properties, soil CO_2 emission and soil C storage.
iii) There is no difference in the microbial decomposer communities found in the various land use types and thus have no impact on CO_2 emission.
iv) CO_2 release in the various land use types is driven by the same soil factors.

CHAPTER 2
LITERTURE REVIEW

2.1. Climate change and greenhouse gases

2.1.1. Climate change

Climate change can be defined as the long-term alteration in the weather patterns which may be attributable to natural factors such as the variations in the solar cycle, sunspot activity and vulcanicity or due to human activities (Khaoma and Naigra, 2007). The world's population has increased by approximately 19.5 million in the past ten years thus leading to the increased demand of food and services (Toru and Kibret, 2019). The major issue in sustaining both humans and the environment is the change in climate as increased food production and manufacturing leads into increased greenhouse gas emissions which are the source of climate change (Liu *et al*., 2015). Greenhouse gases (GHGs) are gases which can absorb and emit infrared radiation and thus act as blankets which surround the earth and trap the suns heat then subsequently increases the temperatures (Easterbrook, 2016).

2.1.2. The types and causes of greenhouse gases

The prime greenhouse gases in the atmosphere include water vapour, ozone (O_3), CO_2, nitrous oxide (N_2O) and methane (CH_4) (Easterbrook, 2016). The emission of GHGs vary significantly between each sector with the energy sector contributing 35% towards the Global emission, the AFOLU (agriculture, forestry and other land uses) sector contributing 24%, the industry sector contributing 21%, the transport sector contributing 14% and the building sector contributing 6% (Lamb *et al*., 2021). CO_2 is a major greenhouse gas and its emission to the atmosphere can be encouraged by burning of fossil fuels, solid waste and soil respiration. Forabosco *et al*. (2017), Grossi *et al*. (2019) and Oertel *et al*. (2016) linked the emission of CH_4 to gases released by transportation, natural gases, OM decomposition and livestock's manure while, Law *et al*. (2012), Oertel *et al*. (2016) and Rojas-Downing *et al*. (2017) linked emission of N_2O to agricultural practices, land use, industrial activities, burning of fossil fuels, treatment of water management and solid waste.

2.1.3. The types and quantities of greenhouse gases emitted under agricultural fields

Although GHGs emission has had a huge influence on the environment over the past decade, there hasn't been much attention being paid towards emissions as a result of agricultural fields even though it forms part of the sector with the second highest GHG emission (Lamb *et al*., 2021). Agricultural fields mainly release N_2O, CH_4 and CO_2 and the emission of these gases has exponentially increased since 1990 (Ntinyari and Gweyi-Onyango, 2021). The study conducted by the FAO (2020) which investigated the trends in GHG emissions from the year 2000-2018 found that CO_2 was the highest GHG being emitted from agricultural fields. The CO_2 emission globally was 9.3 billion tonnes of CO_2 equivalent (CO_2eq) (which is a measure of comparison of CO_2 emission to the global warming potential of CO_2), while the combined global emissions of CH_4 and N_2O were only 5.3 billion tonnes CO_2eq in the year 2018 (FAO, 2020).

2.1.4. The effects of greenhouse gases

The increase in greenhouse gases will lead to the subsequent increase in global change which will cause changes to the weather conditions, the ocean, human and animal health. The changes in weather will include increase or decrease in temperature, rainfall and increase in wildfires, flooding, droughts, cyclones, and storms (Seneviratne *et al*., 2012). Climate change may also result in the melting of ice glaciers, rise in the sea level and ocean acidification. These changes will have a huge impact in the health of humans, animals and plants. Climate change may also pose as a threat to the biodiversity of animals and plants as these extreme conditions are not suitable for them (Doney *et al*., 2012). Climate change has a great influence on agriculture with the changes in temperature and rainfall having the greatest impact as most production practices are dependent on the adequacy of these factors (Bryan *et al*., 2013). Thus, studying and understanding climate change is key to sustaining the environment, food security and the livelihood of animals and humans.

2.2. Soil organic C

2.2.1. The C cycle and soil organic C

Carbon is one of the most common elements found in the universe and it is the basis of all living things (Gupta, 2018). C is found in various reservoirs such as the atmosphere, the soil, rocks, ocean, plants and animals (Gupta, 2018). It is in a constant state of flow from one reservoir to another through varies processes such as photosynthesis, respiration and burning of fossil fuels (Hilton and West, 2020). This process of C movement from one reservoir to another is called the C cycle (Figure1). The environment is a closed type, thus the amount of C found within the environment does not change but, the C within different reservoirs may change over time. The process of C cycling is important in ensuring hospitable environments for plants and animals (Hilton *et al*, 2020).

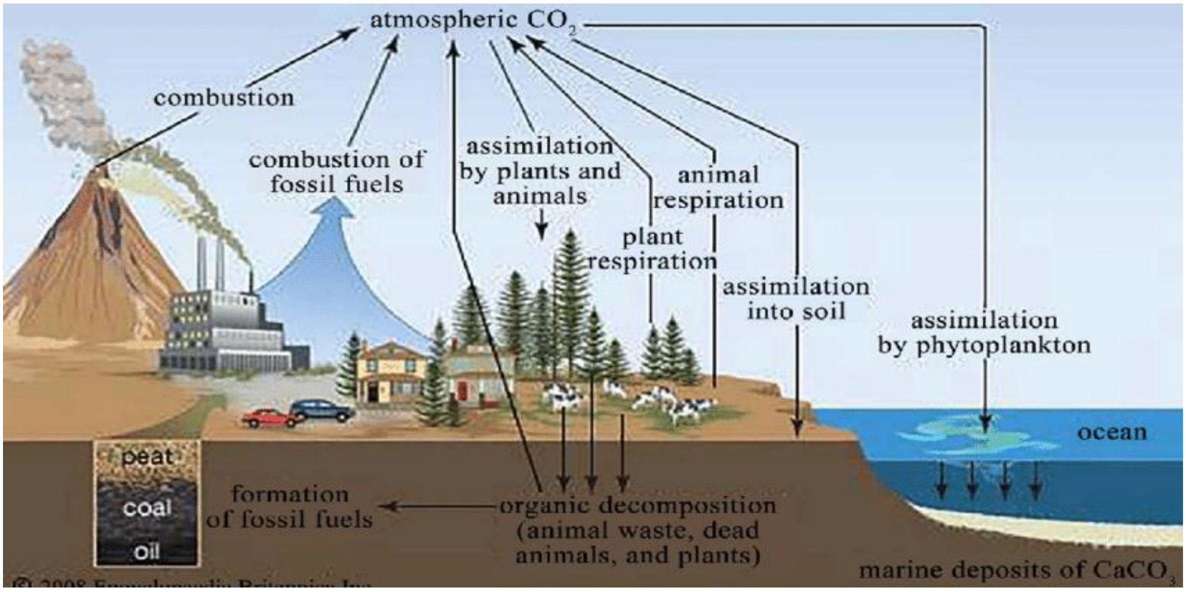

Figure 1: The C cycle (Vadillo, 2019).

The soil represents the chief and most vital long term C reservoir in the terrestrial environment, and it also partakes in the C cycle. The soil can store and emit different forms of C which can be classified as organic and inorganic C (Trivedi *et al*., 2018). Inorganic C can be defined as mineral-based carbons such as carbonates and lime, while organic C is formed from soil OM and C compounds such as waxes, proteins, sugars, carbohydrates, starches, organic acids, lignins and resins (Abbas *et al*., 2020). Soil organic matter (SOM) is defined as material which is composed mainly of hydrogen, oxygen and C with trace amounts of phosphorus, potassium, magnesium, sulfur, nitrogen and calcium. SOM is classified into dead or living components.

Soil organic carbon (SOC) is considered a measurable component of SOM and its quantity in the soil is largely affected by various processes in the ecosystem such as photosynthesis, respiration, and decomposition (Ontl, 2020). Lefèvre *et al*. (2017) stated that, the C in the soil can be stored as soil organic C or as carbonates formed through dissolving of CO_2 in soil water where the calcium and magnesium minerals in the soil combine with it especially in dessert or arid soils to form caliche. The soil organic C found within the soil moves from the soil into the atmosphere and plants through processes such as photosynthesis, respiration, plant assimilation, OM decomposition and burning of fossil fuels as illustrated in figure 1.

2.2.2. The importance of soil organic C

The soil organic C influences various soil properties directly and indirectly. The direct impacts of SOC include improvement of soil structure or the tilth. This allows for improved physical properties of the soil such as porosity and aeration (Lehman *et al*., 2015). Through improved soil structure the soils water retention is also subsequently improved thus reducing the risks of soil erosion and nutrient leaching (Rawls *et al*., 2003). The improved aeration and water holding capacity of the soil creates environments conducive for soil microorganisms which aid in the decomposition process (Khosro *et al*., 2011). The enhanced environment for soil microbes also aids in the increase in microbial biomass and activity (Trivedi *et al*., 2018). This is essential to soil fertility as these microbes are able to convert unavailable nutrients to forms which are readily available for plant uptake such as the process of nitrogen fixation (Khosro *et al*., 2011). This enables plant growth as nutrient required by the plants are made readily available to the plants for uptake.

The study conducted by Dexter (2004) found that soils with higher organic C enhanced root development due to improved aggregation of the soil. Lehman *et al*. (2015) stated that important soil functions which determine the quality of the soil include the ability of the soil to allow water to flow and is able to retain the water, ability to transport and retain dissolved nutrients, good aggregate stability, the ability to cycle nutrients and soils that can maintain biodiversity. The SOC can directly or indirectly influence these important soil functions and it can thus be used as an indicator of the soil quality. Good maintenance of the soil organic C is vital for the sustainability of agriculture and aid in reducing the contribution of agricultural fields to CO_2 emission (Rahman, 2013).

2.3. Soil C storage and emission

The soils serve as an important reservoir of C as it stores greater quantities than the atmosphere and the plant biomass (Anokye *et al*., 2021). The C found in the soil is largely accounted for by the process of C sequestration which refers to the process of fixation of the C from the atmosphere through plants or organic residues which is then stored in the soil allowing for minimization of its re-emission into the atmosphere (Lal *et al*., 2015). The studies conducted by Lefèvre *et al*. (2017) and Ontl (2020) stated that the process of atmospheric C sequestration can occur in three stages which include the process of CO_2 extraction from the atmosphere by plants for the process of photosynthesis, the transmission of CO_2 from the plants into the plant biomass and through transfer of the C in the plant biomass into the soil. The C sequestered by the plants may also ultimately be taken up by animals through feeding on the plants (Ontl, 2020). Abbas *et al*. (2020) and Ray *et al*. (2020) stated that this C can be returned to the atmosphere through respiration of animals, or it can be added to the soil through animal manure and plant root respiration and exudation or through death of the plant and the animal.

The additions of SOC into the soil are mainly determined by the root biomass of the plant and residues deposited by the plant litter. The plant roots or biomass contributes to the SOC content directly through root growth and death as well as indirectly through the transfer of C compounds from the plant roots to the soil microbes in symbiotic associations (Abbas *et al*., 2020). The process of decomposition of SOM by soil microorganisms results in both addition and loss of C in the soil through emission of CO_2 into the atmosphere and retention of C through the formation of humus (Ontl, 2020). The extent of decomposition is largely affected by climatic conditions such as the temperature and the water content of the soil as these factors directly influence the plant root respiration and the microbial activity responsible for the decomposition process (Lefèvre *et al*., 2017). The C in the soil can also be lost through root exudates as oxalic acids or through the process of erosion and leaching of dissolved C resulting in C loss into the rivers or leaching into the ground water (Lefèvre *et al*., 2017).

While soils can serve as a major sink of atmospheric greenhouse gases, they are also considered one of the major sources of greenhouse gases such as CO_2 as majority of the terrestrial ecosystem is covered by soils (Wachiye *et al*., 2020). Soil respiration is amid the chief processes of the transfer of CO_2 between the atmosphere and the terrestrial ecosystem (Phillips and Nickerson, 2015). It can be defined as the process of CO_2 release from the soil. The study conducted by Rahman (2013) specified that the main sources of soil respiration include the decomposition of SOM by soil microorganisms and the respiration of soil fauna and plant roots, where soil microflora contributes 99% of the CO_2 resulting from OM decomposition. These sources of respiration change throughout the year and vary with changes in the soil temperature, soil moisture and land use type (Dilekoğlu *et al*., 2017). The organic C found within the soil experiences minor transformations over long periods of time. The studies conducted by Ray *et al*. (2020) and Dilekoğlu *et al*. (2017) both associated these transformations with variations brought about by seasons and the type of land use. A great understanding of the dynamic relationship between the season and the land use and how it will affect the emission and storage of soil C is essential for development of procedures aimed at reducing CO_2 emissions into the atmosphere (Krull *et al*., 2003).

2.3.1. The effect of soil temperature, moisture and microbial biomass on soil C storage and emission

2.3.1.1. The effect of soil temperature on soil C storage and emission

The temperature of the soil is not only important for seed germination or plant growth but is also considered one of the major factors influencing the soil C cycle (Oertel *et al*., 2016). The ability of the soil to store C is influenced by various soil properties with the soil temperature being one of the most common factors. The factors which affect the temperatures of the soil include the amount of solar radiation, the soil cover, OM content, soil moisture, soil colour, slope and the texture of the soil (Onwuka, 2016). Soils which are darker in colour, have higher OM content, are course textured or which receive higher solar radiation will likely have higher soil temperatures. The study conducted by Zhao *et al*. (2017) associated increase in the soil temperature with increased microbial biomass and activity. This was due to the presence of conducive environments for soil microbes thus their high activity and biomass as stated in the studies conducted by Heinze *et al.* (2017).

The increase in soil temperatures results in increased decomposition which subsequently increases the soils organic C input in the form of humus (Hartley *et al*., 2021). However, decomposition does not only add C to the soil but releases a higher quantity of C into the atmosphere due to microbial respiration (Ontl, 2020). Soils which have lower temperatures due to either higher soil cover, lighter colours or lower solar radiation tend to have higher organic C contents. This is due to the conducive environment required by most decomposer microbes for the process of decomposition to occur (Thornley and Cannell, 2001). This will thus result in the accumulation of OM in the soil.

The studies conducted by Guo *et al*. (2017), Iqbal *et al*. (2008) and Oertel *et al*. (2016) found that higher soil temperatures were the main drivers of CO_2 emission as increased temperatures promoted increase in microbial biomass and promoted root growth which all together led to high release of CO_2 into the atmosphere. However, the study conducted by Akbolat *et al.* (2018) stated that the impact of soil temperature on the emission of CO_2 from the soil is limited to the first five centimetres of the soil. The study conducted by Atkin *et al*. (2000) stated that although high temperatures encourage decomposition, temperatures higher than 30°C result in the death of most plants, thus lower CO_2 will be released into the soil. The decrease in soil temperatures results in reduction of soil microbial activity thus the subsequent reduction in microbial respiration thus lower CO_2 emission (Akbolat *et al.*, 2020).

2.3.1.2. The effect of soil moisture on soil C storage and emission

Most studies such as those conducted by Dilekoğlu *et al*. (2017) and Ray *et al*. (2020) found that the moisture content of the soil has a great impact on the storage and emission of C to similar extents as that of the soil temperature. Other studies such as that conducted by Oertel *et al*. (2016) and Novara *et al*. (2012) stated that under field conditions, the effect of soil temperature and soil moisture overlap and defining clear boundaries between these factors becomes relatively difficult. This also makes determination of the association between these two factors challenging.

The moisture content of the soil also has a huge impact on the microbial biomass and activity as it partakes in creation of conducive environments for the soil microbes. The study conducted by Moyano *et al*. (2013) states that the ideal moisture content for decomposition is at field capacity or when approximately 60% of the soil pore spaces are filled. This is because the environment provides the microbial decomposer communities with adequate moisture and aeration. Under field capacity conditions, most of the soil organic C will be lost due to respiration and decomposition. Only a smaller fraction of the OM will be converted to humus by the soil microbes (Ontl, 2020).

Under conditions where more than 80% of the soil pore spaces are filled with water or under saturation, the ability of microbes to respire will be hindered as aeration is decreased, this will lead to lowered microbial biomass and activity with the subsequent decrease in OM decomposition (Novara *et al*., 2012). Under these conditions, more OM will accumulate in the soil. The state of saturation also hinders root respiration, this will subsequently reduce the amount of CO_2 being emitted from the roots into soil and from the soil into the atmosphere (Novara *et al*., 2012). In contrast to field capacity where CO_2 is produced under aerobic conditions, saturation creates anaerobic conditions and the study conducted by (Rahman, 2013) found that these conditions result in emission of CH_4. The emission of CH_4 is however dependent on the quantity of organic C in the soil, where larger quantities result in higher emissions and vice versa (Rahman, 2013).

The soil moisture content at the permanent wilting point will also result in reduction of the microbial biomass and activity. This will be due to inadequacy of moisture required by the soil microbes to be able to carry out decomposition (Herndon *et al*., 2015). The decreased microbial biomass and activity thus increased storage of C as CO_2 emission will be reduced. The studies conducted by Guo *et al*. (2017) and Oertel *et al*. (2016) found that adequate moisture is essential for microbial activity and moisture is of importance mostly in soils which are relatively dry as it affects the microbial communities which are the main sources of respiration in those soils. The combination of the ideal soil temperature, soil moisture content and SOM may result in conditions which will promote CO_2 emission and can be hastened by certain soil management practices (Oertel *et al*., 2016).

2.3.1.3. The effect of soil microbial biomass and diversity on soil C storage and emission

Soil microbial biomass refers to the quantity of the living component of SOM which is responsible for the process of decomposition such as protozoa, archaea, fungi, and bacteria (Dunlap, 2001). The microbial diversity refers to the range of different kinds of microbes. The common microorganisms in soils are the bacteria and fungi. Soil microorganisms play vital roles in the processes of fixation or making plant essential nutrients available for plant uptake (Khan, 2005). The soil microbes also play important roles in the soil structure, aggregate stabilization, pathogen suppression and nutrient cycling (Pankhurst and lynch, 1995). The microbial biomass and activity play a major role in the storage and emission of soil C and there are various factors which have an impact on their biomass and activity. Soils with low moisture content, organic C, temperature, too low or too high soil pH or course textured soils are bound to have low microbial biomass and activity (Müller and Höper, 2004). This will result in lower CO_2 emission and thus may promote C storage or accumulation.

The studies conducted by Ahmed *et al*. (2019), García-Orenes *et al*. (2010) and Thornley *et al*. (2001), found that the highest microbial biomass and activity are mainly influenced by the temperature, moisture and the amount of OM found in the soil. The ideal environment for majority of microbial activity is said to be in warm temperatures, moist soils, neutral or slightly acidic pH soils and adequate OM would result in higher and faster OM decomposition (Deenik and McClellan., 2007). This will result in addition of C into both the atmosphere and the soil. While the study conducted by Thornley *et al*. (2001) found that even if the amount of OM available such as plant litter or animal residues are high, if the temperature, moisture and sometimes the pH of the soil are either too low or too high, microbial activity may still be low. Thornley *et al*. (2001) stated that the conditions required for maximum microbial biomass and activity should not be considered individually as one may act as a limiting condition.

2.3.2. The effect of seasonal variation on soil C storage and emission

A season can be defined as the time of the year characterized by specific climatic conditions and the changes of the climatic conditions is referred to as seasonal variations (Fischer *et al*., 2020). The world experiences different climatic conditions during different times of the year and the different climatic conditions are grouped into four seasons namely, summer, autumn, winter, and spring (Khavrus and Shelevytsky, 2012). The seasons experienced in the southern and northern hemisphere throughout the year differ due to the position of the Earth in relation to the sun, for example summer in the southern hemisphere occurs from the beginning of December till late February in contrast summer in the northern hemisphere occurs from June to August (Khavrus *et al*., 2012).

The summer season is characterised by longer days, highest temperatures with bulk areas receiving most of its rainfall. The winter season is characterised by shorter days, lower temperatures and close to zero rainfall in most areas, while others receive snow (Khavrus *et al*., 2012). In Autumn, the temperatures and the amount of rainfall decrease but these are usually still higher than those experienced during the winter season. The other common characteristic associated with autumn is the shedding or loss of leaves by most trees. In contrast to autumn, spring is characterised by increase in temperature and rainfall and is associated with the processes of plant sprouting, unfurling of leaves and blossoming of flowers (Khavrus *et al*., 2012). Soil C levels result from the interactions between the various ecosystem processes which include photosynthesis, respiration, and decomposition (Wuest, 2014). All these processes are somewhat affected by the soil's moisture content, temperature, and biomass accumulation (Rohr *et al*., 2013).

