QUALITY PARAMETERS OF ORGANIC AMENDMENTS FROM UMBUMBULU AND MSINGA FARMS AND THEIR EFFECTS ON NITROGEN AND PHOSPHORUS MINERALIZATION

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DECLARATION

I, Khethukuthula Pacia Hlatshwayo hereby declare that:

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ABSTRACT

Conventional agricultural management practices that farmers in Africa and South Africa have practiced have led to a decline in soil fertility. Organic amendments have shown to improve soil quality and fertility status when incorporated into the soil. Smallholder farmers manage their fields differently according to resource endowment, distance of fields from the homestead (i.e homefield and outfield), and labour. The use of organic inputs as fertilizers to remediate the soils from which the loss of nutrients occurred depends on their decomposition rates and nutrient release patterns. Factors such as soil type, climate and application rates of the amendments affect the decomposition and mineralization of these amendments in soils. The objective of this study was to determine (i) carbon and phosphorus pools from different fields from uMbumbulu and Msinga as affected by farmer typology and (ii) the characteristics of organic amendments and their decomposition and mineralization of nitrogen and phosphorus in soil. Three typologies (i.e. resource constrained, moderately resourced and resource endowed) were selected for both Msinga and Mbumbulu. Two fields per typology were used, namely homefield (<100m from homestead) and outfield (>150m from home) for Msinga while for uMbumbulu it was fields with mixed cropping and monocropping system. Three farms were selected per typology and field type with three replications. Soil samples were collected from the farms of different typologies at 0 – 20cm and analyzed for soil organic carbon (SOC) and phosphorus pools. Organic amendments including cattle manure, goat manure, accelerator and maize residues were sampled from different farms in Msinga and uMbumbulu and characterized. Composite samples of these amendments, separately and in combination, were then incorporated in soils and incubated for 84 days during which soil pH, P and mineral-N (ammonium-N and nitrate-N) were analyzed. Farmer typologies did not affect carbon and phosphorus pools of the soils on farms at Msinga and uMbumbulu. Carbon pools under different cropping systems and typologies for uMbumbulu showed significant difference with total carbon concentrations being the highest under monocropping system (40.3 g/kg) followed by c-POMC, f-POMC, MAOC and DOC and also under resource constrained typology, total carbon was the highest (44.6 g/kg). Carbon pools under Msinga did not follow the same trend both under cropping system and typology since there was no significant difference. More P was in a reductant P form in uMbumbulu soil both under different cropping systems and typology with concentration of 224-310 mg/kg under cropping system and 145-447 mg/kg within typology. Available P had lower concentrations in both cropping system (8.9-11.8 mg/kg) and typology (9.6-11.7 mg/kg) with Al-P and Fe-P showing no significant difference in uMbumbulu soil. Msinga soils followed the same trend of P pools showing no significant different in Al-P and Fe-P as uMbumbulu.

Msinga soils showed more positive correlation between carbon and phosphorus pools than uMbumbulu soils. Msinga amendments appeared more beneficial than uMbumbulu with high pH levels and cattle manure having low C/N ratio content which allows rapid decomposition. More nutrients were available for plant uptake as Msinga amendments had higher concentrations of bases. The Accelerator had higher ammonium-N concentration (128 g/kg N on day 84) than other treatments showing higher decomposition rate in the uMbumbulu soil. When the manures were combined with maize residues, they had lower ammonium-N concentration due to C:N ratio of the maize residues. After day 7 of incubation, nitrate-N and mineral-N concentration increased in all treatment in both mg/kg soil and g/kg of N present. Like in the first incubation experiment (uMbumbulu soil), the control in the Msinga soil had higher nitrate-N than all treatment combinations containing maize residues between 14 to 56 days of incubation except for the accelerator+maize residues. Maize residues in both experiments (uMbumbulu and Msinga soils) showed lower mineralization of N and P and Msinga amendments had higher nutrient mineralisation than those from uMbumbulu. The findings of the study imply that carbon and phosphorus pools in the two study sites could be affected by environment factors more than management practices and that maize residues will require a longer period of time to allow maximum decomposition and mineralize nutrients compared to the accelerator, cattle, and goat manure. More studies need to be done on environmental factors such as climate, parent material, and topography, as they might be the primary drivers of carbon and phosphorus pools.

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DEDICATION

I would like to dedicate this dissertation to my late sister Nomasonto Kunene and grandmother Ntombemhlophe Kunene whose passing I did not mourn because I had to stay focused to finish my research.

CHAPTER ONE
GENERAL INTRODUCTION

1.1. Background

Soil fertility depletion in smallholder farms has been the main fundamental cause of a decline in food production leading to food insecurity (Sanchez *et al.*,1997). Soil mismanagement also contributes to production challenges in smallholder farms of sub-Saharan Africa (Belay *et al.*, 2015; Henryson *et al.*, 2018; Najera *et al*., 2015). For example, continuous cropping with lower addition of fertilizer or no fertilizer coupled with removal of crop residues from the field has led to poor fertility status of the soils (Shepherd and Soule 1998). Many studies have shown the importance of restoring the soil phosphorus and organic carbon as it affects the soil fertility and productivity leading to food insecurity across the world. However, soil fertility management is largely dependent on farmer typology, which has been identified as a key factor in smallholder production due to its influence on farm management decisions (Tittonell *et al.*, 2010). Farmer typology is determined by the socio-economic status of the farmer and relates to resource endowment and resource (e.g., fertilizers, labour) allocation to farms. This has resulted in more heterogeneity in the management of smallholder farm with implications for nutrient storage or losses. Different management practices in smallholder farms are thus an important source of variability creating areas of nutrient accumulations and depletions (Negasa *et al.*, 2017). Soil organic C is the most important component that maintains soil quality because of its role in improving physical, chemical and biological properties of the soil. The soil is known to be the potential carbon sink and can offset rising atmospheric carbon dioxide (CO_2) its capacity to store and sequester carbon mainly depends on the rate of carbon inputs from the plant productivity relative to carbon exports controlled by microbial decomposition. Input of organic amendment is a management practice that can improve the nutrient status of the soil and increase SOC levels (Rochette and Gregorich 1998). Smallholder farmers mainly depend on local organic amendments including animal manure and crop residues as sources of nutrients and improvement of soil organic carbon (SOC).