Studies conducted by Anokye *et al*. (2021), Brito *et al*. (2015) and Dhital *et al*. (2014) showed that the emission of CO_2 from the soil tend to increase during the summer season as the temperature and rainfall increases. The high soil temperatures combined with suitable moisture provide conducive environments for soil microbes. This will encourage microbial activity and division which will be responsible for the decomposition of the OM in the soil (Mellander *et al*., 2004). This will thus lead into loss of CO_2 into the atmosphere and thus account for higher CO_2 emissions from soils during the summer and spring season than the colder and dryer autumn and winter seasons (Anokye *et al*., 2021).

The studies conducted by Iqbal *et al*. (2008) and Ray *et al*. (2020) also found that the seasonal variation was highest during the summer season, lowest during the winter season and moderate during autumn and spring. These seasonal variations brought about changes mainly with the soil temperatures and soil moisture content which was linked to higher microbial biomasses and activities thus higher CO_2 fluxes during the summer season than winter season. Iqbal *et al*. (2008) found that the higher CO_2 fluxes were not only influenced by increased microbial activity but by the active root growth which is associated with higher temperatures.

2.3.3. The effect of land use on soil C storage and emission

The type of land use, the vegetation cover and the type of management practice occurring in an area highly affects the soil disturbance and the soil C dynamic (Toru *et al*, 2019). The process of conversion of forests or grasslands to cultivated lands causes reduction in the soil organic C levels as stated by Tolimir *et al*. (2020) and Girmay *et al*. (2008). The presence of trees usually implies that the soil organic C will be higher than that in the cultivated land. Trees provide shade to the ground which will reduce the amount of sunlight in direct contact with the soil surface (Anokye *et al*., 2021). The reduced contact between the soil surface and the sunlight will promote lower soil temperatures in forest lands than those in exposed cultivated fields. The decomposition of OM will therefore be slower than that in cultivated fields (Rajput *et al*., 2017). This will result in higher organic C storage than C emission in forested land.

The type of vegetation is also crucial in the accumulation of soil organic C. Forested lands produce organic material which are much more difficult to decompose or breakdown than those produced in cultivated fields (Lemenih *et al*., 2005). The complex structures of the OM produced by trees takes more time to break down and thus this slows down the process of decomposition implying that there will be a higher accumulation of organic material and thus lower CO_2 emission.

The studies conducted by Girmay *et al*. (2008), Lai *et al*. (2016), Lemenih *et al*. (2005) and Sharma *et al*. (2019) determined that conversion of forest lands to cultivated land leads to a drastic loss of soil organic C. This loss of C is accounted for by the overall reduction of the OM added to the soil. This means there's less organic material to add on to the existing soil organic C content. Also, cultivation usually involves tilling the soil which helps breaks down residues and improves aeration but also hastens the oxidation process resulting in the loss of C through CO_2 (Yu *et al*., 2020). The exposure of cultivated field also hastens the process of oxidation and the breakdown of OM which results in emission of CO_2 (Lai *et al*., 2016).

In general, the plant biomass plays a critical role as the main source of soil organic C. When the biomass decomposes some parts of the organic carbon are degraded easily than others. The much more stable OM such as those produced by trees is shielded from decomposition mainly through the various stabilization mechanisms and it will therefore contribute to C sequestration (Yeasmin *et al*., 2020). The conversion of forest land to cultivated land will have lower soil organic C losses than that which will be lost from conversion of grasslands to cultivated lands. This is because the soil organic C produced in forests is much more stable than the labile organic C produced under grasslands (Toru *et al*., 2019). The type of management practice also has a huge impact on the storage and emission of C in the soil (Paustian *et al*., 2000). The storage of C in the soil is enhanced where there are less disturbances such as those in forest lands than in grasslands or cultivated land. This is proven true by studies conducted by Toru *et al*. (2019) and Rajput *et al*. (2017) where fields exposed to low till or no-till fields had higher soil organic C as this practice allows for increase in the accumulation of soil organic C. This aids in retaining the crop residues on the soil surface intact for longer periods than it being broken down under tillage (Paustian *et al*., 2000). Since the OM is broken down to an extent through tillage, the process of decomposition will be faster as less amount of work is required to degrade the matter (Adl *et al*., 2006).

This will result in higher release of C from the soil into the atmosphere, thus lower soil organic C content (Dignac *et al*., 2017).

Some agricultural fields practices add green manure to the surface of the soil. This aids in retention of organic C in the soil (Cooperband, 2002). The increase in the coverage of the soil allows for increase in moisture retention and reduction in the amount of solar radiation that the surface will receive. This will create moist and relatively cool soil conditions. Under such soil conditions, the microbial biomass and activity is low thus the process of decomposition will be slower and will promote longer retention of soil C than in exposed hot and moist soil conditions (Franzluebbers, 2002). The type of green manure will also play a huge role in the rate of decomposition of the organic material (Yu *et al*., 2020). The use of highly degradable OM such as the labile organic material of grasses will mean the rate of decomposition will be higher thus resulting in higher rate of C emission.

2.4. Work not done on problem statement

With the evident increase in the emission of CO_2, there is a need for development of attenuation strategies which can be effectively attained through CO_2 forecasting as stated by Meng *et al.* (2022). The Limpopo province is highly abundant in agricultural resources thus majority of the area is utilized as agricultural land, with maize, banana and forestry forming part of the major entities in the province (Oni *et al.*., 2012). However, the emission rate of CO_2 of these land use types in the seasonally arid subtropical conditions are not well known (Brito *et al*., 2015). Although many studies have been conducted regarding the drivers of CO_2 emission from the soil, contradicting results have been found in the studies conducted by Anokye *et al*. (2021), Iqbal *et al.* (2008) and Ray *et al*. (2020) where the soil temperature was the main driver of CO_2 emission, while that conducted by Koerner and Klopatek (2002) and Natali *et al*. (2015), soil moisture was the main driver. In contrast to the temperature and moisture being the main driver Fernandes *et al*. (2002) found that the soil temperature and moisture only had small impacts on CO_2 emission rates. With these contradicting results, there is a need for gathering information on the main drivers of CO_2 emission in the seasonally arid tropical conditions to enable precise CO_2 emission forecasting.

CHAPTER 3

VARIATION IN SOIL CARBON STORAGE AND EMISSION IN DIFFERENT LAND USE TYPES OF THE LETABA CATCHMENT, LIMPOPO PROVINCE, SOUTH AFRICA

Abstract

The soils are becoming one of the most important natural resources as there's an increased demand to sustain life on earth. One of the soils essential functions is its ability to retain C and sequester that in the atmosphere. The aim of this study was to identify how the soil stores and releases the C under different land use types and what drives the storage and emission of C under each land use type. In this study, the emission and storage of C under five land use types was investigated. The effect of the season and land use type on the emission rate of CO_2 was significant ($p<0.001$) for all the land use types. The CO_2 emission rate as affected by the season and the land use type was rank in following order: (season) summer > autumn > spring >winter and (landuse) forest > banana > maize > bush > eucalyptus. The regression analysis was positive between the moisture and CO_2 emission rate as well as that between the soil surface temperature and CO_2 emission rate. In contrast, the regression relationship between CO_2 emission rate and soil physical properties was only significant while compared to the soil C stocks. The results illustrate that the season and land use affect the amount of C found in the soil. This is further accounted for by the soil properties such as the C stocks, the type of OM, the soil pH, bacteria, fungi and the management practices.

Keywords: C, emission, land use, moisture, temperature

3.1. Introduction

The soils are increasingly becoming an important resource as the challenges brought about by climate change, population growth, biodiversity loss and land degradation increase (Vargas-Rojas *et al*., 2019). This thus acts as the driver into expanding the knowledge of the soil dynamics. Carbon has long been considered an important soil property, but with the changing environment there is more attention being paid to the importance of the soil with respect to climate change (Minasny *et al*., 2013). Soil C is described as the quantifiable portion of the soil OM and plays a vital role in all living things. It is essential for soil health and serves as the largest reservoir of C in the terrestrial environment (Anokye *et al*., 2021).

The increase in the CO_2 emission has forced scientists to branch into investigating other ways in which C can be reduced (Stevens *et al*., 2020). Since the soil stores high quantities of C, its contribution to reducing CO_2 being emitted into the atmosphere is being investigated. The soils can store C in the form of OM and through decomposition, the C can be transformed into much complex structures which are not easily degradable such as humus (Wachiye *et al*., 2020). This allows for the storage of C in the soil for longer periods. Although the soil is considered as a solution to CO_2 emission, it is also one of the contributors of CO_2 into the atmosphere. CO_2 is lost from the soil mainly through soil respiration which is affected by the microbial activity and the respiration of the roots (Gougoulias *et al*., 2014). Thus, a good understanding of the relative relationship between the soil C storage process and emission is essential in maintaining an adequate C content in all the reservoirs within the ecosystem (Minasny *et al*., 2013).

3.2. Methodology and analytical procedures

3.2.1. Description of study area

The research was conducted at the Letaba Catchment which is located between longitudes 30°0′ and 31°40′ East and latitudes 23°30′ and 24°0′ South in the Limpopo Province of South Africa. The catchment is part of the Luvuvhu / Letaba Water Management Area (WMA) as illustrated in Figure 2 (Sinha and Kumar, 2015). This area experiences a mean annual temperature which ranges between of 18 °C to 28 °C. The study area receives precipitation which ranges from 300 mm/a to 1200 mm/a (Querner *et al.*, 2016). The land use types in the basin are mainly grasslands, savannahs and shrub lands which take up to 68% of the area. The cropland covers approximately 26% of which 1.7% is irrigated. The woodlands and forests account for 6% of the remaining area. Agriculture in the Letaba catchment is typically extensive, however the irrigation of cultivated land is the sector which demands the most water in the Letaba catchment (Lane-Visser *et al.*, 2014). The banana land use is located at an elevation of 794.0 m with the Grand Nain banana cultivar of the *Musa acuminata* being the commercially grown tree species. The banana land use type received irrigation through the drip irrigation system. The cultivated forest is located at an elevation of 734.6 m with the *Eucalyptus grandis* (Rose gum) being the dominant tree species. This land use type did not receive any irrigation throughout the study period. The bush land use type located at an elevation of 610.2 m was classified as a Kalahari bush veld with the *Acacia erioloba, Tarchonanthus camphoratus* and *Grewia flava* as the dominant tree species, while the *Digitaria eriantha* as the dominant grass species. The bush land use type also didn't receive irrigation. The traditional variety of maize was produced in the communal maize field and it did not receive any irrigation throughout the study period. It is located at an elevation of 658.5 m and the soil was tilled before plantation of the maize. The forest land use type (Valley Bushveld) located at elevation of 611.6 m had the evergreen *Scutia myrtina*, *Azima tetracantha*, *Capparis serpiaria* as the dominating tree species and the perennial *Megathyrsus maximus* as the dominant grass species. The forest land use type also didn't receive any irrigation throughout the study period.

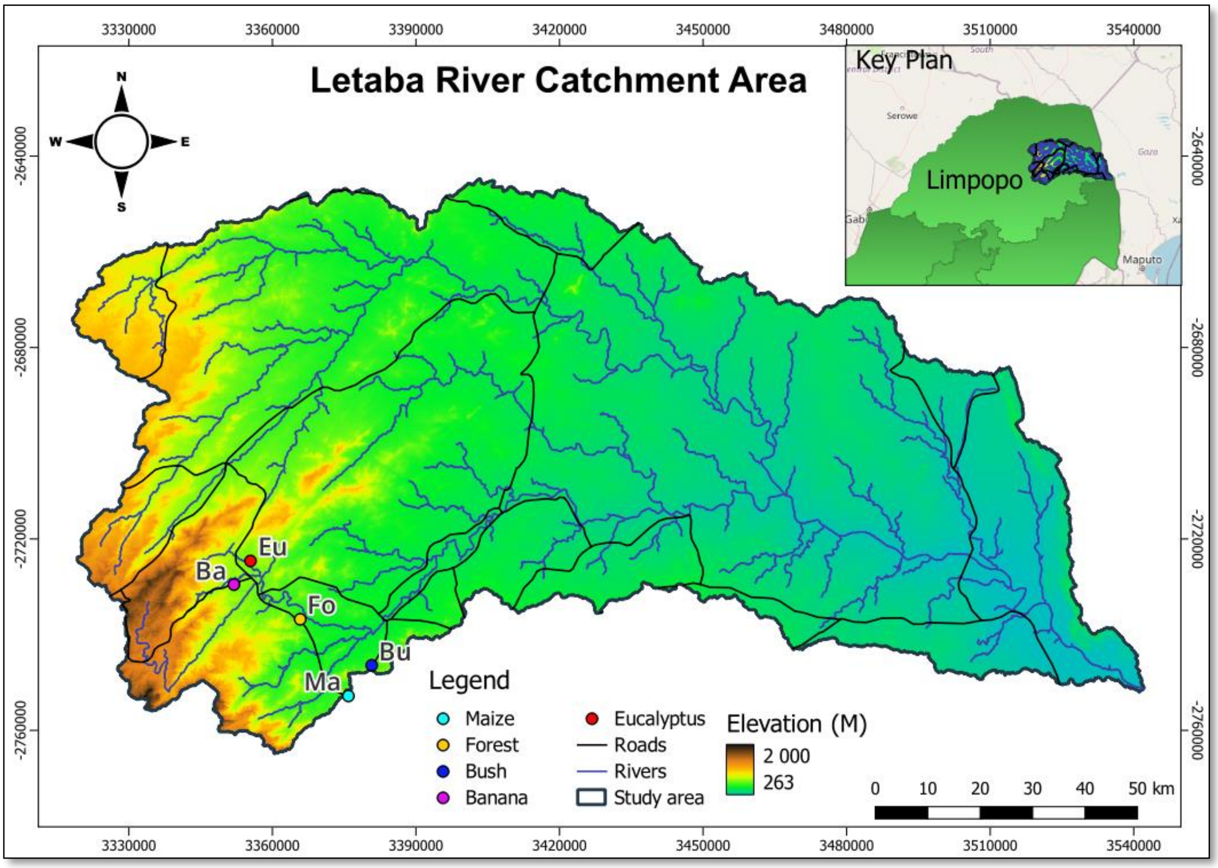

Figure 2: Locality map of Letaba Catchment, Limpopo, South Africa. Ba = banana, Bu = bush, Eu = eucalyptus, Fo = Forest and Ma = Maize.

3.2.2. Experimental design, data collection and soil sampling

Around the Letaba catchment, five various land use types were selected based on the closeness of each land use type to the other as data collection for CO_2 is time sensitive. These land use types were also selected because they form part of the major land use practices in the province by area. The land use types included *Eucalyptus grandis* plantation, banana orchards, communal maize field, forest, and natural bushes. A split plot design was applied, with the seasons (summer, autumn, winter, and spring) as the main plots and the land use types (*Eucalyptus grandis* plantation, banana plantation, communal maize field, natural forest, and natural bushes) as subplots. Three 20 m x 20 m experimental plots were set up randomly in each land use type.

In each experimental plot, one CO_2 chamber was constructed and installed following method outlined by Munjonji *et al*. (2020) where CO_2 emission and soil temperature readings were collected every two weeks between 10h00 and 14h00 for a full year from the C chambers using a GMP343 probe fitted with an infra-red sensor (GMP343, Vaisala, Helsinki, Finland). The C chambers consisted of two separate parts namely: the chamber ring and the chamber lid as illustrated in figure 3 below. The chamber rings were constructed from PVC rings of 20 cm in diameter and 15 cm in height and were inserted into the soil to a depth of 5 cm. The chamber lid was constructed from PVC rings of 20 cm in diameter and 10 cm in height. It was sealed on one side with a PVC circle, and it consisted of a small gas ball valve to avoid pressure build up during data collection. The chamber lid also had an opening which connected the CO_2 GMP343 probe.

Figure 3: CO_2 chamber with the MI170 data logger connected

During data collection, the CO_2 GMP343 probe was connected to an external MI170 data logger. The chamber lid was then attached to the chamber ring and was sealed tightly. The temperature was also measured in the gas chamber by the GMP343 probe which was fitted with a Pt1000 temperature sensor. The CO_2 emission and soil temperature within the chamber were recorded by the MI170 data logger every 30 seconds for 5 minutes. The volumetric moisture (measured in %) of the soil was measured using a soil moisture meter (SM150T, Delta-T Devices Ltd, Cambridge, United Kingdom) across the land use types, where the probe was inserted into the soil to a depth of 5 cm. The soil moisture data was collected in field every two weeks for a full year.

Soil samples for chemical analysis were collected from the 0-15 cm and 15-30 cm soil depths from each plot across the five land use types using augers resulting in 30 samples. A total of 15 soil samples for aggregate stability were also collected under each plot across the five land use types. A spade was used to clear and collect clods from dry soil which were carefully transferred into labelled bags and transported to the lab for analysis. An additional 15 samples were collected for soil bulk density following the core ring method (Cresswell and Hamilton, 2002). In each plot across the five land use types a cylindrical core was pressed into the soil to a depth of 5 cm and were thereafter removed, trimmed to remove excess soil, and placed in labelled bags. The soil samples were then transported to the University of Limpopo soil science laboratory where they were air-dried and sieved for further analysis. Soil samples for soil microbial analysis for each plot across the five-land use types were collected using a clean auger where the samples were then transferred into clean labelled bags and into a cooler box with ice. Immediately after collection the samples were transported to the lab for microbial analysis.

3.2.3. Soil analysis procedure

Soil carbon dioxide emission

The soil CO_2 emission was measured and calculated following procedure outlined by Munjonji *et al*. (2020). The CO_2 probe recorded CO_2 as parts per million (ppm). The ideal gas law:

$\mathrm{PV} = \mathrm{nRT}$ …equation 1

Where P is the pressure, V is the molar volume, n is the moles of the gas, R is the molar gas constant (8.3145 J mol^{-1} K^{-1}) and T is the temperature in Kelvin. The molar volume of an ideal gas at 1 atm pressure and 25°C is 22.4 L mol^{-1} and at different pressures, the molar volume can be calculated by equation 2.

$$\mathrm{Molar\ Volume} = \frac{\mathrm{RT}}{\mathrm{P}} \text{ …equation 2}$$

The CO_2 concentration in mg m^{-3} at different temperatures was then calculated using equation 3.

$$CO_2\ (\mathrm{mg\ m^{-3}}) = \left(\frac{\mathrm{CO_2\ ppm} \times \mathrm{Molar\ weight\ (CO_2)}}{22.4\ \mathrm{Lmol^{-1}}}\right) \times \left(\frac{273.15\mathrm{K}}{\mathrm{T(K)}}\right) \times \left(\frac{\mathrm{P\ (kPa)}}{101\mathrm{kPa}}\right) \text{ …Equation 3}$$

The concentration of CO_2 in mg m^{-3} was then plotted against time to give slope in mg m^{-3} m^{-1}. The concentration of CO_2 in mg m^{-3} m^{-1} was then multiplied by the volume (0.00628 m^3) of the gas chamber and then divided by the area (0.0314 m^2) across the gas chamber to give CO_2 emission in mg m^{-2} min^{-1}. The cumulative CO_2 was calculated by assuming that the emission rates between two measurements points was constant. The emission of CO_2 in mg m^{-2} min^{-1} is converted into tons ha^{-1} day^{-1} using equation

$$CO_2\ \mathrm{tons\ ha^{-1}\ day^{-1}} = \left(\frac{\frac{CO_2 mgm^{-2}min^{-1}}{1000000000}}{\frac{1}{10000}}\right) / \left(\frac{1}{1440}\right) \text{…equation 4}$$

Soil organic C

The SOC was determined using the Walkley Black method by weighing 1g of the air-dried soil samples into 500 cm^3 Erlenmeyer flasks. The soil was then mixed with 10 cm^3 of $\mathrm{K_2Cr_2O_7}$ solution. Once the soil was completely dispersed, 20 cm^3 concentrated sulphuric acid was added rapidly into the solution. After cooling the solution for 30 minutes, 1 cm^3 of the indicator was then added and titrated with excess dichromate until it turned into a sharp green. The reduced dichromate is presumed to be corresponding to the organic C in the soil sample. The value of organic C was determined in percentage where it was converted to g/kg (Walkley and Black, 1934).

Particle size distribution

The hydrometer method was used to determine particle size distribution as per procedure outlined by Bouyoucos (1962). The samples were treated with sodium hexametaphosphate and other cations. The soil suspension densities were measured utilizing a hydrometer when sand and silt has settled. Corrections were therefore made for the density and temperature of the dispersing solution.

Soil chemical properties

The soil pH and EC were measured using the pH and EC meters. The soil pH was measured in both water and KCl. P, Mn, Zn, Cu and K were extracted in Ambic-2, with 0.25M NH_4HCO_3 and determined using Inductively Coupled Plasma (ICP). Exchangeable Ca, Mg and extractable acidity were extracted in 1M KCl. The effective CEC was calculated as the summation of Ambic-2 extractable K and KCl-extractable acidity, Mg and Ca. Percent acid saturation of the ECEC was calculated as "extractable acidity" x 100 / (Ca, Mg, K, "extractable acidity"). The total C, N and S were determined by means of the Automated Dumas dry combustion method. Exchangeable Na, ammonium N (NH_4^+) and nitrate N (NO_3^-) were determined following the method outlined by Manson and Roberts (2000).

Soil aggregate stability

The soil samples were analysed for aggregate stability using the wet sieving method as outlined by Elliott (1986). Air-dried soil aggregates were separated into four fractions (small and large macroaggregates, microaggregates and silt and clay) by wet sieving. The mean weight diameter (MWD), a measure of soil aggregate stability was calculated by the following equation 4.

$$\mathrm{MWD} = (2 \times \mathrm{LM}) + (1.106 \times \mathrm{sM}) + (0.131 \times \mathrm{m}) + (0.025 \times (\mathrm{s} + \mathrm{c})) \ldots\text{equation 5}$$

Where MWD denotes the mean weight diameter, LM denotes the large macro-aggregates %, sM denotes the small macroaggegates %, m denotes the microaggregates and s and c denotes silt % and clay %, respectively as outlined by Blaser *et al*. (2017).

Soil Bulk density

The soil bulk density of the samples was determined following the core ring method as outlined by Cresswell *et al.* (2002). Steel core rings of known height (5 cm) and diameter (7 cm) were used to collect undisturbed soil samples in the first five cm of the soil surface. The samples were then taken to the lab and were weighed. The soil samples were then dried at 105°C in the oven for 24 hours before being reweighed and the bulk density was calculated using equation 5.

$$\mathrm{BD} = \frac{(\mathrm{W2} - \mathrm{W1})}{\mathrm{V}} \text{ …equation 6}$$

Where BD is the bulk density (g cm^{-3}), W2 is the wet mass of the soil (g), W1 is the dry mass the soil and V is the volume of the ring (cm^3).

Microbial biomass and diversity

Microbial biomass and diversity (mycology for fungi and Plant growth promoting Rhizobacteria for bacteria) were determined using the serial dilution procedure outlined by Alexander (1983). A nutrient agar was prepared and placed into petri dishes where the soil solutions were pipetted on. The petri dishes were wrapped with a parafilm and incubated for a week at 37°C. The number of the bacterial and fungal colonies were counted. Identification of microbes was done using method outlined by Bisen *et al.* (2012).

3.2.4. Statistical analysis

The basic statistics were computed following Webster (2001) including minimum, maximum, average, median, standard deviation, F-probability and standard error of the sample data. A analysis of variance (ANOVA) was run using Genstat (20th edition, 2022) to determine if there were any significant difference between the different land use types in CO_2 emission, storage of C, microbial biomass and diversity in different seasons. Where differences were significant, the Tukey HSD (honestly significant difference) was used to separate means at a significant level of 0.05. All ANOVA tables are shown in the appendices.

3.3. Results

3.3.1. Weather conditions during study period

The Figure 4A below displays the daily minimum and maximum temperatures recorded at the Politsi weather station covering the land use types over one year. The daily minimum temperatures were lowest during the month of July with the lowest recorded temperature reaching a temperature of 2.30°C, while the highest daily temperatures were observed during October with the highest temperature recorded being 37°C. The figure 4B illustrates the total monthly rainfall and the mean temperature over a period of one year. The lowest total monthly rainfall was recorded during the months of April, May, June and July with a mean monthly rainfall as low as 1 mm recorded during the month of May. In contrast, the highest total monthly rainfall was recorded during the months of March, October, November, and January. The highest mean monthly rainfall was received during October which recorded approximately 74 mm of rainfall. However, the rainfall received during the study period (March 2021 till March 2022) was very low with the total rainfall recorded throughout the year summing up to only 332 mm.

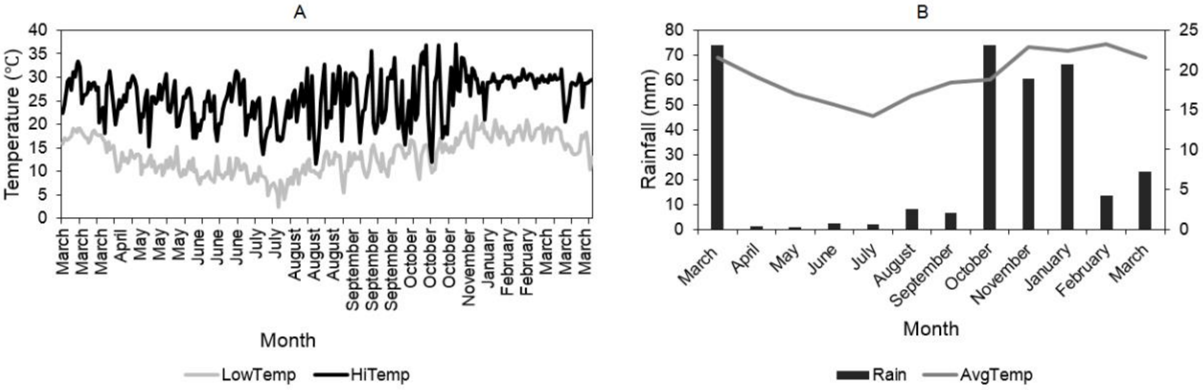

Figure 4: Weather condition maps: Daily minimum and maximum temperatures over one year (minimum = solid grey and maximum = solid black) (A) and the total monthly rainfall over one year (March 2021 till March 2022) (Black bars) with mean monthly temperatures (solid grey line) (B).

3.3.2. Seasonal variation of soil surface temperature, moisture, CO_2 emission and cumulative CO_2 emission across five land use types

3.3.2.1. Seasonal variation of soil surface temperatures across five land use types

The Figure 7A displays the variation of the soil surface temperature over one year for each land use type. Although no actual soil temperature measurements were done, the soil surface temperature was used as a proxy for soil temperature and this was justified by studies conducted by Islam *et al*. (2015), Kätterer and Andrén (2009) and Sharma *et al*. (2010) which found strong relationships between soil and soil surface temperature and stated that soil surface temperature can be used as an indicator of soil temperature. The banana land use type generally displayed the lowest soil surface temperatures of all the land use types throughout the year except in the beginning of March 2021 and the period between September and November 2021 where the eucalyptus land use type was the lowest. In contrast the highest soil surface temperatures alternated between the bush and maize land use types during the study period.

The variation in the soil surface temperature across four seasons is illustrated in Figure 7B. The mean soil surface temperature over one year ranged from a minimum of 16.67°C and a maximum of 44.3°C. The soil surface temperature varied significantly across the four seasons at significance level of $p<0.001$. The summer (30.2°C) season had statistically higher soil surface temperature than winter (26.4°C), spring (29.9°C) and autumn (30.2°C) as illustrated in Figure 7B. The soil surface temperature during the summer season was 21.1%, 10.4% and 9.8% greater than winter, spring and autumn respectively. The soil surface temperature was ranked from highest to lowest in this order: summer > autumn > spring > winter.

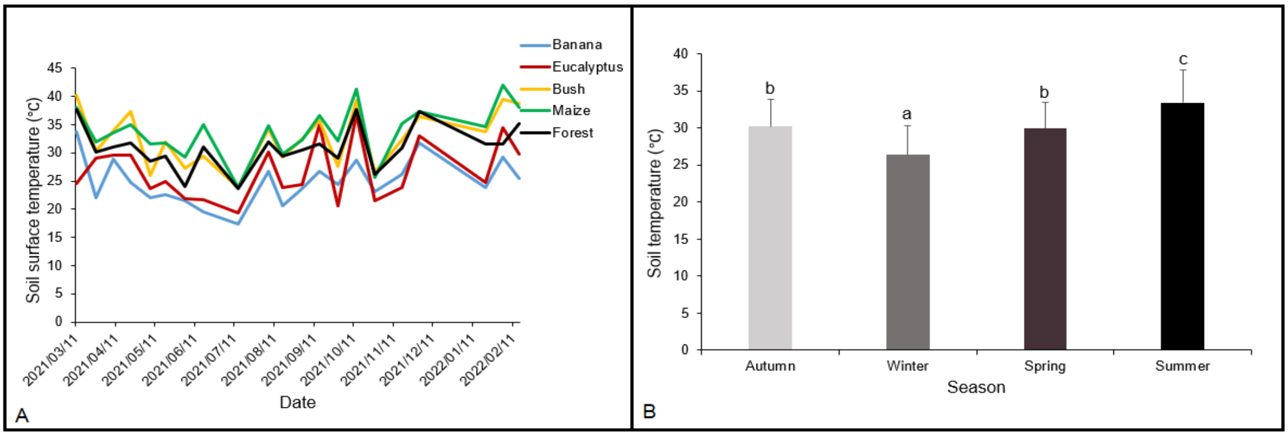

Figure 5: Seasonal variation in soil surface temperature: Line graph of seasonal variation in soil surface temperature of five land use types over one year (A) and bar graph of seasonal variation in soil surface temperature across four seasons (B).

The combined impact of the season and the land use type on the soil surface temperature was significant at significance level $p<0.001$. The soil surface temperature across all four seasons was highest under the maize land use type and was lowest under the banana land use type as illustrated in Figure 6. The soil surface temperature displayed greater variations during the summer season. Temperatures recorded under the eucalyptus and banana land use types only had significant differences during the summer season as illustrated in Figure 6D. The same is true for the bush, maize and forest land use types where the forest recorded lower soil surface temperatures than the bush and maize land use types during summer.

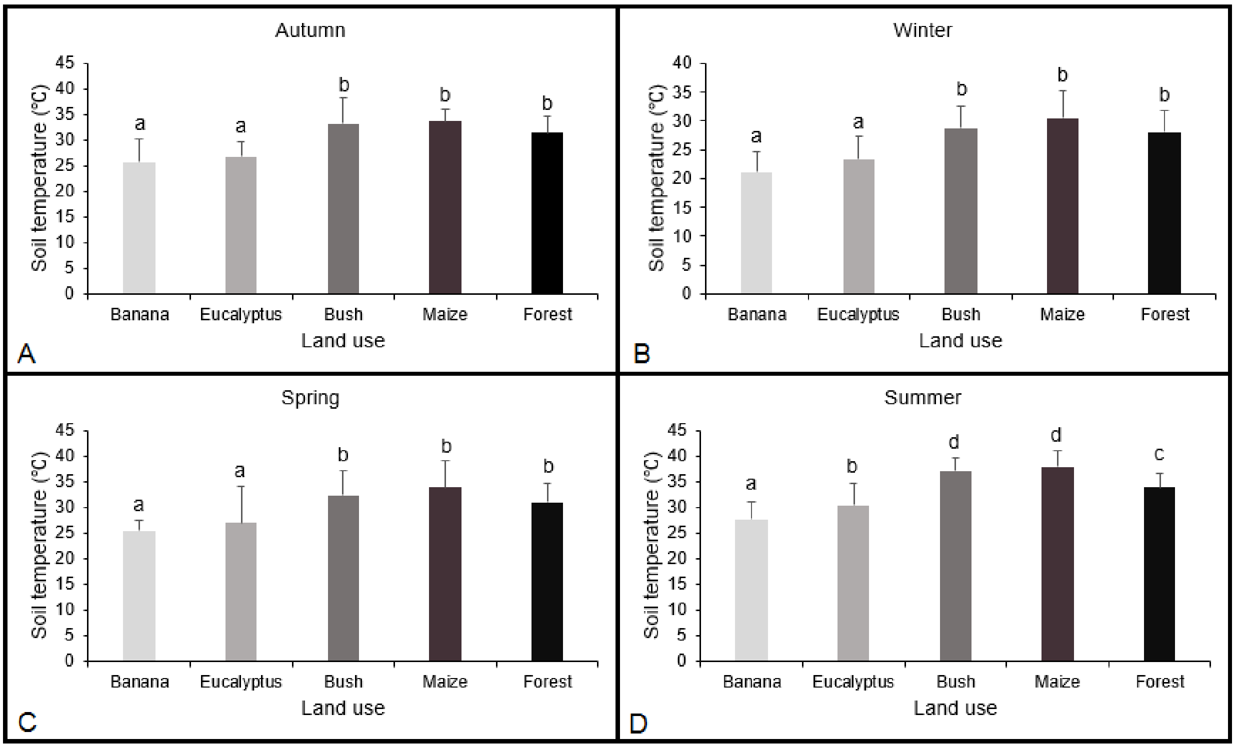

Figure 6: Seasonal Impact of land use on soil surface temperature: Autumn (A), Winter (B), Spring (C) and Summer (D).

3.3.2.2. Seasonal variation of soil moisture across five land use types

The soil moisture content was highest under the banana land use type throughout the year except in April 2021 where that recorded under the eucalyptus land use type slightly surpassed that under the banana land use as illustrated in Figure 7A. The lowest soil moisture contents staggered between the bush and maize land use types over the year. However, the maize land use type clearly displayed lower soil moisture contents than that under the bush land use types during the period between late November 2021 and March 2022.

The Figure 7 illustrates the variation in the soil moisture content across four seasons. The overall soil moisture over one year reached a minimum of 0.1% and a maximum of 40.3%. The soil moisture varied significantly across the four seasons (Figure 7B) at significance level of $p<0.001$. The summer (19.3%) season had extremely higher soil moisture content than that observed during winter (7.5%), spring (8.6%) and autumn

(12.7%). The differences observed in the moisture content of the soil during the winter and spring seasons were however insignificant as the moisture observed during spring was only 1.14% higher than that recorded in winter. The moisture content during all four seasons was highest under the banana land use type as illustrated in Figure 7A and 10. In contrast, the moisture contents were lowest under the bush land use type during autumn and spring and the maize field during winter and summer.

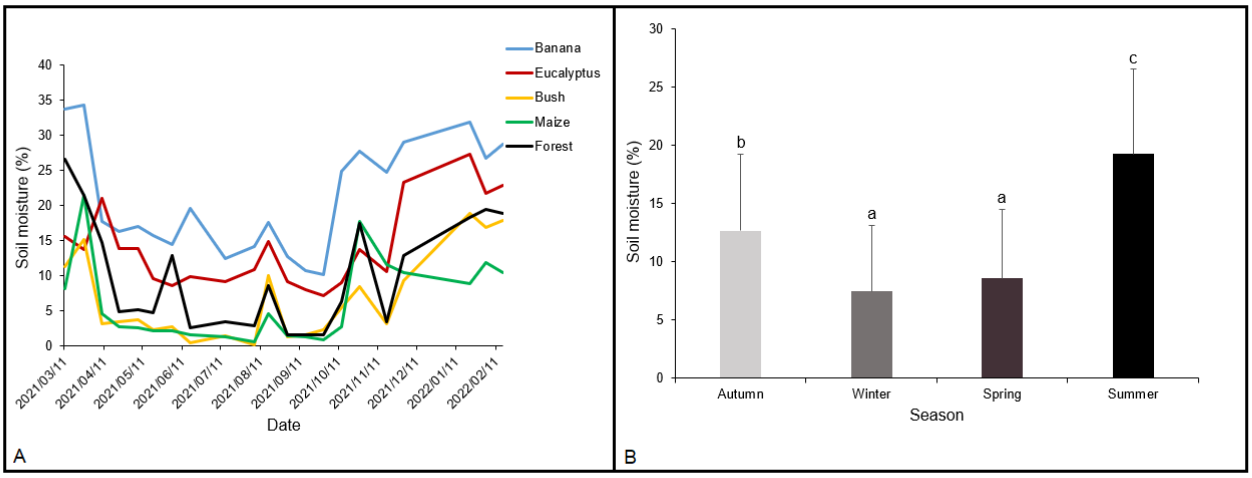

Figure 7: Seasonal variation in soil moisture: Line graph of seasonal variation in soil moisture across five land use types (A) and bar graph of seasonal variation in soil moisture across four seasons (B).

The combined impact of season and land use type on the soil moisture content was insignificant implying that the moisture content recorded under the different land use types during different seasons only displayed minor differences. However, the impact of the land use type on the moisture content of the soil was significant at $p<0.001$ as illustrated in Figure 8 below. The bush and maize land use types only displayed minor differences in the soil moisture content and these land use types had very low soil moisture content values in comparison to the other land use types. The banana land use type had the highest moisture content which was approximately three times than that recorded under the bush and maize land use types.

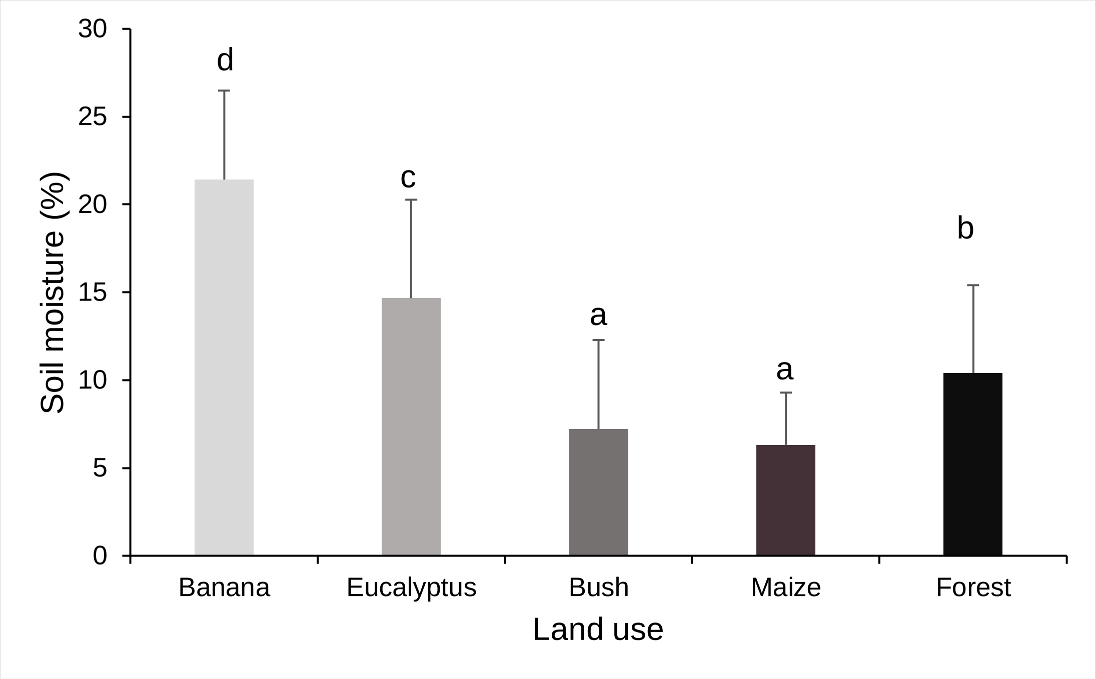

Figure 8: Impact of land use on soil moisture content.

3.3.2.3. Seasonal variation of soil CO_2 and cumulative CO_2 emission across five land use types

The emission rate of CO_2 over one year had minimum, maximum and average values of 0.01, 0.25 and 0.06 tons/ha/day respectively. The season had an impact on the CO_2 emission rates as significant variations were observed across the four seasons at significance level of $p<0.001$. The Figure 9A illustrates the variation in CO_2 emission across five land use types with change in seasons. During the first two and a half months of 2021, the forest land use type had higher CO_2 emission rates than that under the banana land use type. This changed during late April 2021 when the banana CO_2 emission rate exceeded that of the other land use types. This lasted till late September 2021 where the rates of emission under the forest greatly surpassed that of the other land use types. In mid-January till March 2022, the CO_2 emission rates under the bush land use type slightly exceeded that of the forest land use type.

The CO_2 emission rate was significantly higher during the summer season (Figure 9B) since it emitted approximately three times the amount of CO_2 than that emitted during the winter season. The CO_2 emission rates were ranked from highest to lowest in the following order: summer (0.11 tons/ha/day) > autumn (0.08 tons/ha/day) > spring (0.05 tons/ha/day) > winter (0.03 tons/ha/day).