Many studies have shown that the use of these organic amendments can improve soil fertility by returning nutrients into the soil for optimum crop growth. A global meta-analysis revealed that plant residues increase SOC level by 14.9% on average when incorporated into the soil and recycled organic amendments have been proven to improve soil fertility (Liu *et al.*, 2020; Xiao *et* *al*., 2018). The soil fertility improvement depends on the influence of the incorporated organic amendments on soil carbon fractions, with labile fractions being involved in nutrient cycling while the more stable fractions are more important for SOC storage. Ghosh *et al*. (2012) stated that freshly incorporated plant residues provide large amounts of labile C which increase SOC. A long-term study conducted in China showed that the incorporation of organic amendments into soil increased SOC stocks across all labile and non-labile organic C fractions over time (Li *et al*., 2021). Another study conducted in Italy by Bonanomi *et al.* (2020) which evaluated the use of synthetic fertilizers and organic amendments such as Alfalfa hay, biochar, glucose and manure showed that soils treated with organic amendments had higher pH values (7.91-8.47) compared to synthetic fertilizers (4.39-5.38). In the same study, the organic amendments increased organic carbon from 14.90 g/kg to 26.45 g/kg. The lower pH in soils amended with synthetic fertilizers could affect availability of plant nutrients such as nitrogen (N), phosphorus (P), calcium (Ca), magnesium (Mg), sulphur (S) and potassium (K). Crop residues and organic input are the main contributors to carbon entering the soil, particularly in smallholder agriculture (Rasse *et al.,*2005). Increasing carbon returns to the soil as crop residues, manure, and other organic amendments, increases SOC storage, (Stewart *et al.,* 2007). Rasmussen *et.al.* (1980) observed that changes induced in SOM levels were controlled by amount of carbon in each residue applied on a wheat-fallow system. In addition to SOC, the use of organic amendments also affects dynamics of nutrients, particularly nitrogen (N) and phosphorus (P).

Animal manure contains significant amount of N and P, which can result in an increase of these nutrients in the soil. The release of these elements from the manure however depends on edaphic and non-adaphic factors influencing decomposition and mineralization processes. Phosphorus as the most required nutrients for plant growth get lost easily from the soil through runoff or become unavailable as majority of its compounds are insoluble or firmly bound to the surface of soil particles (Miretzky and Fernandez-cirelli 2008). Soil pH is one of the soil properties that determine the chemical complexation of P. Acidic soils are also known to have high fixation capacity due to high Al and Fe (Brady and Weil 2014; Mkhonza *et al.*, 2020) while at high soil pH (above 6.5) P react with calcium decreasing the availability of P (Torren 1997; Borggard *et al.,* 2004). Many studies have shown that application of organic amendments such as manure increases soil pH increasing P fractions that are available for plant uptake. Warmer and wetter conditions enhance the activities and diversity of microorganisms which lead to faster decomposition and mineralization of nutrients from the amendments (Lin *et al.,* 2017).

Application and incorporation of residues and manure into the soil have been practiced making phosphorus available to the crops, although some pools tend to be lost during the process affecting the performance of the soil to the crops. Many long-term fertilizer experiments worldwide have shown that balanced fertilization with application of organic manure can improve the nutrient status of the soil and maintain high crop yield with high levels of residues turnover to the soil that increase the SOC concentration (Holeplass *et al.,* 2004). It is thus important to understand how these management practices affect soil fertility, especially carbon and phosphorus fractions, in a local environment, and how locally available organic amendments can improve soil quality and carbon storage.

1.2. Justification of the study

Many studies have shown a decline in food production due to land degradation and fertility depletion resulting from poor soil management practices and over cultivation (FAO *et al*., 2017). About 75% of the farmlands are classified as mostly depleted due to poor soil management in Africa (FAO. 2002). In smallholder farms soil management practices are primarily driven by socio-economic, biophysical, and institutional factors (Asrat *et al.,* 2004; Nigussies *et al*., 2017). The use of biological, organic, and inorganic fertilizers to improve soil fertility have been implemented across the world but most studies show how inorganic fertilizers have drastically affected the soil fertility. A study done by Wang *et al*. (2011) showed how the addition of chemical fertilizers decreased the soil microbial biomass. Hao *et.al*. (2008) also showed that the addition of nitrogen fertilizers led a decrease in soil pH consequently reducing availability of plant nutrients with the need to lime for optimum crop yields. Management practices such as burning, or removal of residues also affect the soil fertility as residue return is known to release nutrients back to the soil improving the soil fertility status. Conventional tillage also destroys the soil aggregate stability causing runoff of water and erosion of soil with associated nutrients. While most smallholder farmers in South Africa may not be aware of the long-term negative effects of these practices to soil fertility, the high costs of inorganic fertilizers force them to use organic amendments such as cattle and goat manures, crop residues and composts. The use of inorganic and organic fertilizer may be affected by the resource endowment of the farmers, with potential effects on soil quality and productivity. Incorporation of manure will increase the soil pH, making P available for plant uptake but factors such as climate, quality of manures and ways of application affect the decomposition and mineralization of these amendments. The effectiveness of these amendments depends on quality of the amendments and biophysical factors of the farm, including climatic and soil characteristics. There is variation in biophysical factors of typical smallholder farms in South Africa with some being drier than others, with soil characteristics also being affected by local topography. Understanding the effects of farm typology on soil quality and characteristics of local organic amendments, in typical smallholder farms, is essential for management of agricultural soils for better productivity and food security.

1.3. Research questions

1. How does farmer typology affect soil C and P pools in smallholder farms of uMbumbulu and Msinga in KwaZulu-Natal Province?
2. Does the quality of different local organic inputs affect decomposition and mineralization of N and P in soils from smallholder farms of uMbumbulu and Msinga in KwaZulu-Natal province?

1.4. Specific objectives

- To investigate how different farmer typology and environmental conditions affect the soil carbon and phosphorus pools.
- To determine how the quality of organic amendments affects the decomposition and mineralization of N and P.

1.5. Hypotheses

- Farmers with different typology have different soil fertility status with C and P pools.
- Properties of organic amendment affect its decomposition rate.

CHAPTER TWO
A REVIEW OF FARMER SOIL MANAGEMENT PRACTICES AND THEIR EFFECT ON SOIL QUALITY IN SMALLHOLDER FARMS

2.1. Introduction

Soil fertility decline remains the major biophysical cause of food insecurity on smallholder farms of sub-Saharan Africa (Mugwe *et al.,* 2009). Exponential increase in population and poor soil management practices are some of the factors contributing to fertility depletion in smallholder farms (Chianu and Mairura 2012). Smallholder farming systems are characterized by significant soil fertility and crop production variations due to wide diversity of farming households and heterogeneity for both biophysical and socio-economic conditions with implications for soil management (Chikowo *et al.,* 2014). Large diversity of soils with respect to physico-chemical, biological, history and their response to inputs has been reported, particularly in sub-saharan Africa (Van Huis and Meerman 1997). Moreover, differences in farmer typology have been found to affect resource allocation in smallholder farms (Tittonell *et al.,* 2010). Within typologies, differences have been observed with field types (i.e., homefield and outfield) with more resource allocation in homefields than outfields (Tittonell *et al.*, 2005a). It is thus important to understand the influence of soil management strategies used in these farming systems to ensure sustainable production and improved rural livelihoods.

Intensive tillage is the most practiced management in many developing countries by smallholder farmers (Giller *et al.,* 2009; Grabowski and Haggblade. 2016; Lalani *et al.*, 2016) but this practice is known to disturb biological functions of soil microorganisms which leads to the loss of soil organic matter (Hobbs *et al.,* 2008; Lal 2001) as different tillage practices influence soil physical, chemical, and biological properties. In Ethiopia, intensive ploughing is mostly practiced as it is known to effectively control weeds and increase soil moisture but has been the main cause of land degradation (Bezuayehu *et al.*, 2002). Fink *et al* (2016) also stated that intensive tillage exposes adsorption sites and intensify decomposition of soil organic matter which increases the adsorption of P by ligand exchange making it less available to plants. Removal, grazing and burning of crop residues also leads to soil degradation (Lumpkin and Sayre, 2009). Smallholder farmers are known to remove residues after harvesting for livestock feed. Removal of these residues has a negative impact on soil fertility as numerous studies have shown that crop residues provide benefits including SOC sequestration and nutrient cycling (Blanco-Canqui 2013).

In recent years, models have been developed to estimate the effect of residue removal on SOC pools, and these indicate that excessive residue removal reduces SOC pools. Bioenergy production is expected to increase in the near future meaning that more crop residues will be removed from croplands leading to depletion of soil organic carbon pools. The loss of SOC pools due to residue removal depends on soil type, tillage, cropping system and climate. A decrease in SOC concentration increases soil's susceptibility to compaction and reduces aggregate stability and soil water retention (Blanco-Canqui *et al.*, 2009; Weil and Magdoff 2004). Changes in soil bulk density, aeration, soil temperature can also affect SOC storage (Ussiri and Lal 2009). Heavy application of chemical fertilizers by wealthier smallholder farmers in trying to balance the soil fertility status also has a negative impact. When erosion occurs, these fertilizers get washed out from the surface leading to eutrophication and a loss of nutrients such as P which is essential for plant growth and fertility. Many management strategies have been implemented by smallholder farmers in attempts to restore carbon and nutrients that have been lost from the soil. Soil fertility management strategies commonly implemented by smallholder farmers include the application of organic inputs such as manure, return of crop residues, crop rotation, zero or minimum tillage and less application of chemical fertilizers. Smallholder farmers use animal manure as a fertilizer to restore nutrients to the soil since it is known to contain large amounts of organic matter and nutrients. Studies have shown that the storage of manure makes a significant contribution to global methane emissions (Moller 2003). During the storage, the turnover of organic matter and nutrients may change the manure composition significantly (Eghball *et al.*, 1997) resulting in the loss of N and C to the atmosphere.

Soil organic carbon is a heterogenous pool of carbon that includes microbial biomass carbon and organic products of microbial decay and other biotic processes that occurs into the soil. Soil organic carbon is the largest carbon sink in the terrestrial biosphere as it plays a fundamental role in the fertility and productivity of terrestrial ecosystems (Lal 2016). It accumulates in soil through processes such as decomposition and transformation of litter by soil microorganisms. Restoring SOC levels is important as it mitigates climate change while improving soil quality, potentially leading to higher crop yields (Lal 2006) and it is needed for maintaining and improving soil physical, chemical, and biological properties. Agroforestry and conservation agriculture have been identified as being among the practices that can restore SOC in the soils. Increase of SOC by conservation agriculture depends on type of cropping system management and historical land use.

Observation from field experiments suggest that agricultural operations that have been managed to improve carbon and phosphorus pools also improve physical soil quality (Ogle *et al.,* 2010). Sequestration of atmospheric carbon in soil through improved management of agricultural land is considered to have potential for global carbon dioxide mitigation (Wiesmeier *et al.*, 2014) and soil can act as a global carbon sink in removal of carbon dioxide from the atmosphere (Paustian *et al.*, 2019). Zero-tillage increases SOM close to the soil surface (Alam *et al.*,2018) and labile P fraction. Studies done by Anderson-Teixeira *et al.* (2009) and Powlson *et al.* (2011) reported that removal of residues also reduce SOC pools. Mineralization of nutrients such as N, C and P during decomposition of organic amendment is essential to help improve the fertility of the soil. Organic manure is known to release carbon and P during decomposition (Zhang *et al.,* 1994). Understanding dynamics of soil management in these systems is imperative as they can affect ecosystem processes. The purpose of this review is to (i) explore soil fertility management strategies in smallholder farming systems; ii) study the evidence of the effects of farmer soil management practices on soil carbon and phosphorus pools and sequestration in smallholder farms and (iii) assess decomposition and nutrient release from organic amendments commonly used in smallholder farms.