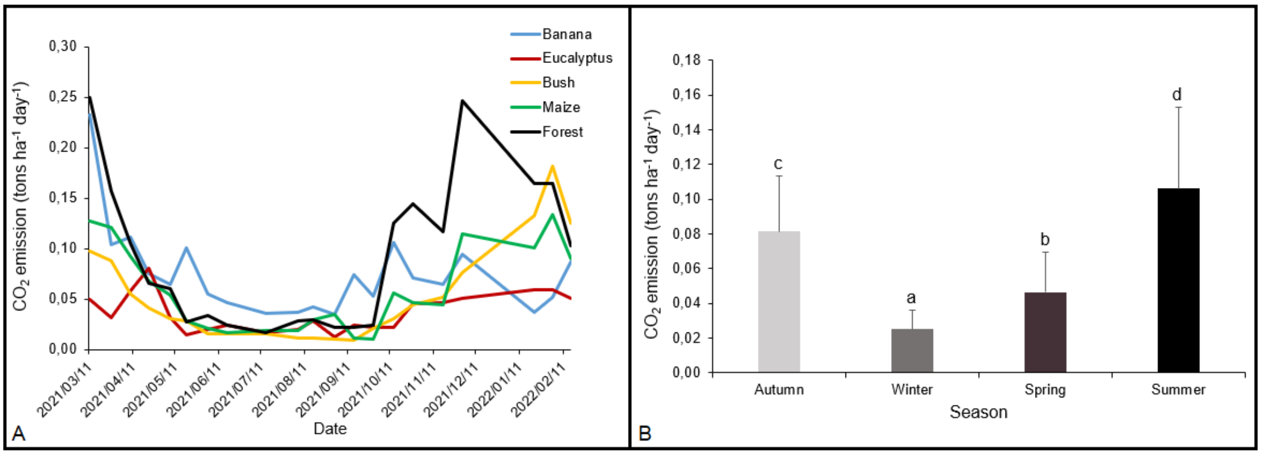

Figure 9: Seasonal variation in soil CO_2 emission: Line graph of seasonal variation in soil CO_2 emission of five land use types (A) and bar graph of seasonal variation in soil CO_2 emission across four seasons (B).

The interaction between the season and the land use type had an impact on the emission of CO_2 ($p<0.001$). The CO_2 emission rate in winter was highest under the banana land use type while in summer the forest emitted the highest CO_2. The bush land use type was among the land use types that recorded the lowest CO_2 emission rates during spring and winter, while the eucalyptus land use type was among the lowest during autumn and summer as illustrated in Figure 10.

The rate at which CO_2 was emitted during autumn and winter under the maize and forest land use types did not differ but this changed for the spring and summer seasons where the forest land use type was statistically greater than that of the maize land use type. The emission rates under the banana and eucalyptus land use types were different through all seasons except in summer as illustrated in the Figure 10D.

In autumn, the CO_2 emission rates recorded under the banana, maize and forest land use types only differed significantly to that recorded under the bush and eucalyptus land use types. While in winter, the CO_2 emission rates from the eucalyptus, maize and forest land use types did significantly differ from each other, while that recorded under the banana land use type was significantly higher than that recorded under all the other land use types.

The emission rates of the eucalyptus, bush and maize land use types in spring did not differ from each other but were significantly lower than those observed under both the banana and forest land use types (Figure 10C). In contrast, during summer the CO_2 emission rates under the forest and banana land use types were statistically different from each other with the forest land use type having a rate which is 0.103 tons/ha/day greater than that under the banana land use type. The CO_2 emission rates of the bush and maize land use types did not vary significantly from each other during summer as illustrated in Figure 10D. The same is true for the rates observed under the banana and eucalyptus land use types.

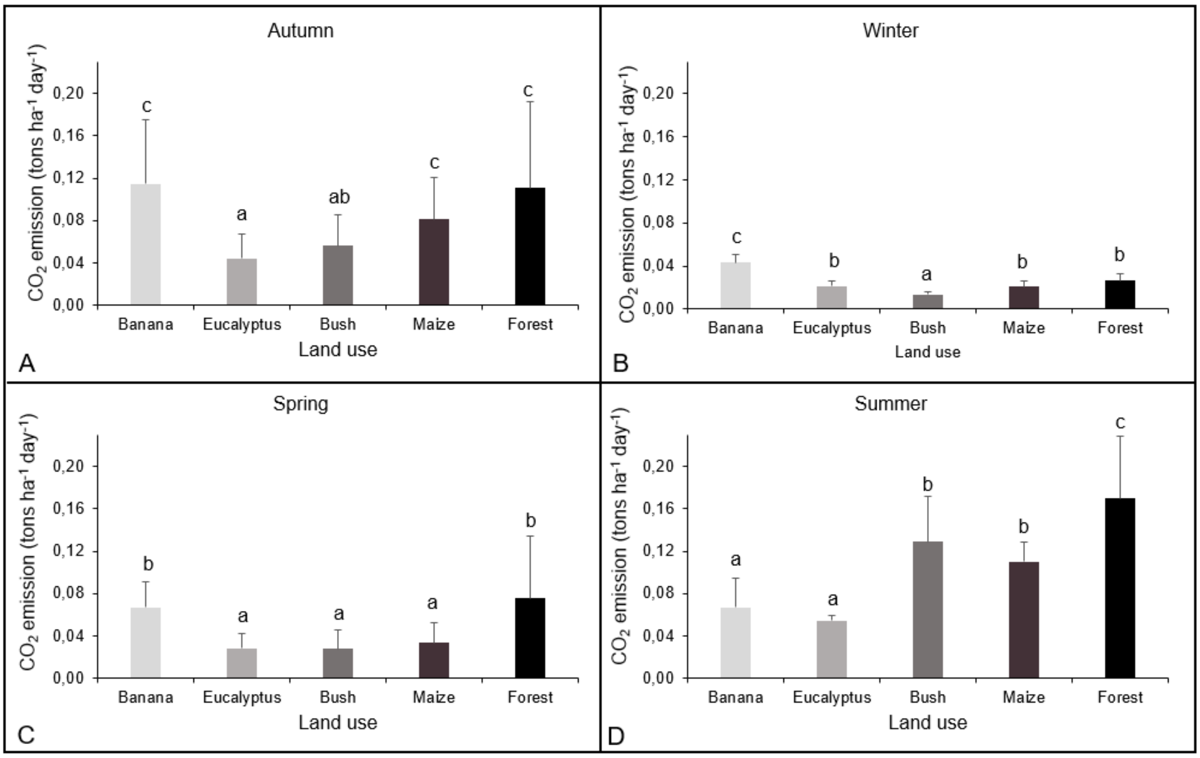

Figure 10: Seasonal Impact of land use on CO_2 emission rates: Autumn (A), Winter (B), Spring (C) and Summer (D).

The Figure 11A below illustrates the variation of the cumulative CO_2 emission rate across 5 land use types over one year. The forest land use type displayed higher cumulative CO_2 emission rates during the periods between March 2021 till mid-May and mid-November 2021 till March 2022. During the period between mid-May till mid-November 2021, the cumulative CO_2 emission rates under the banana land use type had exceeded those recorded under the forest land use type. The lowest cumulative CO_2 emission rates were observed under the eucalyptus land use type throughout the year. There were minor differences observed between the cumulative CO_2 emission rates under the eucalyptus and bush land use types. The variation between these land use types had however increased during mid-November where the rates recorded under the bush land use type clearly exceeded that of the eucalyptus land use type.

The cumulative CO_2 emission rates varied significantly ($p<0.001$) across the seasons as illustrated in the Figure 11B. The cumulative CO_2 emission rate was highest during summer season and was lowest during the winter season. The cumulative CO_2 emitted during the summer (5.27 tons/ha) season was 5.5 times greater than that recorded during the winter (0.96 tons/ha) season. The differences between the emission rates recorded during the winter and spring season were however insignificant from each other.

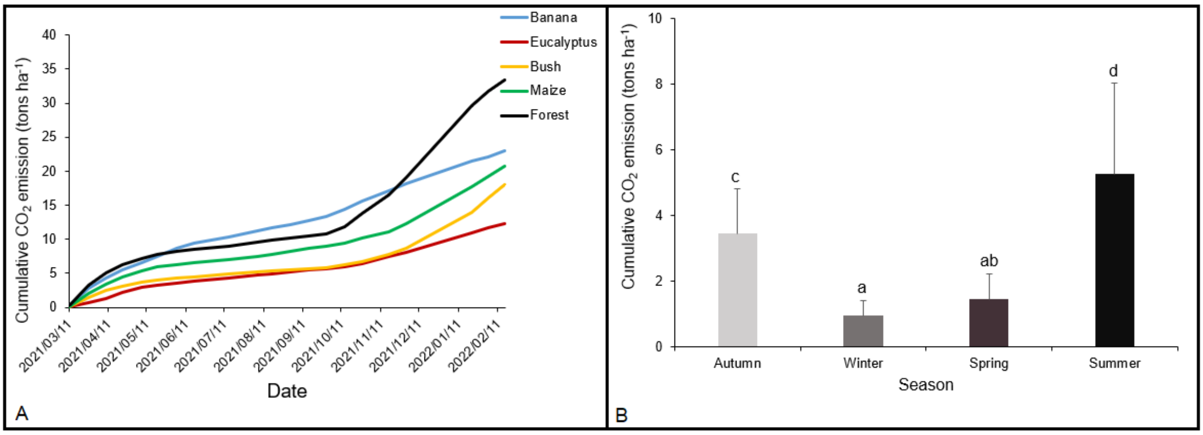

Figure 11: Seasonal variation in soil cumulative CO_2 emission: Line graph of seasonal variation in soil cumulative CO_2 emission of five land use types (A) and bar graph of seasonal variation in soil cumulative CO_2 emission across four seasons (B).

The combined impact of season and land use on the cumulative CO_2 emission rate was significant ($p<0.001$) as there were observable variations across the five land use types. The cumulative CO_2 emission rates during winter and spring were highest under the banana land use type while the forest land use type displayed the highest cumulative CO_2 emission rate during the autumn and summer seasons (Figure 12). In Figure 12, the lowest cumulative CO_2 emission rates was observed under the eucalyptus land use type during both the autumn and summer seasons while the bush land use type displayed lower rates during the winter and spring seasons.

The cumulative CO_2 emission rate during the autumn season was highest under the forest land use type and the lowest was under the eucalyptus land use type. In winter, the banana land use type had the highest cumulative CO_2 emission rate with that under the bush, maize and the eucalyptus land use types being the lowest as illustrated in figure 12B.

The cumulative CO_2 emission rate also varied significantly across the land use types during the spring season as illustrated in Figure 12C. The banana land use type also had significantly higher cumulative CO_2 emission rates in spring as compared to the other land use types. The cumulative CO_2 emission rate under the banana was 13%, 34%, 56% and 57% higher than that recorded under the forest, maize, bush, and eucalyptus land use types respectively.

In summer, the cumulative CO_2 emission rate varied significantly across the land use types with the forest land use type being significantly higher than that observed under the other land use types as illustrated in Figure 12D. The forest land use type had about two times the cumulative CO_2 emission rate than that recorded under the eucalyptus land use type.

It can be safely concluded that the banana and forest land use types consistently had the highest cumulative CO_2 emission rates in all the seasons while the bush and maize land use types recorded the lowest throughout the four seasons.

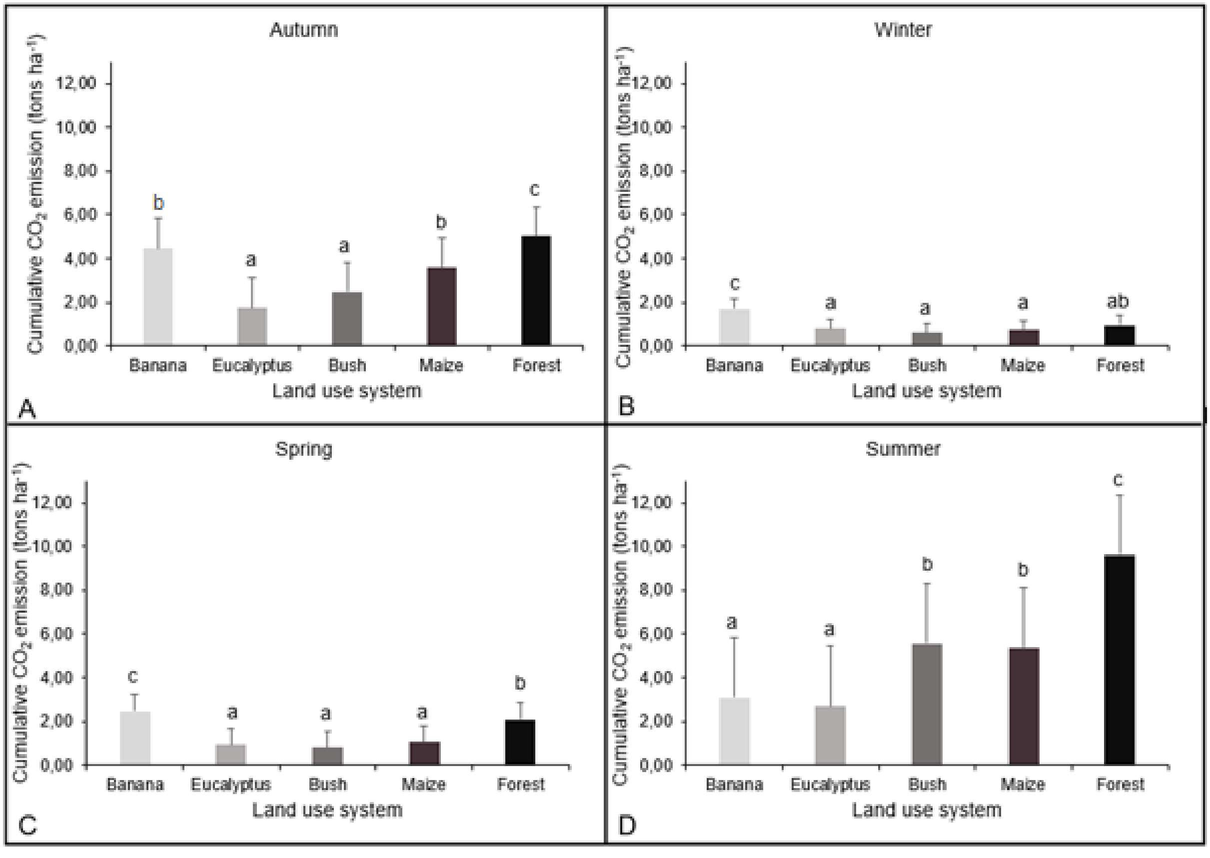

Figure 12: Seasonal Impact of land use on cumulative CO_2 emission rates: Autumn (A), Winter (B), Spring (C) and Summer (D).

3.3.3. Variation of soil chemical, physical and biological properties across five land use types

3.3.3.1. Soil chemical properties

The Table 1 shows the chemical properties of the soil in the 0-15 cm and 15-30 cm soil depths under the five land use types. The soil chemical properties were significantly different from each other in both depths with exception of P and Ca in the 0-15 cm depth and Mg in the 15-30 cm soil depth.

The variation in total nitrogen (N) content across the 5 land use types was significant at $p<0.001$ in both soil depths (Table 1). The N content in the bush and maize land use types were significantly higher in the 0-15 cm soil depth and bush, maize and forest were significantly higher in the 15-30 cm soil depth. The banana had significantly lower N content in both the 0-15 and 15-30 cm with it being 86% and 84% lower than the highest N content in the 0-15 and 15-30 cm soil depths respectively.

The variations observed in the soils phosphorus (P) content were not significant under the 0-15 cm soil depth across all the land use types (Table 1). Although differences were not significant across the land use types, the banana had extremely higher P content in comparison to the other land use types. In contrast, the P content in the 15-30 cm soil depth varied significantly ($p<0.001$) across the five land use types as illustrated in Table 2. The P content under the maize land use type was statistically higher than that under the eucalyptus and bush land use types making the P content 83.04% and 71.77% lower than that under the maize land use type respectively.

The potassium (K) content also differed across the land use types as significant ($p<0.001$) variations were observed in both soil depths. The K content was significantly higher under the banana (213.96 mg/kg) and maize (208.01mg/kg) land use types in both soil depths. The bush and forest had significantly lower K contents in the 0-15 cm and 15-30 cm soil depths respectively, making the K content under the bush 75.14% lower and the forest 80.95% lower than the highest K contents in the corresponding soil depths.

The variations observed in the soils calcium (Ca) content were not significant under the 0-15 cm soil depth across all the land use types. In contrast, the Ca content in the 15-30 cm soil depth varied significantly at a significance level of $p<0.05$ across the five land use types as illustrated in Table 1. Although variations were not significant across the land use types in the 0-15 cm soil depth, the bush land use type displayed extremely higher Ca content than the other land use types in both soil depths as it contained approximately 3 and 4 times the amount of Ca found under the banana land use type in the 0-15 cm and 15-30 cm soil depths respectively.

The magnesium content (Mg) varied significantly in the 0-15 cm soil depth at significance level of $p<0.001$. In contrast, the Mg content observed under the 15-30 cm soil depth was insignificant. The Mg content was highest under the bush land use type in both soil depths as it contained about 4 times the quantity of Mg than the lowest Mg content found in the banana land use type.

The exchangeable acidity displayed changes with changes in land use type as it varied significantly in both soil depths. The bush land use type had significantly ($p<0.01$) higher exchangeable acidity than that under the banana land use type in the 0-15 cm soil depth. In contrast, the exchangeable acidity varied at significance level of $p<0.05$ in the 15-30 cm soil depth with the bush being significantly higher and the exchangeable acidity under the banana 76.79% lower than that of the bush.

The land use type had an impact on the soil pH as significant variations were observed across the five land use types at significance levels of $p<0.01$ and $p<0.05$ in the 0-15 cm and 15-30 cm soil depths respectively (Table 1). The soils under the banana land use were classified as acidic while those under the eucalyptus, bush, maize and forest were all classified as slightly acidic in the 0-15 cm soil depth. The highest soil pH was under the eucalyptus and maize land use types in the 0-15 cm soil depth making the pH under the banana 1.47 units lower than that of the maize and eucalyptus. In contrast, the banana and forest land use types were classified as acidic while the eucalyptus, bush and maize land use types were classified as slightly acidic in the 15-30 cm soil depth. The soil pH was highest under the maize land use type making it 1.4 units higher than that observed under the banana land use type.

The zinc (Zn) content varied significantly ($p<0.001$) across the five land use types in both soil depths as illustrated in Table 1. The Zn content was extremely higher under the bush land use type than that observed under the eucalyptus land use type in the 0-15 cm soil depth. In contrast, the Zn content in the 15-30 cm soil depth was highest under the maize land use type than that observed under the eucalyptus land use type.

The manganese (Mn) content varied with the land use type as significant differences were observed at significance level of $p<0.001$ in both the soil depths as illustrated in Table 1. The Mn content contained under the maize land use type in the 0-15 cm and 15-30 cm soil depths was 2.9 and 3 units higher than that under the forest land use type.

The land use type showed variation in the copper (Cu) content at significance level of $p<0.001$ in both soil depths. The Cu content was highest in the maize and forest in the 0-15 cm soil depth and forest was highest in the 15-30 cm soil depth. The eucalyptus land use type had significantly lower Cu contents in the 0-15 cm and 15-30 cm soil depths, making the Cu content under the eucalyptus 61.73% and 69.41% lower than the highest Cu contents in the corresponding soil depths.

Table 1: Soil Chemical properties of the 0-15 cm and 15-30 cm soil depth under the five land use types.