2.2. Importance of soil organic carbon and phosphorus pools in soil fertility and CO_2 emissions

There is been high concerns of soil degradation and sustainable agriculture across the world which are often related to the loss of SOC. The SOC levels are usually high in undisturbed soils because there is little loss from vegetative or grain removal or erosion. The importance of SOC in maintaining soil chemical, physical and biological fertility is well known and its potential to reduce greenhouse gases has also been recognized (Allmaras *et al.,* 1999; Sainju *et al.,* 2002). Agricultural expansion is a major cause of soil carbon losses (D’Acunto 2014). In Europe, croplands are estimated to be the largest biosphere source of carbon lost to the atmosphere due to high decomposition occurring into the soil releasing the carbon with less carbon input. Gregorich *et al.* (1998) observed that mineralization may be the dominant mechanism of SOC loss during the initial years following the conversion of natural to agricultural ecosystems. Fujiski *et al*. (2017) in France also found that from the loss of tree cover due to deforestation, soil temperature increased, increasing mineralization rate leading to a loss of SOC. The loss of soil organic carbon can lead to degradation which may not only affect soil productivity but also environmental health (Tang *et* *al.,* 2006). Carbon and mineral-N availability is known to influence soil N_2O and CO_2 emissions. Soil CO_2 production accounts for about 25% of total global CO_2 and its emission increases with P application for soils cover. Few studies have examined the effects of P on CO_2 emission. P fertilization can reduce N_2O emission but increase CO_2 emission (Gebremichael *et al.,* 2022). This is due to that increased CO_2 emission is related to increased soil respiration due to the stimulating effect of P on aboveground and belowground biomass. On the other hand, reduced NO_2 is associated with abundant denitrifying organisms. In 2008, Burton *et al.* (2008) observed an increase in CO_2 evolution due to P addition in some phosphate-deficient soils. Adnan *et al.* (2018) also did an incubation study and examined the impact of liming and addition of P sources on soil CO_2 emission and found that CO_2 emission was higher in soils amended with organic P sources as compared to soils amended with mineral sources. Increased CO_2 emission following P fertilization maybe due to increased soil respiration as P stimulates both aboveground and belowground biomass production (Gebremichael *et al.,* 2022)

Carbon dioxide emission is known to also results from intensive tillage which cause the loss of carbon from the soil due to breakdown of aggregates exposing protected C, while increasing aeration. Intensive tillage is the most practiced management in many developing countries by smallholder farmers (Giller *et al.,* 2009; Grabowski *et al.,* 2016; Lalani *et al.,* 2016) but this practice is known to disturb biological functions of soil microorganisms which leads to the loss of soil organic matter and lower soil fertility (Hobbs *et al.,* 2008; Lal, 2001). Microorganisms play an important role in mediating the availability of P to plants as it contributes to its mobilization (Brucker *et al.,*2020). Removal, grazing and burning of crop residues leads to soil degradation (Lumpkin and Sayre, 2009). Smallholder farmers are known to remove residues after harvesting for livestock feed. The loss of SOC pools due to residue removal depends on soil type, tillage and cropping system and climate. Different tillage systems influence soil physical, chemical, and biological properties.

As most studies have shown how carbon is lost through different management practices, new strategies need to be implemented to decrease a loss of carbon from the soil to the atmosphere as it is known that when carbon escape from the soil to the atmosphere, it results in global warming causing climate change. SOC is needed for maintaining and improving soil physical, chemical, and biological properties reducing soils susceptibility to erosion, pollutants in runoff and sustaining crop production (Blanco-Canqui, 2012). Retention of crop residues may be one of the mitigation strategies to be implemented since residues are known to provide numerous ecosystem services such as SOC sequestration, nutrient cycling, wind erosion and crop production and they also contain large amount of carbon. It is because of the historic loss of SOC pool through mineralization, leaching, erosion, or shift in vegetation, estimated at 30 to 60 Mg C/ha or 50 to 70% of the antecedent pool (Lal, 2000), that most agricultural and degraded soils contain lower SOC pool than their potential determined by the specific climatic conditions and soil profile characteristics. Management practices that increase carbon input such as the use of cover crops, manure and compost application, no-till row, crop rotations and conservation tillage may be potential strategies to reduce losses of SOC. The adoption of conservation tillage increases SOC concentration by reducing soil disturbance, decreasing soil erosion, increasing infiltration, conserving soil water, and increasing soil biodiversity (Del Grosso *et al.*, 2002). Many studies have shown positive results from the use of these mitigation strategies. In Georgia, Sainju *et al.* (2002) observed that practicing no till with hairy vetch can improve SOC concentration. Franzluebbers *et al.* (2001) also observed in Georgia, that improved forage management can enhance SOC pool. Also, Drinkwater *et al.* (1998) showed the use of cover crops such as legume-based cropping systems reduce C and N losses from soil. On the contrary, Griffin and Porter (2004) found that cover crops or legume green manure had no effect on SOC concentration, but application of animal manure and compost increased total C and N pools by 25 % to 53 %. Similarly, in Michigan, Fronning *et al.* (2008) reported that rye cover crop did not increase SOC pool, but annual addition of beef manure increased SOC concentration by 25 % while annual addition of compost increased SOC concentration by 41 % in the 0 to 25-cm soil depth after 3 years. Livestock manure is known to contain about 15% carbon and compost contains similar amount of carbon but this depends on the source (Eghball, 2002).

2.3. Drivers of soil fertility in smallholder farms

Soil fertility is known as the ability of the soil to supply essential plant nutrients and water in adequate amounts and proportions to crop production. Soil is one of the important resources, especially under agricultural sectors of which its fertility status is driven by many factors. Poor soil fertility has been accepted as a major limiting production factor in developing countries, especially in smallholder farms (Sanchez *et al.*, 1997). There is a huge gap in soil fertility between commercial and subsistence farmers. Commercial farms are known to have high fertility status producing high crop yield due to the usage of fertilizers that provide nutrients to the soil whereas in subsistence farming it is known that farmers mostly use minimum organic amendments to improve soil fertility. Such practices in subsistence farms are driven by many factors such as location, typology, climate and resource endowments. In sub-Saharan Africa smallholder farming systems are driven by diverse biophysical and socio-economic environments. Rural families develop different strategies which are driven by opportunities and constraints encountered in such environments. Agroecology, markets and local cultures determine different land use patterns and agricultural management practices across the regions. Many studies have shown management practices as the primary factors that drive the fertility of smallholder farms but less information on environmental factors such as climate, soil type, field type and location. Many countries have adapted to the use of organic amendments for nutrient release, restoring the fertility of the soil. Decomposition and nutrient release from these amendments are determined by climatic, edaphic, quantity and resource quality factors (Swift *et al.*, 1967).