Soil depth	Land use	N (%)	P (mg/Kg)	K (mg/Kg)	Ca (mg/Kg)	Mg (mg/Kg)	Exch. Acidity (cmol/L)	pH (KCl)	Zn (mg/Kg)	Mn (mg/Kg)	Cu (mg/Kg)
0-15 cm	Banana	0.07^{a}	61.07	213.96^{b}	631.58	117.97^{a}	5.52^{a}	4.55^{a}	6.38^{b}	33.75^{c}	5.19^{b}
	Eucalyptus	0.17^{a}	2.34	65.89^{a}	1305.35	199.29^{a}	8.38^{ab}	6.02^{b}	0.64^{a}	27.51^{bc}	2.17^{a}
	Bush	0.50^{b}	5.35	53.18^{a}	1643.53	484.54^{c}	16.65^{c}	5.12^{a}	11.36^{c}	22.30^{ab}	3.26^{a}
	Maize	0.50^{b}	13.73	208.01^{b}	947.66	210.81^{a}	8.82^{ab}	6.02^{b}	9.10b^{c}	43.24^{d}	5.67^{b}
	Forest	0.25^{a}	14.95	68.44^{a}	1362.47	327.66^{b}	10.83^{b}	5.11^{a}	1.20^{a}	15.17^{a}	5.67^{b}
		***	Ns	***	ns	***	**	**	**	***	***
15-30 cm	Banana	0.08^{a}	8.07^{b}	187.35^{c}	433.32^{a}	90.54	4.05^{a}	4.32^{a}	2.68^{ab}	22.59^{b}	5.31^{c}
	Eucalyptus	0.12^{b}	1.94^{a}	70.04^{b}	750.69^{a}	144.35	5.35^{a}	5.20^{bc}	0.29^{a}	19.64^{ab}	1.97^{a}
	Bush	0.50^{c}	3.23^{a}	35.88^{a}	2003.96^{b}	389.29	17.30^{b}	5.37^{bc}	5.01^{b}	25.21^{b}	2.69^{b}
	Maize	0.50^{c}	11.44^{b}	185.44^{c}	823.84^{a}	185.77	8.03^{a}	6.02^{c}	8.02^{c}	39.77^{c}	5.29^{c}
	Forest	0.50^{c}	9.91^{b}	35.69^{a}	983.94^{a}	305.06	8.66^{a}	4.72^{ab}	0.46^{a}	13.05^{a}	6.44^{d}
		***	***	***	*	ns	*	*	***	***	***

*Significance levels: *P<0.05, **P<0.01, ***P<0.001, ns means not significant*

3.3.3.2. Soil physical properties

The soil textural classes varied across the land use types in both the soil depths. The soil under banana and eucalyptus in both soil depths were classified as sandy clay. Those under the bush and the forest in both soil depths were classified as sandy loam, while those under the maize in both soil depths were classified as sandy clay loam.

The soil C stocks measured to 5 cm soil depth displayed significant variations across the five land use types at significance level of $p<0.05$ as illustrated in Figure 13A. The soil C stocks observed under the forest (1.19 kg/m^2) land use type were significantly higher than that under the bush (0.29 kg/m^2) and maize (0.35 kg/m^2) land use types. The C stocks under the forest land use type was more than 70% greater than that observed under the maize and bush land use types. The maize and the bush land use types had the lowest C stocks in comparison to the other land use types although it only statistically differed to that of the forest. The soil C stocks were ranked from highest to lowest in the following order: forest > eucalyptus > banana > maize > bushes with values ranging from 1.19 to 0.29 kg/m^2.

A significant ($p<0.05$) variation was observed in the mean weight diameter (MWD) of soil aggregates across the five land use types. The bush (1.76 mm) and eucalyptus (1.49 mm) had significantly higher MWD values in comparison to that of the maize (0.96 mm) and banana (0.97 mm) as illustrated in Figure 13B. The MWD of the aggregates under the forest were 45% thicker than that under the bush land use type. Thus, the aggregate stability ranged from the highest to lowest in the following order: bush > eucalyptus > forest > banana > maize with values ranging between 1.76 to 0.96 mm.

The bulk density is the only physical property which had an overall statistically insignificant variation across the five land use types with p value of 0.089 (Figure 13C). Despite the overall insignificance in the bulk density values across the five land use types, the banana land use type (1.59 g/cm^3) was higher than that under the forest (1.25 g/cm^3). The bulk density of the banana land use type was only 0.34 g/cm^3 higher than that under the forest. Although the differences were statistically insignificant, the minor differences in the bulk density across the five land use types were relatively more compacted in the banana and less compacted in the forest.

There were significant ($p<0.05$) variations in the infiltration rate of the soil across the five-land use types (Figure 13D). The maize (25.37 mm/h) land use type displayed extremely higher infiltration rates than that of the eucalyptus (3.63 mm/h), banana (2.51 mm/h) and forest (2.29 mm/h) making its rate approximately 5.2, 7.6 and 8.3 times faster respectively. The infiltration rate was ranked from highest to lowest in the following order: maize > bush > eucalyptus > banana > forest with values ranging between 25.37 to 2.29 mm/h.

The clay content of the soil significantly differed across the five land use types as illustrated in Figure 5E. The clay content was significantly higher under the banana (42%) and eucalyptus (38%) land use types in comparison to the other land use types in the 0-15 cm soil depth. The clay content observed under the banana land use type was 57% greater than that observed in the bush land use type. The clay content was ranked from highest to lowest in the following order: banana > eucalyptus > maize > forest > bush with values ranging between 18% and 42%.

The variations in the soil C content across the five land use types was significant ($p<0.05$) as illustrated in Figure 13F. The forest (1.93%) had significantly higher organic C content than the bush (0.50%), maize (0.53%) and banana (0.90%) land use types. The soil organic C content was about 3.9 times greater than the lowest organic C observed under the bush land use type. The soil organic C was ranked from highest to lowest in the following order: forest > eucalyptus > banana > maize > natural bushes with values ranging from 0.50% to 1.93%.

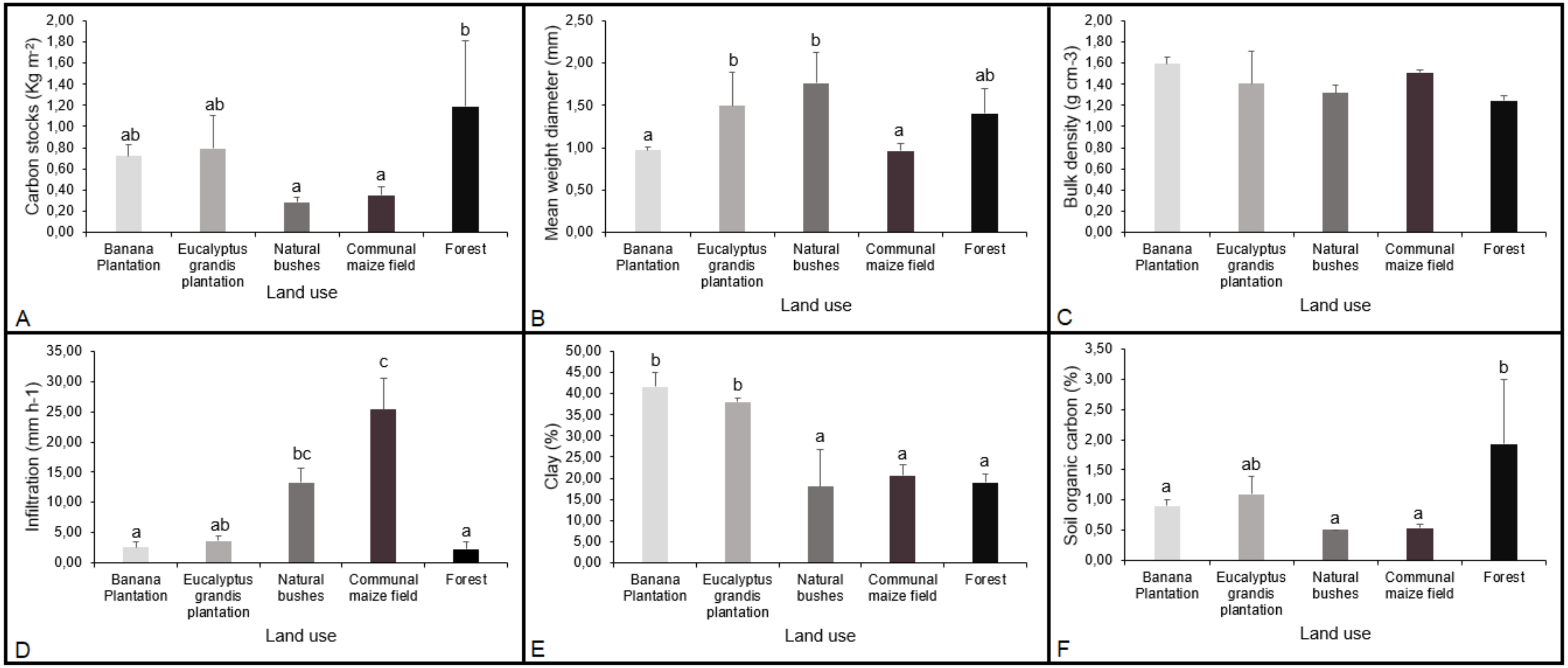

Figure 13: Soil physical properties across five land use types: C stocks (A), Aggregate stability (B), Bulk density (C), Infiltration (D), Clay (E) and Organic C (F).

3.3.3.3. Soil biological properties

The Figure 14 below illustrates the variation of the soil fungal and bacterial counts across the five land use types. The variation of the soil fungal count was significant at $p<0.001$ as illustrated in Figure 14A. The fungal counts measured under the eucalyptus, bush and maize land use types were statistically not different from each other but only differed to that under the banana and forest land use types. The forest land use type had extremely higher fungal counts than the other land use types. The fungal counts recorded under the forest land use type had mean value of 540×10^5 cfu g^{-1} making it approximately 14.6 times greater than the fungal counts recorded under the banana land use type (Figure 6A). The fungal counts were ranked from highest to lowest in the following order: forest (540×10^5 cfu g^{-1}) > eucalyptus (100×10^5 cfu g^{-1}) > bush (110×10^5 cfu g^{-1}) > maize (88×10^5 cfu g^{-1}) > banana (37×10^5 cfu g^{-1}).

In contrast, the variation in the bacterial counts across the five land use types was insignificant as illustrated in the Figure 14B with p value of 0.703. Although there were small differences in the bacterial counts across the five land use types, the bush land use type had the highest bacterial counts with the lowest being recorded under the banana land use type. The differences between the highest and lowest bacterial counts were not as significant as that recorded for the fungal counts as the bush was only 2 times greater in bacterial count than that recorded under the banana land use type.

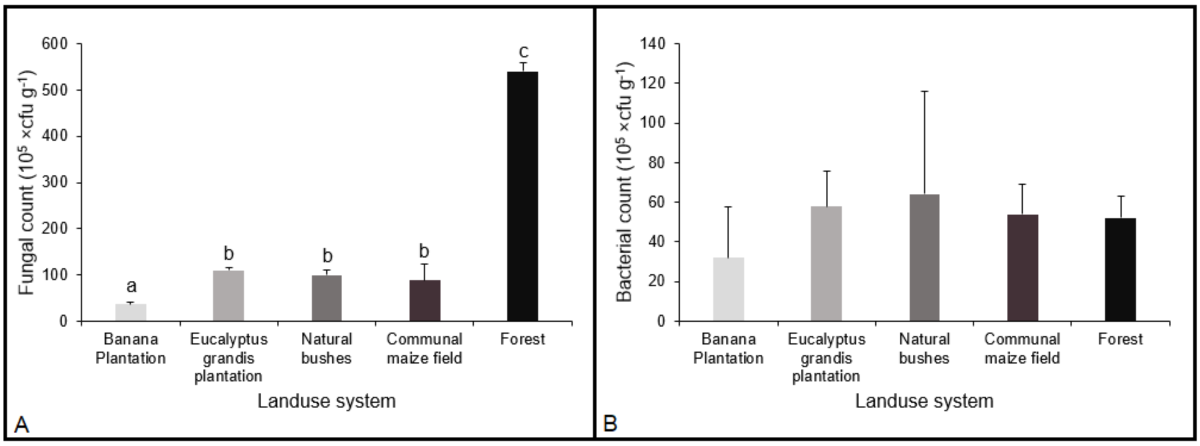

Figure 14: Soil biological properties across five land use types: Fungal count (A) and Bacterial count (B).

3.3.4. The influence of soil surface temperature and soil moisture on CO_2 emission

3.3.4.2. The influence of soil surface temperature on CO_2 emission

The Figure 15 displays the relationships between soil CO_2 emission rates with the soil surface temperature in the five land use types. There was a significant ($p<0.001$) moderately strong positive relationship between soil surface temperature and soil CO_2 emission rates in the banana, bush, maize and forest land use types as illustrated in Figures 15 A, C, D and E ($r^2= 0.40$, $r^2= 0.29$, $r^2= 0.25$ and $r^2= 0.34$ respectively). Significant ($p<0.05$) weak positive relationships were observed in the eucalyptus ($r^2= 0.08$) land use type as illustrated in Figure 15B. The findings show that a one unit increase in the soil temperature will result in only 0.001 tons/ha/day, 0.005 tons/ha/day, 0.005 tons/ha/day, 0.007 tons/ha/day and 0.0115 tons/ha/day increase in soil CO_2 emission rate under the eucalyptus, bush, maize, banana and forest land use types respectively.

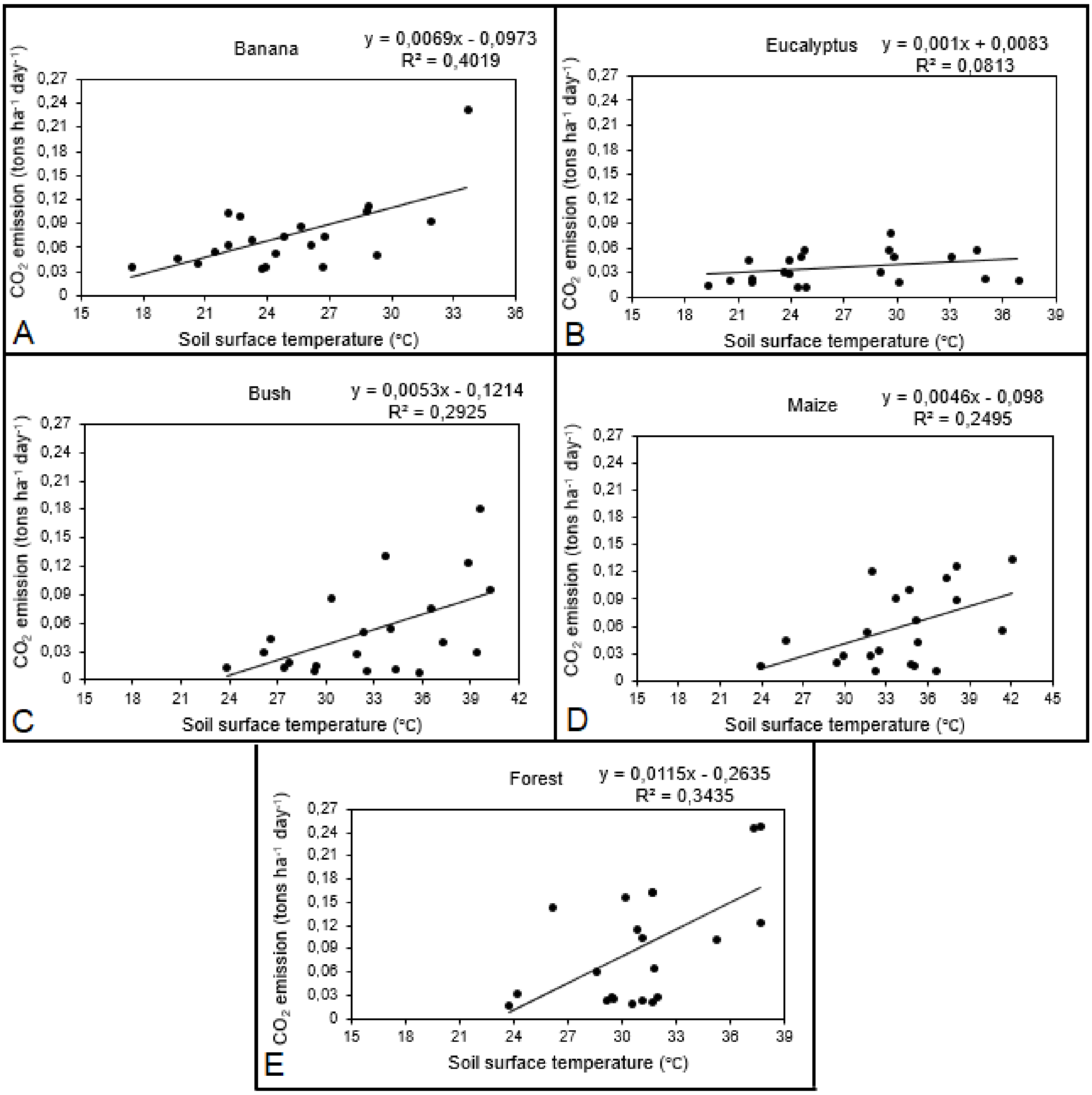

Figure 15: Regression relationships between soil surface temperature and CO_2 emission rates: Banana (A), Eucalyptus (B), Bush (C), Maize (D) and Forest (E).

3.3.4.3. The influence of soil moisture on CO_2 emission

The relationship between the soil CO_2 emission rate and soil moisture content displayed much stronger relationships than that with the soil temperature as illustrated in Figure 16. The relationship between the soil moisture content and CO_2 emission rate was significant ($p<0.001$) under the eucalyptus, bush, maize, and forest land use types. In contrast, the relationship between the soil moisture content and CO_2 emission rate under the banana land use type was insignificant. The findings showed that the forest ($r^2= 0.61$) and bush ($r^2= 0.77$) land use types had strong positive relations between soil moisture content and CO_2 emission rates implying that for every unit increase in the soil moisture content there will be a 0.01 tons/ha/day increase in the CO_2 emission rate (Figures 16 C and E). The maize (r^2= 0.43) and eucalyptus (r^2= 0.53) land use types had moderately strong relationships between the soil moisture content and CO_2 emission rate and for every unit increase in the soil moisture content there will be a 0.005 ton/ha/day and 0.002 ton/ha/day increase in the CO_2 emission rate respectively (Figures 16 B and D). The banana (r^2=0.24) land use type was the only one which display insignificant weak positive relationships between the soil moisture content and CO_2 emission rate (Figure 16A).

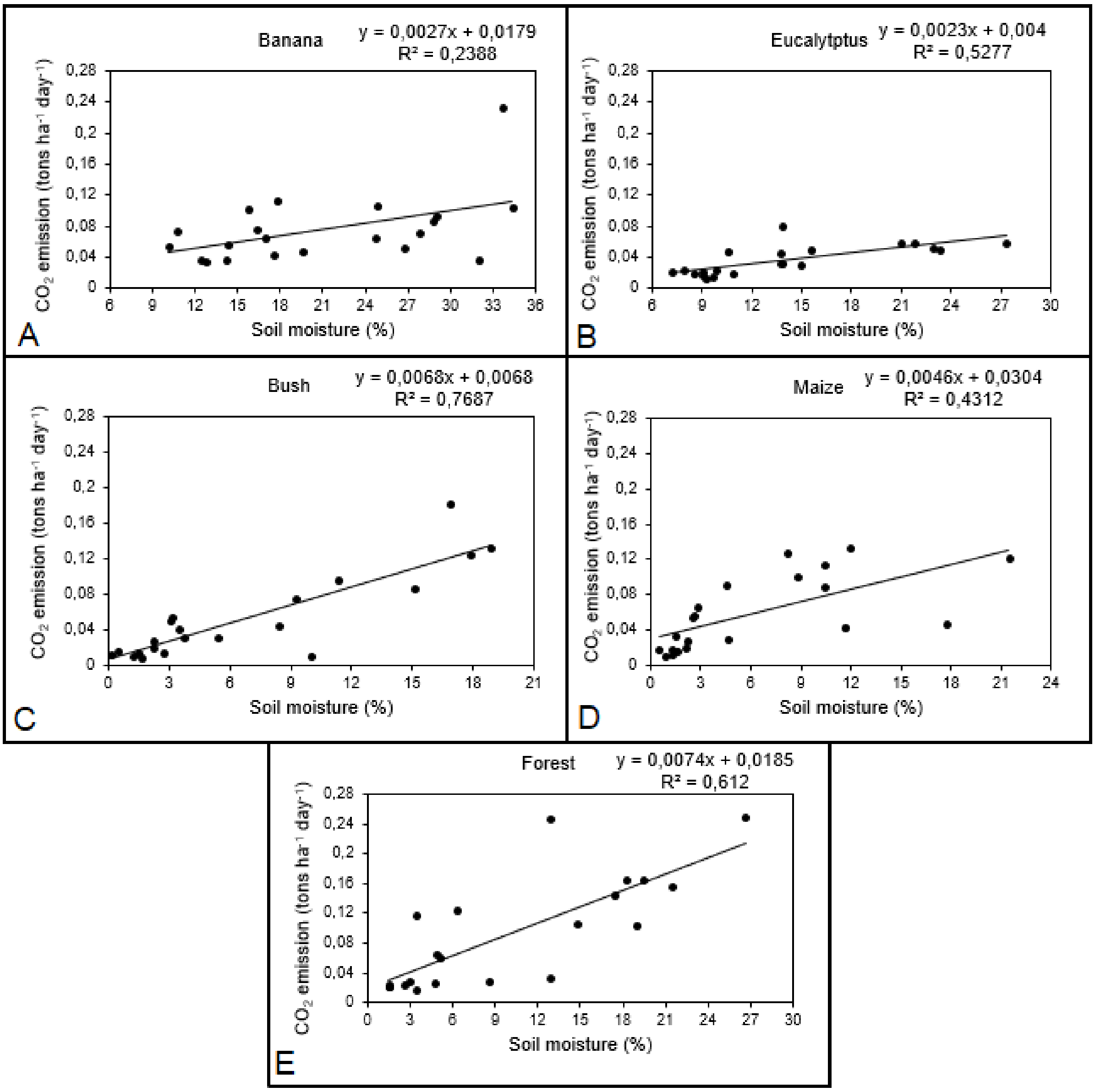

Figure 16: Regression relationships between soil moisture and CO_2 emission rates: Banana (A), Eucalyptus (B), Bush (C), Maize (D) and Forest (E).