2.3.1. Climate

Climate is one of the environmental factors that has a huge impact on the change of soil fertility over the years in agricultural practices. Observational evidence indicates that climate change in the twentieth century has already affected a diverse set of physical and biological systems particularly in the agriculture sector (McCarthy 2001; Ben Mohamed *et al.*, 2002; Jalloh *et al.*, 2013; Karfakis *et al.*, 2011). Durán Zuazo and Rodríguez Pleguezuelo (2008), stated that reduced precipitation or increased temperature accelerates land degradation through the loss of plant cover, biomass turnover, nutrient cycling and soil organic carbon storage which results in greenhouse emissions. Changes in temperature and precipitation do not only accelerate land degradation but also cause a decline in soil organic carbon stocks which reduce agricultural productivity. There is evidence that dry soils under warmer temperatures also increase SOC losses via higher rates of wind erosion (Lee *et al.,* 1996). Negative changes due to climate change have the potential to threaten soil fertility, agricultural productivity, and food security (Nikolskii *et al.,* 2010). Areas with higher temperatures due to climate change tend to increase decomposition and mineralization of the organic matter in the soil, reducing organic carbon content, and hence lead to a soil fertility decrease (Lal, 2010).

Emerging evidence suggests that warmer temperatures have the potential to significantly affect nutrient status by altering plant phenology (Nord and Lynch, 2009). The developmental stages of crops are extremely sensitive to climate conditions and are particularly responsive to temperature (Cleland *et al.,* 2007). A study by Mitchell *et al.* (1993) indicated how experimental warming of temperature shortened phenological stages of wheat, that resulted in a 9% yield decrease per 1°C increase in temperature. Soil temperature also influences root characteristics which affect plant nutrient acquisition efficiency (Bassirirad, 2000). Soil temperature affects the function of soil microbial communities influencing the decomposition of organic materials and nutrient release, through increased mineralization with increase in soil temperature. Smallholder farmers from undeveloped countries are failing to adjust to climate change, leading to poorer crop production, which results in food insecurity. When these areas start to receive less precipitation, crops get stressed and do not reach maturity. Microbial organisms and enzyme activities are also affected decreasing the fertility of the soil as some microbes need water to function. Drought disrupts root-microbe associations, which play a huge role in decomposing incorporated organic material which improve soil fertility in smallholder farmers. Drought also changes the composition and activity of soil microbial communities that have an impact on soil fertility and nutrient cycling (Schimel *et al.,* 2007). Soil fertility is also affected by excessive precipitation which reduces crop yields (Paul and Rasid 1993; Kawano *et al.*, 2009). Intense rainfall events can be a major cause of erosion in sloped cropping areas and where soil instability results from farming practices that degrade soil structure (Meadows, 2003). Surface erosion during intense precipitation is a conspicuous source of soil nutrient loss in developing countries (Tang *et al.,* 2008; Zougmore *et al.,* 2009). Because of its high mobility in soil, nitrate leaching after intense rainfall can also be a significant source of N loss in agriculture (Sun *et al.*, 2008).

2.3.2. Soil type

There is large heterogeneity of soils in landscapes, and this variation determines the response of the soils to management, including organic inputs. According to AGRA (2009) many parts of sub-Saharan Africa have high diversity of soils with respect to their chemical, physical, biological properties, history and their response to inputs. Soils which are more than 85% sand tend to be excessively drained, low in soil organic C, and very low in nutrient content (Landon, 1991). It has been indicated that sandy soils in the tropical regions such as South America, South Africa, Sahel and Arabia are characterized by low SOC, cation exchange capacity (CEC) and high risk of nutrient leaching. Blanchart *et al.* (2005) and Manlay *et al.* (2002) showed how tropical sandy soils tend to have a low potential of C storage and that they are hypothesized to be less effective in mitigation of greenhouse gases emissions. In Thailand, low yields of rice have been a problem due to sandy soil with low organic C content and high salinity. A decay of SOM through rainfall pattern and soil texture results in a poor nutrient availability and unstable structure of the soil (Pieri, 1992). A study done by Reeve *et al.* (2010) showed that fine-textured soils had significantly greater total N and C, P and other micronutrients than coarse-textured soils. This is due to that coarse textured sand soils are difficult to manage as they easily lose nutrients through leaching and are highly susceptible to erosion (Burt *et al.,* 2001). Soils which are highly weathered are known to be acidic which limit organic matter decomposition resulting in more carbon present. Weathered soils are generally more P-limited due to fixation that occurs than other soils with limited nutrients (Wardle *et al.,* 2004).

2.3.3. Farmer typology and field type

Smallholder farms consist of multiple plots with homefields receiving more organic inputs compared to plots at different distances from homesteads (Elias *et al.,* 1998; Shepherd and Soule 1998). In many farming systems in the tropics, strong gradients of decreasing soil fertility are thus found with increasing distance from the homestead (Ruthenberg, 1980; Prudencio, 1993). Studies done in Africa indicated that farmers invest more resources in the relatively fertile fields near homesteads which create zones of soil fertility within farms and does not result in efficient allocation of farm resources (Samake´*et al.,* 2005; Zingore *et al.,* 2007; Tittonell *et al.,* 2007). Tittonell *et al*. (2013) did a study on six sites between midland and highland areas investigating how different fields differ in fertility with management. The results indicated that fields closer to the homestead had more variability in soil organic carbon, available P and exchangeable K than fields far from homestead < 50m. This led to significant differences in soil fertility between sites and field types. Landscape also controls how farmers managed different fields. Not only does organic material input differ within fields but also tillage and weed management differs resulting in variability of soil fertility. Tillage is known to be effective in producing high yield, but poor farmers do not afford labor costs resulting in low yield. Weed management is important in crop production as the weeds compete with crops for nutrients and moisture, which reduces affecting fertility of the soil and crop productivity. Conventional ploughing systems have been invented to control weeds (Crittenden *et al.,* 2015) but only wealthy farmers can hire labor necessary to improve management resulting in more fertility soils (Zingore *et al.,* 2009).

Resource endowment also plays a huge role in how smallholder farmers manage different fields which leads to variation in soil fertility status and crop productivity. When nutrient resources are scarce, farmers tend to apply such resources in the fields around their homestead, where crops are better protected from marauding livestock (Crowley and Carter, 2000). This results in field types having different fertility status. Soils from homesteads with limited or no resource endowments differ from soils from homesteads with endowments. Resource limitation cause creation of spatial soil variability as gradients of soil fertility decline with distance from the homesteads (Giller *et al.,* 2011). A study that was done in Kenya showed how the differences in resource endowments between different farmers resulted in soil C and nutrient stocks differences (Tittonell *et al.,* 2010). Soil spatial variability liwas observed within farms of poor soils and less livestock ownership.