3.3.5. The influence of soil properties on soil CO_2 emission and C stocks

3.3.5.2. The influence of soil properties on soil CO_2 emission

The relationship between the soil physical properties and CO_2 emission rates were insignificant and negative for all the soil physical properties with exception of C stocks as illustrated by Figure 17. The relationship between the aggregate stability (r^2= 0.05), bulk density (r^2= 0.01), infiltration (r^2= 0.07) and clay (r^2= 0.06), and the CO_2 emission rates all displayed weak negative relations. Soil C stocks (r^2= 0.24) displayed moderately strong positive relations with the CO_2 emission rate, thus a unit increase in the soil C stocks would result in 0.024 ton/ha/day increase in CO_2 emission rates.

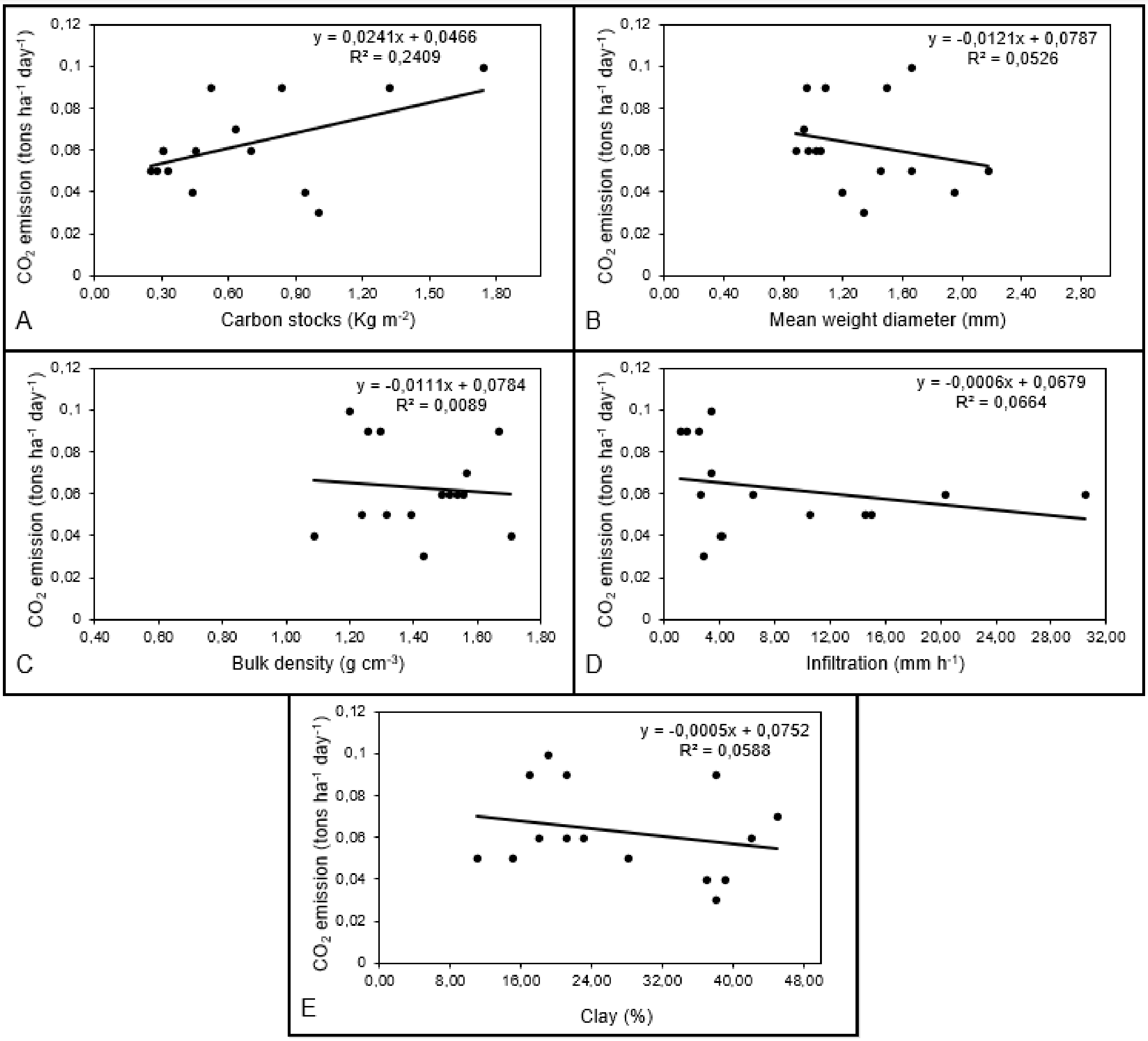

Figure 17: Regression relationships between soil physical properties and CO_2 emission rates: C stocks (A), Aggregate stability (B), Bulk density (C), Infiltration (D) and Clay (E).

The relationship between the CO_2 emission rate and the soil fungal counts was significant at $p<0.01$ and it displayed a positive moderately strong relationship (r^2= 0.44) as illustrated in Figure 18A. This thus implied that for every unit increase in the fungal count of the soil there will be a 0.00007 ton/ha/day increase in the CO_2 emission rate from the soil. In contrast to the positive relationship between the CO_2 emission rate and the fungal counts, bacterial counts displayed opposite relations. The regression relationship between CO_2 emission rate and the bacterial count of the soil was insignificant with p value of 0.41. The relationship was also negative and weak as displayed in the Figure 18B. The increase in the soil bacterial count would cause insignificant decrease in the emission rate of CO_2.

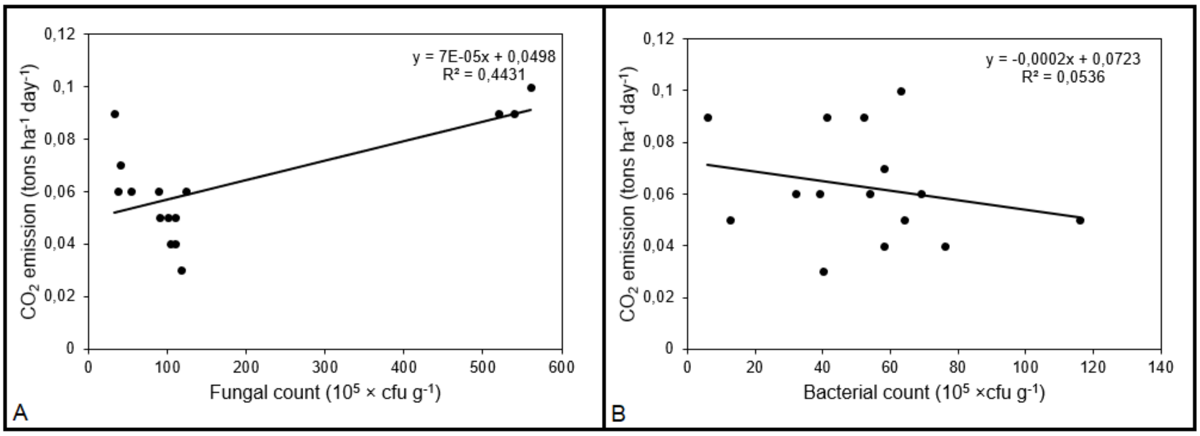

Figure 18: The relationships between soil biological properties and CO_2 emission: Fungal count (A) and Bacterial count (B).

The emission rate of CO_2 displayed negative strong relationships with the soil fungal count under the eucalyptus (r= -0.995) and bush land use types (r=-0.945) while that under the banana (r=-0.516) land use type was only moderately strong as illustrated in the Table 2 below. In contrast, the correlation between the soil fungi and the emission rate of CO_2 from the soil under the maize (r=0.924) and forest (r=0.996) land use types was very strong and positive.

The relationship between the soil bacteria and the emission rate of CO_2 under the banana land use type is also negative but is about 3 times weaker than that between the soil fungi and CO_2 emission rate. The eucalyptus (r=0.995) and forest (r=0.996) land use types are the only two land use types which displayed strong and positive relations between the soil bacteria and emission rate of CO_2. The bush (r=-0.945) and maize (r=-0.924) land use types displayed very strong negative relationships between the soil bacteria and CO_2 emission rate.

Table 2: Correlation relationships between soil CO_2 emission, soil fungal counts and soil bacterial counts for each land use type.

Land use		CO_2 emission	Fungal count	Bacterial count
Banana	CO_2 emission	1.000		
	Fungal count	-0.516	1.000	
	Bacterial count	-0.516	1.000	1.000
Eucalyptus	CO_2 emission	1.000		
	Fungal count	-0.995	1.000	
	Bacterial count	0.995	-1.000	1.000
Bush	CO_2 emission	1.000		
	Fungal count	-0.945	1.000	
	Bacterial count	-0.945	1.000	1.000
Maize	CO_2 emission	1.000		
	Fungal count	0.924	1.000	
	Bacterial count	-0.924	-1.000	1.000
Forest	CO_2 emission	1.000		
	Fungal count	0.996	1.000	
	Bacterial count	0.996	1.000	1.000

3.3.5.3. The influence of soil properties on soil C stocks

The Figure 19 illustrates the relationship between the soil physical properties and soil C stocks. All the soil physical properties with exception of clay displayed insignificant relations with the soil C stocks as illustrated in Figure 19 A, B and D. The soil bulk density (r^2= 0.01) and infiltration rate (r^2= 0.32) were both negatively correlated with the soil C stocks, with the bulk density displaying weak relations and infiltration displaying moderately strong relations (Figure 19 B and C). In contrast, the aggregate stability (r^2= 0.001) and clay content (r^2= 0.02) displayed weak positive relations with the soil C stocks as illustrated in Figure 19 A and C. The results showed that for every unit increase in the aggregate stability and clay content there will only be 0.03 kg/m^2 and 0.01kg/m^2 increase in the soil C stocks.

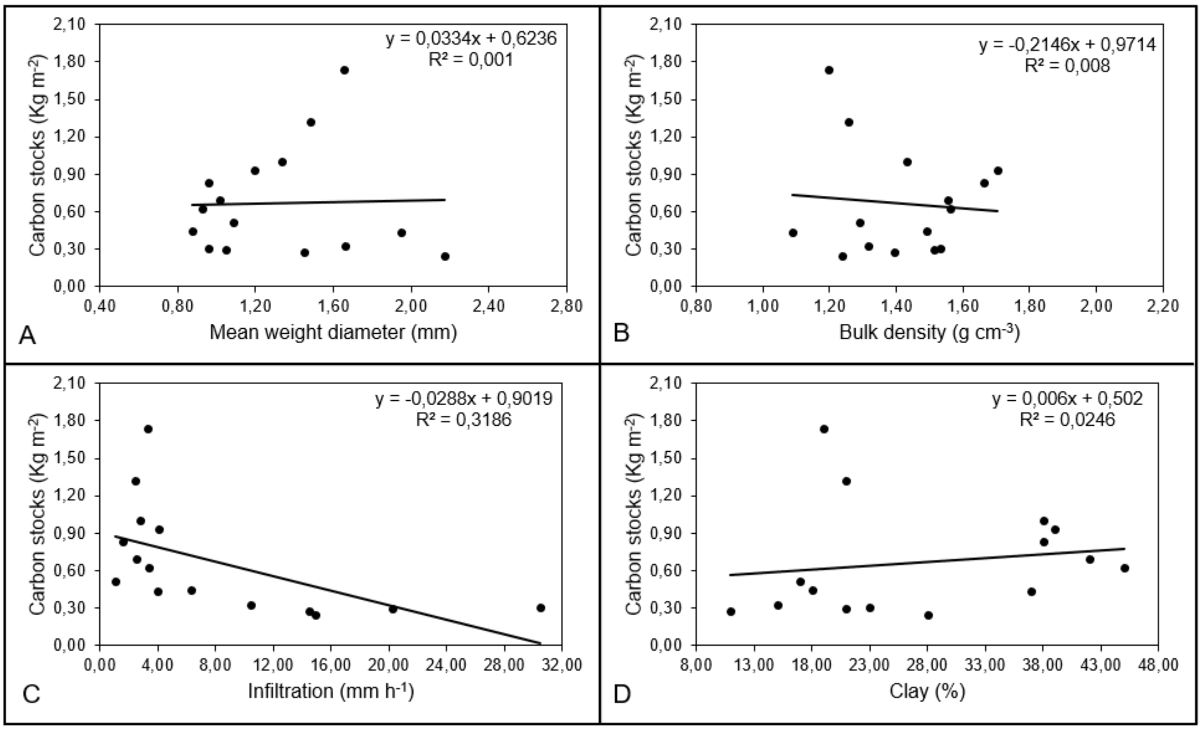

Figure 19: Regression relationships between soil physical properties and C stocks: Aggregate stability (A), Bulk density (B), Infiltration (C) and Clay (D).

The influence of the soil fungal counts on the soil C stocks was also significant ($p<0.05$) and displayed a positive moderately strong relationship ($r^2= 0.37$) (Figure 20A). This implied that for every unit increase in the soil fungal count, the C stocks would increase by 0.014 kg/m^2. The influence of the soil bacterial counts on the soil C stocks was however insignificant. It displayed weak negative relations with the soil C stocks and thus only minor decrease in the soil C stocks would occur for every unit increase in the soil's bacterial counts.

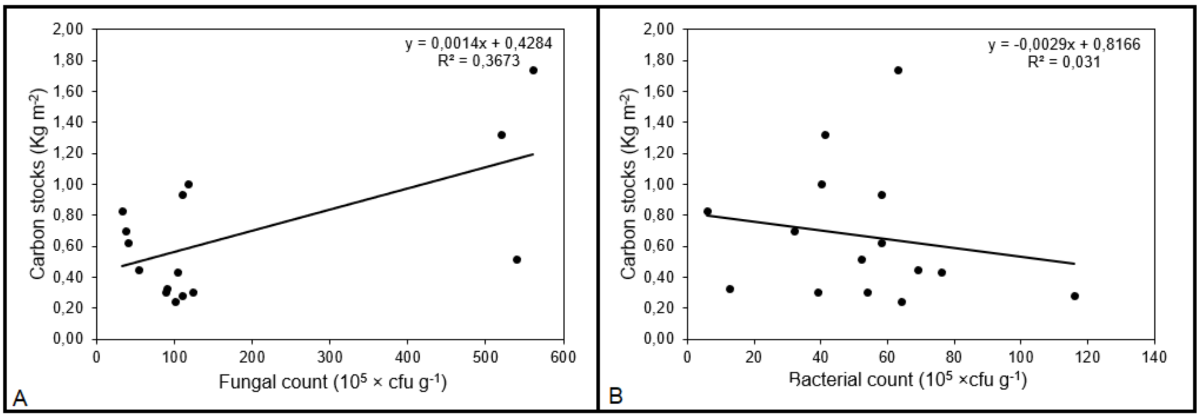

Figure 20: Regression relationships between soil biological properties and C stocks: Fungal count (A) and Bacterial count (B).

The soil fungi only had positive relations with the C stocks under the eucalyptus and forest land use types. Although the correlation between the soil C stocks and soil fungi under the eucalyptus and forest land use types were positive, the relation was however only strong under the eucalyptus (r=0.985) land use type as illustrated in Table 3. In contrast, the relationship between the soil C stocks and the soil fungi was negative and very strongly correlated under the banana (r=-0.985) and maize (r=-0.854) land use types. That under the bush (r=-0.608) land use type was moderately strong.

The soil C stocks displayed strong negative relations with the soil bacteria under the banana (r=-0.985) and eucalyptus (r=-0.913) land use types, while that under the bush (r=-0.608) land use type was moderately strong. The maize (r=0.854) land use type displayed strong positive correlations between the soil C stocks and bacterial count. The same relationship was observed under the forest land use type except that it was approximately 2.5 times lower than that observed under the maize land use type.

Table 3: Correlation relationships between soil C stocks, soil surface temperature, soil moisture content, soil fungal counts and soil bacterial counts for each land use type.

Banana	C stocks	Soil temp.	Soil moisture	Fungal count	Bacterial count
C stocks	1.000				
Soil temp.	-0.697	1.000			
Soil moisture	0.955	-0.879	1.000		
Fungal count	-0.985	0.565	-0.890	1.000	
Bacterial count	-0.985	0.565	-0.890	1.000	1.000
Eucalyptus					
C stocks	1.000				
Soil temp.	0.730	1.000			
Soil moisture	0.216	-0.510	1.000		
Fungal count	0.913	0.945	-0.200	1.000	
Bacterial count	-0.913	-0.945	0.200	-1.000	1.000
Bush					
C stocks	1.000				
Soil temp.	-0.197	1.000			
Soil moisture	0.179	-1.000	1.000		
Fungal count	-0.608	-0.659	0.672	1.000	
Bacterial count	-0.608	-0.659	0.672	1.000	1.000

Maize					
C stocks	1.000				
Soil temp.	-0.883	1.000			
Soil moisture	0.876	-0.546	1.000		
Fungal count	-0.854	0.509	-0.999	1.000	
Bacterial count	0.854	-0.509	0.999	-1.000	1.000
Forest					
C stocks	1.000				
Soil temp.	0.680	1.000			
Soil moisture	0.377	-0.423	1.000		
Fungal count	0.337	0.920	-0.745	1.00	
Bacterial count	0.337	0.920	-0.745	1.000	1.000

3.3.6. The drivers of CO_2 and soil C storage in each land use type

Table 4 below illustrates the multiple linear regression analysis of the soil CO_2 emission rate and the soil surface temperature and the soil moisture content. The combined impact that the soil moisture and temperature had on CO_2 emission was greatest under the bush ($r^2= 0.82$) land use type and was lowest under the banana ($r^2= 0.46$) land use type (Table 4). This indicates that approximately 82% of the CO_2 emission rate under the bush land use type is explained by soil moisture content and soil surface temperatures. In contrast, only 46% of the CO_2 emission under the banana land use type is due to the soil moisture content and soil surface temperature. Under the eucalyptus ($r^2= 0.53$), maize ($r^2= 0.65$) and forest ($r^2= 0.76$) land use types, over 50% of the CO_2 being emitted is accounted for by the soil surface temperature and moisture content.

Table 4: Regression statistics of soil CO_2 emission rate and the soil surface temperature and moisture content of the soil across five land use types.

Land use	Multiple R	R squared	Significance F
Banana	0.68	0.46	$p<0.01$
Eucalyptus	0.73	0.53	$p<0.01$
Bush	0.90	0.82	$p<0.001$
Maize	0.81	0.65	$p<0.001$
Forest	0.87	0.76	$p<0.001$

The soil moisture content was the soil property which drove the emission of CO_2 under all the land use types with exception of the banana land use type. The impact of soil moisture on the emission of CO_2 under the eucalyptus, bush, maize and forest land use types was significant at $p<0.001$, while that under the banana land use type was not significant (Table 5). The soil surface temperature also had a significant impact on the CO_2 emission under the banana ($p<0.05$), bush ($p<0.05$), maize ($p<0.01$) and forest ($p<0.01$) land use types. In contrast, the impact of the soil surface temperature under the eucalyptus type was insignificant. Thus, the main driver of CO_2 emission under the banana land use type was the soil surface temperature.

Table 5: Regression coefficients for each land use type.