2.4. Effect of farmers management practices on carbon and phosphorus pools and soil properties of smallholder farms

Many studies have shown that management practices in smallholder farms across the world are affected by resource endowment. Resource limitation forces farmers to allocate the available labor and nutrient resources to certain fields which contribute to creation of spatial soil variability (Tittonell *et al.,* 2005b). Such limitation leads to the status and variability of soil fertility of smallholder farms to vary between households, as some households are cattle owners having easy access to manure. Continuous cropping with few nutrient inputs and crop removal from the fields has led to a general poor fertility status of the soils due to the availability of resources at household that also plays a huge role on farm management practices (Shepherd *et al.,* 1998).

2.4.1. Cropping systems

Crop rotation and intercropping plays an important role in smallholder farm soils as crop rotation is known to regulate the dynamics of carbon cycling and the storage of soil carbon affecting soil biotic activity and the amounts of residues returned to the soil (Gregorich *et al.*,2001). Studies have shown that rotation increases carbon and nitrogen after decades of cropping compared with monoculture. Legumes rotation with non-leguminous crops can maintain higher organic matter levels than continuous cropping systems (Campbell *et al.,* 1991). Different management practices also control the quantities of residues used for carbon inputs to the soil. A study conducted in India by Ghosh *et al.* (2017) showed how intercropping chickpea, rice, wheat and maize increased carbon fractions. It was found that inclusion of chickpea in cereal-cereal rotation increased total organic carbon content due to higher belowground biomass of legumes. Ganeshamurthy (2009) also reported that pulse inclusive rotation maintained higher soil organic carbon due to addition of more belowground biomass in the form of roots.

Crop diversification is considered as one of the most ecologically feasible and cost-effective way of reducing uncertainties such as low crop production, insecurity mostly in smallholder farmers (Joshi 2005). The crop diversification strategy is to maximize the use of land, water and other resources while controlling pests and disease, improving soil fertility and bringing about nutrition diversity and health (Lin 2011). Crop diversification includes polycultures, agroforestry systems and crop rotation systems (Lin 2011), with farmers practicing crop diversity to produce more crop for food security. It is also known to have a positive impact to climate change effects through the ability of local flora to hold carbon thus generating less carbon dioxide (Makate *et al.,* 2016). Different crops are known to have a diverse productive potential and adsorption of P from the soil Rotation of different cover crops to access P from the soil can increase soil P availability changing the P cycle in the long-term (Soltangheisi *et al.,* 2018; Damon *et al*.,2014**).** Findings by Malhi *et al.* (1992) indicated that there were no differences in P availability influenced by crop rotations or tillage system which was in contradiction with Soltangheisi *et al.* (2018) who found differences in P availability.

2.4.2. Residue management

There are different cropping systems that are practiced by smallholder farmers in producing high crop yield for food security. Removal, burning and incorporating of residues are some of the systems. Burning of crop residues has become a common practice but it leads to the loss of plant nutrients and creates health and environmental problems (Graham *et al.,* 1986; Prasad and Power 1991). Incorporation of crop residues is known to increase nutrient contents of soils thus increasing crop yields. It helps maintain soil carbon stocks (Minasny *et al.,* 2017), but this can be toxic due to organic acids produced during decomposition in cooler regions. A study by Prasad *et al.* (1999) showed how plots with incorporation of residues after harvest increased organic carbon and available P content compared with residue burning and residues removal plots. Incorporation of wheat residues has been shown to gradually improve soil fertility as it is an eco-friendly practice. A study by Mtambanengwe and Mapfumo (2006) showed how incorporation of different quality organic materials significantly increased topsoil organic carbon content of a sandy soil. Crop straws contain nutrients such as nitrogen and organic carbon, thus removing or burning these residues can result in a decline in soil quality (Lu *et al.,* 2010a). However, most farmers tend to allow free grazing by livestock after harvesting which can lead to a reduction in soil quality (Li *et al.,* 2018a; Wang *et al.*, 2020). Several studies have shown that free grazing changes the cycle of soil nutrients indirectly. Wu *et al.* (2010) showed that long-term fencing increased SOC and soil total nitrogen storage compared with grazing meadows. Incorporation of organic residues is known to decrease surface temperature and increase P availability as they decrease P sorption through blockage of exposed hydroxyl groups on the surface of Fe and Al oxides making it more available for plant uptake.

This is also supported by a study that was done in Rwanda by Iyamuremye *et al.* (1996) that showed how the application of manure and alfalfa resulted in significant increases of available P, mineralizable Po and other inorganic P fractions. Another study by Kretzschmar *et al.* (1991) showed that residue treatments affected P concentration in the soil solution with the residue retained treatment having a P concentration three times higher compared to those of removed residues. Residues input positively improves soil P availability due to increasing phosphatase enzyme activities (Kumar and Goh 1999). The quality of organic residues applied also affects different P fractions and the residues of high N, low lignin and low polyphenols increasing labile fractions as they are easily mineralized and residues of low N, high lignin and high polyphenols increases exchangeable P and mineralizable organic P fractions as these are resistant to mineralization (Sukitprapanon *et al.,* 2021). When residues are removed or burned, P fractions behave differently. Kolawole *et al.* (2003) conducted a study in Nigeria on effects of residue management on P fractions and found that total P was higher where the residues were incorporated than burnt. In contrast, Kang *et al.* (1997) reported an 87% increase in P due to burning of plant residues.