Land use	Property	Coefficient	Std error	t- Stat	p-Value
Banana	CO_2 emission	-0,09863	0,047533	-2,07503	0,05260
	Soil surface temperature	0,005689	0,002069	2,749918	0,01317
	Soil moisture	0,001528	0,001058	1,444266	0,16585
Eucalyptus	CO_2 emission	-0,00252	0,016342	-0,1543	0,879089
	Soil surface temperature	0,000282	0,00062	0,45415	0,655149
	Soil moisture	0,002243	0,000537	4,173517	0,000571
Bush	CO_2 emission	-0,06354	0,033769	-1,8816	0,076164
	Soil surface temperature	0,002296	0,001078	2,129476	0,047273
	Soil moisture	0,006109	0,000856	7,137535	1,2E-06
Maize	CO_2 emission	-0,11614	0,044246	-2,62486	0,017177
	Soil surface temperature	0,004363	0,001294	3,371707	0,003398
	Soil moisture	0,004475	0,000982	4,555603	0,000245
Forest	CO_2 emission	-0,21565	0,070659	-3,052	0,006863
	Soil surface temperature	0,007895	0,002338	3,376449	0,003362
	Soil moisture	0,006344	0,001126	5,635029	2,4E-05

3.4. Discussion

3.4.1. Seasonal variation of soil surface temperature, soil moisture content, soil CO_2 and Cum CO_2 emission across five land use types

Changes in the soil surface temperature and the soil moisture content were the most compelling fluctuations which were brought about by the different seasons in this study. The soil surface temperature was highest during the summer season and lowest during winter. The higher soil surface temperature observed was accounted for by the weather conditions experienced during the summer season such as longer days and the angle at which the sun's rays hit the earth, which is more direct thus increasing the amount of energy reaching any given point (Salierno *et al*., 2005). This is substantiated by the studies conducted by Chen *et al.* (2021) and Morecroft *et al*. (1998) where the highest temperatures occurred during the summer season. In winter, the days are shorter and there's less radiation due to the angle at which the sun's rays hits the earth thus the amount of heat the soil surface will receive is lower (Khavrus *et al*., 2012). The spring and autumn seasons displayed soil surface temperatures which were lower than that observed during summer but higher than that observed during winter.

The moisture content of the soil was also highly affected by the season as illustrated in Figure 7. This is because the moisture found in the soil is highly dependent on the changes brought about by the different seasons such as the rainfall, falling of leaves and the temperature (Curiel *et al*., 2007). In this study, the moisture content of the soil was highest during the summer season for the land use types did not receive irrigation. Although the summer season brings about the highest temperatures which may lead to evaporation of the water in the soil, it also is the season which brings about higher amounts of rainfall input into the soil. The same results have been obtained by the study conducted by Wachiye *et al*. (2020).

The autumn season had the second highest moisture content of the four seasons. This was due to the higher addition of OM in the form of leaves as most trees or plants shed leaves during this season. The added layer of OM will act as blanket on the soil surface to help reduce the amount of water lost through evaporation thus allowing for improved soil moisture content (Jarvis *et al*., 2007). This may also be due to the decreased temperatures experienced during autumn than that experienced during summer which allow for reduced loss through evaporation like in the studies conducted by Gupta *et al*. (2010).

The lower soil temperature reduces the amount of water uptake by the plants as the viscosity is increased, the absorption rate of water decreases (Sobirovich *et al*., 2020). However, this is not always the case as the study conducted by Rodriguez-Zaragoza *et al*. (2005) observed soil moisture contents which were higher in winter than those observed during summer as some regions receive bulk of the rainfall during winter season than in summer.

The rate at which CO_2 is emitted from the soil is affected by the changes brought about by the seasons (Dilekoğlu *et al*., 2017). This is illustrated in Figure 9 where the rate at which CO_2 was emitted during each season varied significantly. The emission of CO_2 is largely due to respiration which is highly affected by the soil temperature and moisture content as stated in the studies conducted by Davidson *et al*. (2000), Mellander *et al*. (2004), Rastogi *et al*. (2002) and Reth *et al*. (2005). The CO_2 emission and cumulative CO_2 emission rates were both highest during the summer season and lowest during the winter season. The same results have been found in the studies by Brito *et al.* (2015), Cao *et al*. (2018) and Lal *et al*. (2001) which found that under the high soil temperatures and moisture contents experienced during the summer season, the emission rate of CO_2 tends to be higher.

Since most of the C emitted from the soil is through respiration as a result of soil microbes through the process of decomposition. The higher soil temperature and moisture content creates conducive environments for the soil microbes enabling their increased biomass and activity which subsequently leads to increase in the emission of CO_2 (Müller *et al.*, 2004).

In autumn, both the CO_2 emission and cumulative CO_2 emission rates were higher than that observed during spring and winter. This may be accounted for by higher plant litter addition in the form of dead leaves and roots from the plants as plants shed during the autumn season. This directly influences the activity of microbes as increased OM leads to increased supply of energy to enable microbial growth and activity (Babur and Dindaroglu, 2020). The higher CO_2 emission rates observed during the autumn season may have also been due to the soil properties which OM affects such as improved soil moisture content through aggregate stability, clay content, infiltration or aeration, which all play part in improving microbial activity (Chellappa *et al*., 2021). The improved aggregate stability, lower bulk density and higher clay aid in retention of water, thus help in improving moisture contents of the soil.

The relationships between the soil CO_2 emission and the soil surface temperature were significant under the banana, bush, maize, and forest land use types, while that under the eucalyptus land use type was insignificant. The CO_2 emission under the banana, bush, maize, and forest land use type is affected by the soil surface temperature. The increase in the soil temperature results in a moderate increase in the rate of CO_2 emissions in these land use types. The eucalyptus land use type on the other hand, only increased very slightly with increased soil surface temperature and this may have been accounted for by the allelopathic effects that the plant species have on soil microbes. Of all the land use types, the forest land use type is affected most by the soil surface temperature as illustrated in Figure 15.

The relationship between the soil CO_2 emission rate and the soil moisture content was much stronger than that between the soil temperature and the CO_2 emission rate. The relationship between the soil moisture and the rate of CO_2 emission was strongest under the bush land use than the other land use types. The banana was the one which was least affected by the soil moisture as it received irrigation throughout the study period. As the soils under the banana land use types are always maintain high moisture level, the temperature under this land use type becomes the most limiting factor as the specific heat of water is high, making it difficult for the temperatures to be increased in this land use type. This may have been due to type of bacteria found in the study area, as some bacteria release CO_2 during the process of decomposition, while others sequester the C.

3.4.2. The variation of soil surface temperature, soil moisture content, CO_2 emission and cumulative CO_2 emission as influenced by properties of each land use

In this study, the soil surface temperature was largely affected by the land use type like in the studies conducted by Amiri *et al*. (2009), Jusuf *et al*. (2007) and Pitman *et al*. (2009) as significant differences were observed across the five land use types (Figure 7). The banana land use type had the lowest soil surface temperatures followed by that under the eucalyptus land use type. In contrast the soil surface temperatures under the bush, maize and the forest were significantly higher. This lower surface temperature under the banana land use is partly accounted for by the high soil moisture content. This is because water has a high specific heat capacity making increase in the soil temperatures difficult (Dai *et al*., 2003). This is exacerbated the amount of coverage the soil surface receives. The banana and the eucalyptus plantations have canopies which shield the ground from receiving direct sunlight unlike the bush which is covered sparsely with trees and grasses. The studies conducted by Chen *et al.* (2021), Golden *et al*. (2007) and Morecroft *et al*. (1998) also found that tree canopies help in reducing the amount of sunlight reaching the ground thus the lower soil surface temperatures under canopy covered land use types (Jeong *et al*., 2018). The banana and eucalyptus land use types may have had higher soil moisture content due to higher clay contents which aid in water retention as illustrated in figure 5.These land use types also produce litter which is more complex and thus takes time to be decomposed (Edmonds, 1991). This allows for accumulation of plant litter in the soil surface which also protects the soil from solar radiation.

The banana land use type had extremely higher soil moisture content than the other land use types (Figure 8). This is accounted for by the canopy cover which shades the ground from the sunlight preventing loss of water through evaporation (Morecroft *et al*., 1998). The maize field and the bush land use types had the lowest soil moisture contents than the other land use types as they had the least coverage of the soil surface and did not receive irrigation, thus the lower soil moisture content (Figure 8). The clay content was highest under the banana land use type and was approximately 56.8% greater than that under the bush land use type. This may have contributed to the higher moisture content of the soil in the banana land use type than the bush as the soil particles which are smaller in size have a larger surface area for a given volume of soil which increases the contact between the particle and the water molecules (McCauley *et al*., 2005). This subsequently creates strong friction and adhesive bonds with the soil solution, thus enabling finer (clayey) soils to retain more water than coarser (sandy) soils (McCauley *et al*., 2005). This is validated by the studies carried out by Rawls *et al*. (2003) and Yang *et al*. (2014) where soils with higher clay content retained more water.

In this study the effect that land use type had on the CO_2 and cumulative CO_2 emission rates was significant as illustrated in the Figures 11 and 13. The forest land use type displayed the highest CO_2 and cumulative CO_2 emission rates of all the land use types while that recorded under the eucalyptus land use type was the lowest. The forest land use type was characterised by thick grass cover and trees, the eucalyptus land use type was dominated solely by trees. This implies that the soil conditions in these respective land use types differed from each other. This is evident in the soil surface temperature, soil moisture content, soil organic C, soil C stocks and the soil clay content of these respective land use types as illustrated in Figures 7 (A, E and F), 9, 6, 7 and 8.

Although the forest land use type had a lower soil moisture content, the surface temperature was slightly higher than that recorded under the eucalyptus land use type. The higher quantity of grass under the forest land use type accounts for higher OM content and C stocks in the soil in contrast to that under the eucalyptus land use type. The combination of these properties under the forest land use type thus account for the higher rate of CO_2 emission from the soil.

The higher organic C found in the soil (Figure 7F) is due to higher grass cover. This enables high microbial activity as the quantity of SOM in the soil is high. The higher the microbial community and activity the higher the emission rate of CO_2. The type of material added to the soil also plays a huge role on the rate at which the CO_2 is emitted from the soil as found in the study conducted by Don and Kalbitz (2005). Thus, the high quantity of grasses which are easily degradable, the higher the rate of decomposition thus the faster the rate of CO_2 emission than that under the more complex OM produced from the eucalyptus land use type as found in studies conducted by Menninger and Palmer (2007) and Wynn and Bird (2007).

The study conducted by Novara *et al*. (2012) stated that the addition of water in the soil may result in increase in CO_2 release as the water molecules replace the CO_2 gas and causing it to be released into the atmosphere (degassing). However this study has also stated that the process occurs when the diffusivity of the gas is high. The diffusivity of gas in the soil is mainly affected by the bulk density, porosity and texture of the soil (Neira *et al*., 2015). The higher the bulk density and clay content the lower the diffusivity of the soil. This may have accounted for the lower emission of CO_2 under the eucalyptus and banana land use types since they had the highest compaction, lowest porosity and highest clay contents of all the land use types.

In contrast to the faster CO_2 emission and cumulative CO_2 emission rates observed under the forest land use type, the eucalyptus land use type displayed the slowest emission rates of CO_2. This is similar to the studies conducted by Carauta *et al*. (2021) and Edmonds (1991) where the tree canopy covers all or majority of the soil blocking out the sun from the soil surface. The lower soil temperature thus means the lower the microbial biomass and activity. Although the eucalyptus land use type had relatively high OM and soil moisture content than that under the bush land use type, the emission rate was generally low due to the low temperatures thus leading to the accumulation of organic material in the soil.

The other major reason for lower soil CO_2 emission under the eucalyptus land use type was the type of OM added to the soil. The litter produced by eucalyptus trees results in production of allelopathic compounds which have an anti-microbe effect, thus reducing the rate at which the eucalyptus plant litter is decomposed (Briones and Ineson, 1996). The decomposition of eucalyptus leaves is also very slow since the oil released during decomposition of these leaves reduces fungal growth which subsequently will reduce the rate at which CO_2 is resealed. This is substantiated by the study conducted by Martins *et al*. (2013).

The eucalyptus land use type also had a higher clay content, although it aids in moisture retention, clay can retain C in the soil by binding them in forms which are not easily degradable thus the lower the rate of CO_2 emission from this land use type than that under the bush and maize land use types which recorded clay contents below 25% (Yang *et al*., 2021).

3.4.3. The effect of soil properties on soil CO2 emission and C storage

The soil physical properties were amongst the factors which affected the soil CO_2 emission under the different land use types. The relationship between the soil C stocks and the soil CO_2 emission rate was the only physical property which had a positive effect on the emission of CO_2. The other physical properties such as the aggregate stability, bulk density, infiltration, and the clay content displayed a negative relationship with the emission rate of CO_2. This was also found in the study conducted by Pengthamkeerati *et al*. (2005).

The relationship between the storage of C and the soil physical properties was only significant between that of C stocks and the clay content of the soil. The soil C stocks will only be affected slightly by an increase or decrease in the aggregate stability of the soil. The increase in the soil aggregate stability and the clay content will result in an increase in the C stocks. In contrast, the increase in the bulk density and infiltration rate of the soil will result in a decrease in the C stocks of the soil. The same results were found in the research conducted by Leifeld *et al*. (2005) and Zhong *et al*. (2018).

The pH of the soil is one of the most common soil chemical property which affects a lot of factors which are attributable to the emission of CO_2 (Glaser *et al*., 2002). The major impact of soil pH would be that of low pH or high pH affecting the microbial cells and thus resulting in the decrease in the microbial communities depending on the type of microbial communities in that particular land use type. This would lead to the subsequent decrease in the decomposition of OM and the subsequent emission of CO_2. This may have been the cause for lower CO_2 emission than the bush, maize and forest land use types. The other influence of pH would be the effect of high or low pH values which may cause stunted plant growth thus reducing the process of root respiration (Zhalnina *et al*., 2015). In a similar sense the absence of the soil micronutrient (Zn, Cu and Mn) may stunt plant growth and thus result in lowered plant rot respiration. This may account for a very small part of lower CO_2 emission under the banana and eucalyptus land use types.

3.4.4. The effect of soil microbial properties on soil C storage and emission

The soil microbes which are mainly responsible for the process of decomposition are the fungi and bacteria (Miltner *et al*., 2012). The study conducted by (Pietikäinen *et al*., 2005) found that the biomass and activity of soil bacteria and fungi was at optimum at soil temperature ranging between 25°C to 30°C and when soil moisture is near field capacity or when 60% of the soil pore spaces are filled with water as stated by Denardin *et al*. (2020) and Guntinas *et al*. (2013). The Figure 6 illustrates the effect of land use on the soil fungal and bacterial count. The soil fungal count was significantly impacted by the land use type as can be seen in Figure 6A. The soil fungal count under the eucalyptus, bush and the maize land use type did not show major differences, but these differed from the lowest (banana) and highest (forest) fungal counts.

The forest land use type had extremely higher fungal counts than the other land use types. Although the soil temperature and moisture content under the forest land use type was not the highest of all, the soil organic C and soil C stocks were highest under the forest land use type. This means that there was more OM under this land use for soil microbes to decompose, thus the higher CO_2 emission rate from this land use type. The findings of Frey (2019) stated that fungi biomass and activity is high under higher OM content as the litter layer serves as a medium onto which the fungi hyphae can grow. The high OM content also serves as a growing medium for the soil fungi under the forest land use type thus the higher biomass and activity of fungi in the forest land use type than that observed under the bush and maize land use types (Brown *et al*., 2000).

Fungi is also more sensitive to changes of the habitat than bacteria since their hyphae grow into the layer of the OM and management practices such as tillage will cause destruction of the fungal hyphae thus reducing fungal biomass and activity (Miller and Lodge, 1997). The findings from the study conducted by Angst *et al*. (2021) stated that the type of OM added to the soil also affects the type of soil microbes which will dominate that soil. Fungi are the main decomposers of C:N rich material such as cellulose which can be found in grasses (Okoth *et al*., 2009). This is also liable for the higher fungal count under the forest land use type than that of all the other land use types as majority of the soil surface under the forest land use type is covered with grass (Okoth *et al*., 2009).

The banana land use type was characterized by the lowest soil surface temperature, the highest soil moisture content and bulk density and as the richest in clay content. It however, recorded the least amount of soil fungi. This is due to the low surface temperature, high bulk density and high amount of clay in the soil. The low temperatures hinder the activity and biomass of the fungi as found in the study conducted by Allison and Treseder (2008), while the combination of high soil bulk density, high clay content and high soil moisture in the banana land use type resulted in creation of anaerobic soil conditions (Linn and Doran, 1984). The more the soil condition becomes anaerobic, the lower the counts of fungi in the soil. This is substantiated by the studies conducted by Momma *et al*. (2013) and Wainwright (1988). The pH of the soil under the banana land use type was also very low thus creating an acidic environment which hinders fungal biomass and diversity (Yule and Gomez, 2009).

The soil bacterial count did not show significant variations across the land use types, but it was however higher under the natural bush and lowest under the banana land use type. The bush land use generally had higher soil surface temperatures, lower soil moisture content and a slightly acidic pH while the opposite was true for the banana land use type with higher soil moisture but lower soil surface temperature and very acidic soil pH. The lower number of bacteria under the banana land use type may be accounted for by the higher bulk density of the soil and higher moisture content than that observed under the bush land use type.

The combination of higher soil bulk density and higher soil moisture content creates soil conditions where oxygen is limited, and thus anaerobic conditions are developed (Linn *et al.*, 1984). Although there are bacteria which thrive under anaerobic conditions, most soil bacteria require aerobic soil conditions for their optimal activity (Msimbira and Smith, 2020). In contrast, the bush land use type had higher soil temperatures which promoted soil bacterial biomass and activity. Similar results were obtained by studies conducted by Lozano-Parra *et al*. (2018) and Tang *et al*. (2022). The study conducted by Borowik and Wyszkowska (2016) found that lower soil bulk densities promote bacteria availability than those which have higher bulk densities. This is similar to the findings in this study as soil bacteria was higher under the bush land use type than the banana land use type as the bush land use type had the second lowest bulk density while the banana land use type had the highest bulk density.

The relationship between the emission rate of CO_2 and the fungal count of the soil was positive and strong, implying that increased soil fungal count should increase the emission rate of CO_2. This is true for the maize and forest land use types. This is similar to results obtained from the study carried out by Kant *et al*. (2010). While most studies such as those conducted by Garcia *et al*. (1994) and Wang *et al*. (2003) found that the relationship between the CO_2 emission rate and the bacterial count is strong and positive, while in this study the opposite is true under the maize and forest land use types. Contrary to the observations under the maize and forest land use types, the relationship between CO_2 emission rate and the soil fungi was positive under the banana, eucalyptus, and bush land use types.

The relationship between the soil C stocks and soil bacteria displayed negative relations which is in contrast with that observed in studies conducted by Bastida *et al*. (2021) and Dong *et al*. (2021). The banana, eucalyptus and bush land use types displayed negative correlations with the soil C stocks. The maize and forest land use type were however the only two land uses which displayed positive correlations between the soil C stocks and the bacteria of the soil as illustrated in the table 3 above. These results are similar to findings in the studies conducted by Chen *et al.* (2019) and Wu *et al*. (2022).

3.4.5. The main drivers of C storage and emission within each land use type

The soil surface temperature and soil moisture accounted for only 46% and 53% of the variation in CO_2 emission rates under the banana and eucalyptus land use types respectively. Thus, 54% and 47% of the variation in CO_2 emission rates under the banana and eucalyptus land use types was accounted for by other factors.

The soil surface temperature was a stronger driver of CO_2 emission from the soil only under the banana land use type as illustrated in Table 5, while the moisture content of the soil was responsible for CO_2 emission under all the other land use types. Contrary to the soil moisture content being the main driver of CO_2 emission in all the other land use types, the impact that the soil moisture content had on the emission of CO_2 from the soil under the banana land use type was insignificant. This is mainly due to the fact that the banana land use type received irrigation throughout the year thus making the soil temperature the most limiting factor. Similar results were obtained in studies conducted by Dilekoğlu *et al*. (2017) and Hill *et al*. (2021). The soil temperature also has an impact on the soil microbes, thus the increase in the temperatures allowed for improved soil conditions which favor microbial biomass activity contributing towards CO_2 emission.

The emission of CO_2 from the soil under the eucalyptus, bush, maize and forest land use types was mainly driven by the moisture content of the soil. These land use types depended solely on precipitation for moisture inputs unlike the banana land use type, thus making the soil moisture content the most limiting factor under the eucalyptus, bush, maize and forest land use type. The same results were found in the studies conducted by Koerner *et al.* (2002) and Natali *et al*. (2015). As the soil moisture was the most limiting factor under the eucalyptus, bush, maize and forest land use type, increase in the moisture content through rainfall resulted in the increase of CO_2 as illustrated in Figure 9A. The period between September 2021 till February 2022 in Figure 9A illustrates the period where there was an increase in the rainfall thus the increase in the soil CO_2 emission rate.