2.4.3. Tillage

Soil tillage breaks down aggregates exposing soil organic matter to microbial attack consequently modifying soil chemical, biological and physical properties. Soil disturbance through tillage is a major cause of reduction in the number and stability of soil aggregates and subsequently soil organic matter depletion (Six *et al.,* 2002). Type and length of tillage and soil texture influences the amount of soil organic carbon present in the soil and its distribution among size fraction (Six *et al.,* 2002). Conventional tillage has been the most adopted tillage by smallholder farmers across Africa resulting to soil disturbance and low crop yields. Reduced tillage can reduce land degradation thus leading to sustainable agriculture (Chen *et al.,* 1998, Steiner, 1998, Biamah and Rockstrom, 2000, Rockstrom *et al.,* 2001). Many studies have shown that production systems that minimize soil disturbance such as reduced tillage increase soil organic carbon and microbial biomass compared to conventional tillage in various soil types and climatic regions (Paustian *et al.,* 2000; Jacobs *et al.,* 2010). Want *et al.* (2011) reported that, where chemical fertilizer was added, soil organic carbon was higher under no-tillage than when the soil was tilled. No-tillage with organic management enhanced soil microbial biomass and activities, whereas conventional tillage with chemical fertilizer inputs had deleterious impact on soil microorganisms and reduced soil organic carbon. The status and distribution of P in soil depends on land use and management practices (Maharjan *et al.,* 2018). Little effort has been made in identifying forms of P that are affected by tillage as reduced tillage systems change the concentration and distribution of P in the surface (Selles *et al.,* 1997). Conservation tillage has been shown to increase extractable P due to the accumulation of residues at the surface compared with conventional tillage (Carter and Steed 1992; Mathers *et al.,* 2007). Most studies have shown that under zero-tillage, soils exhibit a strong stratification of P and other immobile nutrients, and this practice increases the labile P fraction concomitantly with the increase in SOC (Robbins and Voss 1991; Muukkonen *et al.,* 2007).

Previous studies have showed that conservation tillage increased total P in the topsoil by 15% compared to conventional tillage in an Oxisol (Selles *et al.*, 1997).

2.4.4. Organic amendments

Many studies have shown the importance of restoring soil organic carbon as it affects the soil fertility and productivity, physical, chemical, and biological properties. Since soil is known to be the potential carbon sink and can offset rising atmospheric carbon dioxide, its capacity to store and sequester carbon mainly depend on the rate of carbon inputs from the plant productivity relative to carbon exports which are controlled by microbial decomposition. Manure amendment is a management practice that has been shown to improve the nutrient status of the soil and increase SOC levels (Rochette and Gregorich 1998). Many long-term fertilizer experiments worldwide have shown that balanced fertilization with application of organic manure can improve the nutrient status of the soil and maintain high crop yield with high levels of residues turnover to the soil that increase the SOC concentration (Holeplass *et al.*, 2004). SOC has profound effect on soil quality as it increases water retention, nutrient supply and soil organism's activity and improves soil fertility and productivity (Karlen *et al.*, 1997). Several long-term field experiments have been conducted to determine the effect of mineral fertilizer and manure application on the SOC pool and on carbon sequestration (Yang *et al.*, 2003). an experiment that was done by Yong-Zhong *et al.* (2006) in China using soils from wheat-maize planted field under different environmental conditions showed how the treatments that were treated with both farmyard manure and NPK fertilizer increased soil organic carbon accumulation and nutrient status with time. These results indicated that the accumulation of SOC into the soil was highly influenced by the organic inputs rather not environmental conditions since in China the annual precipitation was 120mm using a silt loam soil and in India the annual precipitation was 650mm using a sandy clay loam soil. Long-term application of inorganic fertilizer in both experiments showed no significant effect on SOC accumulation. Another study done by Majumder *et al.* (2006) of long-term effect on manure application in west Bunjal, India showed that continuous cropping without the use of NPK fertilizers and organic material for 19 years caused a net decrease in total soil carbon content (13.3%) compared with that under fallow, whereas cropping with organic amendment and NPK fertilizer increased the total soil carbon content by 26.7%. This might be due to that the carbon that was applied through organic inputs was more stable thus more resistant to decomposition. Organic manure is known to have higher C/N ratio and lignin content (Villegas-Pangga *et al.*, 2000). Aoyama *et al.* (1999) also observed an increase in soil organic matter with addition of manure and consequently the formation of slaking-resistant macroaggregates resulting in high accumulation of SOC which improved the soil fertility. Organic matter is an important source of soil phosphorus which enhances microbial biomass and activities which can lead to higher P turnover in the soil (Ehlers *et al.,* 2010; Krey *et al.,* 2013). Many studies have shown that the application of organic amendments to soil may increase P solubility and replenish soil P pools (Sanyal and De Datta 1991, Gopinath *et al.,* 2008). Use of manure from different animal species in many studies showed that organic P can amount to 80% of total P (Pagliari and Laboski 2012). A study by Mohammadi *et al*. (2009) showed that there was a significant increase in extractable P when dairy manure was applied. Also, Muktamar *et al.* (2020) did a study in Indonesia in determining P availability during organic amendment application. He found that the amendments (Vermicompost, chicken manure and cattle manure) increased P availability in Ultisols until the end of incubation. Another study by Amanullan (2007) showed that the P content of poultry manure increased steadily from 15 to 75 days of the incubation. The drawback of application of organic amendments is its low release of plant nutrients such as phosphorus (Muktamar *et al.,* 2020).

2.4.5. Nutrient management

Farmers use fertilizers and organic material to provide nutrients for crop growth as soils tend to lose nutrients with years of cultivation through processes such as erosion, deep tillage and removal of crop residues. Many studies have reported that fractions of soil organic carbon respond differently to land use and management. Malhi *et al.* (2011) showed the retention of straw to increase in total organic carbon, nitrogen and light fraction organic carbon compared to removal of straw. Also, Sainju *et al*. (2007) showed that soil carbon fractions were lower in spring-tilled treatments than under no-till.

Organic amendments are known to return carbon into the soil and get stabilized as SOC and are distributed into different pools. This process is governed by factors such as climate, cropping system and substrate composition (Benbi *et al.,* 2012). Different management practices affect different carbon fractions and can provide knowledge about the mechanisms of carbon sequestration (Six *et al.,* 2002). In addition to returning organic carbon, organic amendments are known to increase phosphorus availability and enhance P-use efficiency in P-fixing soils