3.5. Conclusion

In this study, the variation in the storage and emission of C from the soil under the different land use types was investigated. There are four main conclusions which can be drawn from this study. The first is that the season influenced the emission and storage of C in the soil. This is because different seasons influenced the soil surface temperatures and moisture content of the soil which were the main determinants of the amount of C stored and emitted from the soil.

Thus, the summer season resulted in the highest emission rates of CO_2 as the soil temperature and soil moisture increased during this season creating conditions which promote CO_2 emission. In contrast, the winter season resulted in the lowest soil CO_2 emission rates as temperatures and moisture contents were lower. During autumn, higher CO_2 emission rates were observed than that during spring and winter which was accounted for by the increased plant litter on the soil surfaces allowing for increased OM essential to microbial decomposition. The spring season resulted in CO_2 emission rates higher than that observed during winter. This was solely due to the higher temperatures and moisture contents observed during the spring season than that observed during winter.

The second conclusion drawn from this study is that the land use type does affect the amount of C stored or emitted from the soil. The effect of the land use type on the C content of the soil is mainly linked to the land use impact on the soil temperature and moisture. The land use type also affects the quantity and quality of soil OM which in turn affects C emission or storage. There were also different management practices across the land use types such as irrigation and tillage which affected the storage and emission of C in the soil. The emission rates of CO_2 from the soil were ranked from highest to lowest in the following order: forest > banana > maize > bush > eucalyptus. The high CO_2 emission under the forest land use type was due to the high amount of OM and the quality of the OM found under the forest land use type as it is easily degradable than that found under the eucalyptus land use type. The land use type affected the soil C storage significantly and the C stocks were ranked from highest to lowest in the following order: forest > eucalyptus > banana > maize > bush.

The emission and storage of C from the soil was also affected by the various land use types as the different soil properties under each land use type played a role in the storage and emission of C. Although the impact of the soil physical properties was not as much as those of the temperature and moisture, it helped put into perspective the cause of the low or high values observed in the soil C content.

Lastly, the soil fungal count had a significant impact on the emission of CO_2 and the storage of C. In contrast, the soil bacterial count did not display a significant impact on the soil’s CO_2 emission rate and displayed weak negative relations with the soil C stocks.

CHAPTER 4

SUMMARY AND CONCLUSION

The importance of soil C emission and C storage has increased drastically as there is an increase in climate change, population growth and the demand for food and services. Due to the increased degradation of soils and increased demand of food as the population is growing, the soil has become one of the most valuable natural resources. The increased pressure being exerted on the environment has led to the need of understanding the dynamic relationships between the soil and the atmosphere to enable mitigation strategies to ensure sustainability. One of the most important functions of soil is its ability to store and retain high quantities of C than that in the air and the plant biomass. Thus, the increased understanding of the factors which affect its ability to retain C is essential.

In this study, the variations in soil C storage and emission as affected by the land use type was of significant importance. As illustrated in the results section, the soil C emission and storage were highly dependent on the soil moisture and surface temperatures. This was attributable to the fact that the soil surface temperature and moisture content affects the process of soil respiration which accounts for majority of the C being lost or stored within the soil. The soil surface temperature was highest during the summer season and lowest during winter. While the same was true for the soil's moisture content. The higher soil surface temperature and moisture content experienced during summer is attributable to the angle at which the sun hits the earth and longer days allowing for higher solar radiation and the greater rainfall adding water into the soil.

The soil surface temperature and moisture content had direct and indirect impacts on the process of soil respiration thus their huge influence on the C content which is found within the soil. The soil surface temperature affects evaporation, plant root respiration and microbial respiration. This thus explains higher CO_2 emission rates in summer than in winter. The increased soil moisture content during summer also allows for conducive habitats for soil microbes thus encouraging decomposition which subsequently increases the rate of soil CO_2 emission.

The land use type also affected the amount of C found within the soil as its values varied significantly across the five land use types. The type and quantity of cover were the major factors affecting the soil C content found in the soil. This is evident as the land use which had the highest CO_2 emission rate also had the highest amount of organic C and C stocks. This implies that although the soil temperature and moisture maybe at adequate levels for optimal soil microbial activity, the type and the quantity of OM added to the soil will largely influence the soils CO_2 emission rate. The type of management practices such as irrigation and tillage under the banana and maize land use types respectively were also used as an explanatory factor with relation to the storage and emission of C within the soil.

In contrast, the soil physical properties (C stocks, aggregate stability, infiltration, clay %) displayed minor influences on the C content found within the soil. This was elucidated by the low regression relationships observed between the soil C content and the soil physical properties and that between the soil CO_2 emission and the soil physical properties. Although the soil physical parameters did not display strong influences on the storage and emission of C in the soil, these measurements played a huge role in the explanation of why certain land use types displayed certain C emission or storage values.

The soil fungi played a huge impact on the emission and storage of C within the soil, as the land use with the highest amount of organic C also displayed higher amounts of fungal counts. The forest land use type was also the one which had the highest CO_2 emission rate. This further implicates that the type and quantity of OM added to the soil is essential, as the higher the amount and the degradability of the OM, the higher the rate at which CO_2 is emitted. In contrast, the overall impact of the bacterial counts was not significant, but it did play a crucial role in the emission rate of CO_2 under some land use types.

The emission rate of CO_2 across the land use types was ranked from highest to lowest in following order: forest > banana > maize > bush > eucalyptus. In this study, the soil moisture content was the most limiting factor under the eucalyptus, bush, maize and forest land use types, thus the soil moisture was considered as the main driver of CO_2 emission under these land use types. In contrast, the soil surface temperature was the most limiting factor under the banana land use type, the soil CO_2 emission was being driven by the soil temperature. This is because the banana land use type was irrigated while the other land use types deepened on rainfall.

The land use type has significant impacts on the storage and emission of C and is largely affected by the soil surface temperature and moisture content as well as the changes brought about by the seasons. The effect that land use has on the storage and emission of C also changes with changes brought about by the various seasons.

In summary, some of the soil properties, the soil surface temperature, moisture content, CO_2 emission and cumulative CO_2 emission varied significantly with the soil temperature, moisture content and CO_2 emission being affected by changes brought about by the season. Bacteria displayed negative correlations with CO_2 emission, while the fungal count was positively correlated with CO_2 emission. Despite the visible influence that the soil temperature had on CO_2 emission in the banana land use type, in our study, the soil moisture was deemed the main driver of CO_2 as soil moisture was the moist limiting factor in the study.

As there is less research about the effect of land use type on soil C storage and emission under the conditions occurring in Southern Africa, this study will serve as a point of reference for future studies and will add on to the body of knowledge about the effect of land use type on soil C storage and emission. This study provides insight about the dynamic relationship between the land use type and C storage and emission as affected by season, soil properties and land management practices. This information can be subsequently used for creating measures to reduce CO_2 release into the atmosphere and means of increasing C storage into the soil.

Although this study provides great insight about the effect of land use type on C storage and emission as affected by soil bacteria and fungi, there is room for further study into further characterization of the microbes found in the soil. This is essential as most of the C in the soil is either released into the atmosphere or sequestered into the soil by these microbes. Thus, further characterization will provide much more conclusive results and increase reliability of the information to be used as point of reference.

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APPENDICES

Appendix 1: One way ANOVA table for the soil chemical properties in the 0-15 cm soil depth.

N

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land use	4	0.45077	0.11269	10.94	0.001
Residual	10	0.10300	0.01030		
Total	14	0.55377			

P

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land use	4	6831.	1708.	1.45	0.288
Residual	10	11771.	1177.		
Total	14	18601.			

K

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land use	4	79820.8	19955.2	33.79	<.001
Residual	10	5906.4	590.6		
Total	14	85727.1			

Ca

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land use	4	1855788.	463947.	2.58	0.102
Residual	10	1800197.	180020.		
Total	14	3655985.			

Mg

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land use	4	242855.	60714.	21.18	<.001
Residual	10	28671.	2867.		
Total	14	271525.			

Exchangeable acidity

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land use	4	206.732	51.683	7.80	0.004
Residual	10	66.281	6.628		
Total	14	273.013			

pH

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land use	4	4.9340	1.2335	6.30	0.008
Residual	10	1.9591	0.1959		
Total	14	6.8931			

Zn

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land use	4	269.604	67.401	9.15	0.002
Residual	10	73.649	7.365		
Total	14	343.252			

Mn

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land use	4	1385.13	346.28	15.25	<.001
Residual	10	227.08	22.71		
Total	14	1612.21			

Cu

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land use	4	30.4142	7.6035	13.03	<.001
Residual	10	5.8337	0.5834		
Total	14	36.2479			

Appendix 2: One way ANOVA table for the soil chemical properties in the 15-30 cm soil depth.

N

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land use	4	0.5740267	0.1435067	352.89	<.001
Residual	10	0.0040667	0.0004067		
Total	14	0.5780933			

P

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land use	4	207.577	51.894	10.09	0.002
Residual	10	51.415	5.142		
Total	14	258.992			

K

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land use	4	72103.6	18025.9	63.17	<.001
Residual	10	2853.7	285.4		
Total	14	74957.3			

Ca

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land use	4	4267523.	1066881.	4.03	0.034
Residual	10	2647505.	264751.		
Total	14	6915028.			

Mg

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Land use	4	178509.	44627.	2.33	0.127
Residual	10	191539.	19154.		
Total	14	370049.			

Exchangeable acidity

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Land use	4	321.57	80.39	5.86	0.011
Residual	10	137.14	13.71		
Total	14	458.72			

pH

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Land use	4	5.0105	1.2526	5.84	0.011
Residual	10	2.1436	0.2144		
Total	14	7.1541			

Zn

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Land use	4	127.921	31.980	17.90	<.001
Residual	10	17.864	1.786		
Total	14	145.785			

Mn

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Land use	4	1172.87	293.22	18.89	<.001
Residual	10	155.24	15.52		
Total	14	1328.11			

Cu

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Land use	4	43.71395	10.92849	213.82	<.001
Residual	10	0.51110	0.05111		
Total	14	44.22504			

Appendix 3: One way ANOVA table for the soil physical properties as affected by the land use type.

Clay

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Land use	4	1560.40	390.10	19.00	<.001
Residual	10	205.33	20.53		
Total	14	1765.73			

Org C

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**

Land use	4	4.0760	1.0190	4.15	0.031
Residual	10	2.4533	0.2453		
Total	14	6.5293			

SOCS

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land use	4	1.6109	0.4027	4.02	0.034
Residual	10	1.0007	0.1001		
Total	14	2.6116			

Aggregate stability

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Land use	4	1.45715	0.36429	4.62	0.023
Residual	10	0.78912	0.07891		
Total	14	2.24626			

Bulk density

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Land use	4	0.23778	0.05944	2.74	0.089
Residual	10	0.21658	0.02166		
Total	14	0.45436			

Infiltration

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Land use	4	693.26	173.32	5.56	0.013
Residual	10	311.95	31.19		
Total	14	1005.21			

Appendix 4: One way ANOVA table for the soil biological properties as affected by the land use type.

Fungal counts (10^5 × cfu g^{-1})

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Land use	4	5.095E+15	1.274E+15	356.53	<.001
Residual	10	3.573E+13	3.572E+12		
Total	14	5.131E+15			

Bacterial counts (10^5 × cfu g^{-1})

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Land use	4	1,78E+13	4,45E+12	0.55	0.703
Residual	10	8,07E+13	8,07E+12		
Total	14	9,85E+13			

Appendix 5: One way ANOVA table for the soil CO_2 emission, cumulative CO_2 emission, soil surface temperature and soil moisture as affected by the season.

CO$_2$ emission

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Season	3	1321.16	440.39	41.80	<.001
Residual	311	3276.39	10.54		
Total	314	4597.55			

Cumulative CO$_2$ emission

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Season	3	2802.29	934.10	56.72	<.001
Residual	101	1663.37	16.47		
Total	104	4465.67			

Soil surface temperature

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Season	3	1686.29	562.10	20.46	<.001
Residual	311	8543.37	27.47		
Total	314	10229.66			

Soil moisture

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Season	3	5743.88	1914.63	29.29	<.001
Residual	311	20330.02	65.37		
Total	314	26073.90			

Appendix 6: Two-way ANOVA for the soil surface temperature, soil moisture, CO$_2$ emission rates and cumulative CO$_2$ emission rates as affected by the season and land use type.

Soil surface temperature

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Season	3	1686.29	562.10	34.61	<.001
Land use	4	3698.65	924.66	56.94	<.001
Season_Land use	12	54.29	4.52	0.28	<.001
Residual	295	4790.42	16.24		
Total	314	10229.66			

Soil moisture content

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Season	3	5743.88	1914.63	55.20	<.001
Land use	4	9510.24	2377.56	68.55	<.001
Season_Land use	12	587.54	48.96	1.41	0.992
Residual	295	10232.24	34.69		
Total	314	26073.90			

CO_2 emission					
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Season	3	1321.160	440.387	58.86	<.001
Land use	4	556.165	139.041	18.58	<.001
Season_Land use	12	513.056	42.755	5.71	<.001
Residual	295	2207.172	7.482		
Total	314	4597.554			

Cumulative CO_2 emission					
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Season	3	2802.294	943.098	185.84	<.001
Land use	4	861.870	215.467	42.87	<.001
Season_Land use	12	374.252	31.188	6.20	<.001
Residual	85	427.249	5.026		
Total	104	4465.665			

Appendix 7: One way ANOVA table for soil moisture as affected by the land use type.

Soil surface temperature in autumn					
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Land use	4	3510.24	2377.56	44.50	<.001
Residual	310	16563.67	53.43		
Total	314	26073.90			

Appendix 8: One way ANOVA table for the soil surface temperature as affected by land use type in each season.

Soil surface temperature in autumn					
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Land use	4	979.85	244.96	16.93	<.001
Residual	85	1229.76	14.47		
Total	89	2209.61			

Soil surface temperature in winter					
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Land use	4	939.63	243.91	15.68	<.001
Residual	70	1048.78	14.98		
Total	74	1988.41			

Soil surface temperature in spring					
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Land use	4	910.47	227.62	10.16	<.001

Residual	85	1903.68	22.40		
Total	89	2814.16			

Soil surface temperature in summer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land use	4	923.00	230.75	20.87	<.001
Residual	55	608.20	11.06		
Total	59	1531.19			

Appendix 9: One way ANOVA table for the soil the CO_2 emission as affected by the land use type in each season.

CO_2 emission Autumn

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Land use	4	345.40	86.35	5.94	<.001
Residual	85	1235.11	14.53		
Total	89	1580.52			

CO_2 emission Winter

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Land use	4	35.2758	8.8189	22.25	<.001
Residual	70	27.7503	0.3964		
Total	74	63.0260			

CO_2 emission Spring

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Land use	4	183.554	45.889	8.65	<.001
Residual	85	450.892	5.305		
Total	89	634.446			

CO_2 emission Summer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land use	4	504.987	126.247	14.07	<.001
Residual	55	493.417	8.971		
Total	59	998.404			

Appendix 10: One way ANOVA table for the cumulative soil CO_2 emission as affected by land use type in each season.

Cumulative CO_2 emission Autumn

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Land use	4	43.164	10.791	2.29	0.088
Residual	15	117.934	4.717		
Total	19	161.098			

Cumulative CO_2 emission Winter

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land use	4	133.303	33.3256	57.33	<.001
Residual	15	11.6254	0.5813		
Total	19	144.9279			

Cumulative CO_2 emission Spring

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land use	4	313.814	78.454	32.86	<.001
Residual	15	59.694	2.388		
Total	19	373.508			

Cumulative CO_2 emission Summer

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Land use	4	745.84	186.46	11.75	<.001
Residual	15	238.00	15.87		
Total	19	983.84			

Appendix 11: Summary of regression analysis for the soil surface temperature and CO_2 emission rates across five land use types.

Banana

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	0.0406	0.040565	18.12	<.001
Residual	61	0.1365	0.002238		
Total	62	0.1771	0.002856		

Eucalyptus

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	0.00175	0.0017466	4.39	0.040
Residual	61	0.02429	0.0003982		
Total	62	0.02604	0.0004199		

Bush

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	0.0366	0.036641	18.65	<.001
Residual	61	0.1198	0.001964		
Total	62	0.1565	0.002524		

Maize

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	0.02161	0.021613	13.26	<.001
Residual	61	0.09941	0.001630		
Total	62	0.12102	0.001952		

Forest

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	0.1133	0.113326	28.32	<0.001
Residual	61	0.2441	0.004001		
Total	62	0.3574	0.005765		

Appendix 12: Summary of regression analysis for the soil moisture content and CO_2 emission rates across five land use types

Banana					
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	1	0.0108	0.010784	3.96	0.051
Residual	61	0.1663	0.002726		
Total	62	0.1771	0.002856		
Eucalyptus					
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	1	0.01007	0.0100692	38.47	<.001
Residual	61	0.01597	0.0002617		
Total	62	0.02604	0.0004199		
Bush					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	0.09465	0.094655	93.42	<.001
Residual	61	0.06180	0.001013		
Total	62	0.15646	0.002524		
Maize					
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	1	0.04285	0.042851	33.44	<.001
Residual	61	0.07817	0.001282		
Total	62	0.12102	0.001952		
Forest					
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	1	0.1776	0.177640	60.28	<.001
Residual	61	0.1798	0.002947		
Total	62	0.3574	0.005765		

Appendix 13: Summary of regression analysis for the soil physical properties and CO_2 emission rates.

C stocks					
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	1	0.001516	0.0015164	4.13	0.063

Residual	13	0.004777	0.0003675		
Total	14	0.006293	0.0004495		

Aggregate stability

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	1	0.000331	0.0003313	0.72	0.411
Residual	13	0.005962	0.0004586		
Total	14	0.006293	0.0004495		

Bulk density

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	0.000056	0.0000561	0.12	0.783
Residual	13	0.006237	0.0004798		
Total	14	0.006293	0.0004495		

Infiltration

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	1	0.000418	0.0004178	0.92	0.354
Residual	13	0.005875	0.0004520		
Total	14	0.006293	0.0004495		

Clay

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	1	0.000370	0.0003704	0.81	0.384
Residual	13	0.005923	0.0004556		
Total	14	0.006293	0.0004495		

Appendix 14: Summary of regression analysis for the soil biological properties and CO_2 emission rates.

Fungal counts (cfu g^{-1})

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	1	0.002789	0.0027885	10.34	0.007
Residual	13	0.003505	0.002696		
Total	14	0.006293	0.004495		

Bacterial counts (cfu g^{-1})

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	1	0.000337	0.0003374	0.74	0.406
Residual	13	0.005956	0.0004581		
Total	14	0.006293	0.0004495		

Appendix 15: Summary of regression analysis for the soil physical properties and C stocks.

Aggregate stability

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	0.002	0.0025	0.01	0.913
Residual	13	2.609	0.2007		
Total	14	2.612	0.1865		

Bulk density

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	0.021	0.0209	0.11	0.751
Residual	13	2.591	0.1993		
Total	14	2.612	0.1865		

Infiltration

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	0.832	0.8321	6.08	0.028
Residual	13	1.779	0.1369		
Total	14	2.612	0.1865		

Clay

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	0.064	0.0642	0.33	0.577
Residual	13	2.547	0.1960		
Total	14	2.612	0.1865		

Appendix 16: Summary of regression analysis for the soil biological properties and C stocks.

Fungal counts (cfu g^{-1})

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	0.959	0.9593	7.55	0.017
Residual	13	1.652	0.1271		
Total	14	2.612	0.1865		

Bacterial counts (cfu g^{-1})

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	0.081	0.0809	0.42	0.530
Residual	13	2.531	0.1947		
Total	14	2.612	0.1865		

Appendix 17: Summary of multiple linear regression analysis for the soil CO_2 emission rate and the soil surface temperature and moisture content across five land use types.

Banana

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	2	0.017918	0.008959	7.791696	0.00365
Residual	18	0.020697	0.00115		
Total	20	0.038615			

Eucalyptus

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	2	0.003794	0.001897	10.27556	0.001055
Residual	18	0.003323	0.000185		
Total	20	0.007117			

Bush

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	2	0.037328	0.018664	39.72151	2.50E-07
Residual	18	0.008458	0.00047		
Total	20	0.045785			

Maize

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	2	0.022741	0.011371	16.81791	7.6E-05
Residual	18	0.01217	0.000676		
Total	20	0.034911			

Forest

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Regression	2	0.084039	0.04202	28.89129	2.41E-06
Residual	18	0.026179	0.001454		
Total	20	0.110219			