(Lyamuremye and Dick 1996). Retention of organic inputs into the soil generally cannot provide sufficient phosphorus for crop growth but it is important in P cycling as some organic P is known to originate from crop residues (Lupwayi *et al.,* 2007). Distribution of soil inorganic and organic P pools are not only affected by the quality and quantity of organic material retained into the soil but also climate and soil chemical characteristics play a role. A study by Motavalli and Miles (1998) showed that the application of fertilization either in the form of fertilizers or manure significantly increased resin P. This might be due to that the applied P fertilizer either as superphosphate or crude-grade acid phosphate added more inorganic P into the soil leading to more available P and manure is known to increase soil organic P (Zhang *et al.,* 1994). Six years of continuous application of organic wastes to the soil surface of Mollisol in Awes, United States increased the total P concentration due to the HCI-P which was transformed to more labile forms through the application of biosolids (Sui *et al.,* 1999). Also, Motavalli and Miles (2002) observed that application of manure resulted in both labile and resistant pools of organic P. Maguire *et al.* (2000) showed how availability of P supplied with sewage sludge was lower than that of fertilizer or manure. This might be due to the precipitation of phosphates caused by the addition of $Al_2(SO_4)_3$ or $FeCl_3$ to the wastewater. Several studies have shown how Po (bound P) plays a key role in P cycling and plant nutrition (Sharpley 1985). Increased microbial activity and resultant biochemical transformations in soil, due to added organic manures may cause mineralization of more recalcitrant P fraction (Nziguheba *et al.,* 1998). Hence plants grown with organic manures accumulate more P than without organic amendments (Mujeeb *et al.,* 2008). Soils from farmers with limitations to the application of fertilizers and organic inputs have poorer performance as crops cannot access carbon and phosphorus pools that are protected within the soil aggregates affecting the fertility of the soil.

Organic amendment has also affected crop yield and quality (Gopinath *et al.,* 2008). A study done in India by Gopinath *et al.* (2008) on wheat grains showed that the use of farmyard manure was better, followed by vermicompost, in terms of growth, yield and quality of wheat during transition to organic production. Wheat grain yields increased in both years in response to increasing application rates of organic amendments. This meant that the quality of farmyard manure was higher than the other amendments as it produced higher yield. Wei *et al.* (2016) in china showed that the organic plus fertilizer treatment significantly increased the wheat, maize and rice yield relative to sole organics and fertilizer only. Some studies have indicated that SOC content does not increase much even after a large amount of organic materials are incorporated into the soil (Gulde *et al.,* 2008; Stewart *et al.*, 2009), and this might be due to the quality of organic material applied. It is of importance to also quantify the quality of the organic amendments used by farmers as these influence decomposability and subsequent release of nutrients for crop uptake.

When stored correctly or for a long period, cattle manure may lose some carbon through carbon emission decreasing its ability to retain more carbon in the soil (Brown *et al.,* 2002). The use of these organic amendment does not only play a role in carbon restoration but also in nutrient release improving soil fertility which depend on how easily the amendment is decomposed by microbes in the soil. The potential benefit of amendment such green manures as a source of nutrients to crops can only be achieved if their decomposition and nutrient release patterns are known so that the synchrony of nutrient release with crop nutrient demand can be improved (Myers *et al.,* 1994). Several methods have been used to determine decomposition and nutrient release of the amendments in the field, and the litterbag technique is probably the most widely used because of its simplicity, replicability, and ability to selectively exclude classes of soil fauna (Vanlauwe *et al.,* 1997). Nutrient addition through these amendments can accumulate 18 to 62% more soil organic carbon than under NPK addition chemical fertilizer (Gami *et al.,* 2001). Plant residues with high nitrogen content show high decomposition and nutrient release (Swift *et al.*, 1979). Soil fauna facilitates the biological turnover and nutrient release of plant residues by fragmenting the plant residues which results in an enhanced microorganism activity (Anderson *et al.*, 1983a).

2.5. Decomposition and nutrient release from organic amendments in smallholder farms

The use of organic amendments does not only play a role in carbon restoration but also in nutrient release improving soil fertility which depends on how easily the amendment is decomposed by microbes in the soil. The potential benefit of organic amendment as a source of nutrients to crops can only be achieved if their decomposition and nutrient release patterns are known so that the synchrony of nutrient release with crop nutrient demand can be improved (Myers *et al.,* 1994). The decomposition of these amendments affects plant growth positively and negatively hence it is important to determine the quality before application. Plant residues are also known to return nutrients when left onto the surface after harvesting. Different vegetation types when returned into the soil as residues have an impact on decomposition and carbon storage due to their differences in litter quality (Liao *et al.,* 2008; Castro *et al.,* 2010). Previous studies on organic matter management have focused mostly on high quality organic amendments from agroforestry tree species, legume green manures and composted cattle manure (Mugwira and Murwira 1997; Mafongoya *et al.,* 1998; Chikowo *et al.,* 2004). These high-quality organic amendments, based on their high nitrogen concentration relative to lignin and polyphenols, can decompose and supply nutrients to growing crops within short time periods (Palm *et al.,* 1997). Low quality organic resources are also good precursors to SOM build-up because of their low turnover rates (Palm *et al.,* 1997), which contribute significantly to the spatial and temporal distribution of SOM in arable lands. Organic amendments when incorporated into the soil tend to recycle nutrients and organic matter to support crop productivity and maintain fertility (Whalen *et al.,* 2001). Many factors are believed to drive this process. Heterotrophic microorganisms are responsible for the decomposition of organic matter which facilitate organic carbon into the soil

2.5.1. Manure

Many farmers have used manure as a source of fertilizers to add nutrients to the soil. The decomposability and composition of manures plays a huge impact on the release of nutrients back to the soil. Fatondji *et al.* (2009) did a study on millet straw and cattle manure to observe decomposition and nutrient release of these organic amendments when incorporated into the soil and left onto the surface through litterbag setup for three months. The results showed that the decomposition of manure when incorporated into the soil at a rate of 1 t/ha and at a 5 t/ha application rate were not statistically significant. Nutrient released from cattle manure was faster than from millet straw with only 3% of the N released from millet straw and 4% of that released from manure and absorbed by the millet plants on average after day 31 of exposure. The lower initial decomposition rate of the millet straw may be due to its lower nutrient content as well as to a preference of the termites for manure compared to millet straw (Fatondji *et al.,* 2009). The millet straw when applied at a lower rate released more rapidly potassium compared to the higher rate whereas the manure applied at a higher rate released potassium more rapidly than the lower rate. Ajwa and Tabatabai (1994) also conducted a field study on the decomposition and release of carbon dioxide from animal manures such as those from chicken, pig and horse. The results showed that pig manure released 5.67 to 6.05 g/kg of CO_2 higher than all the manures. This might be due to that the decomposition rates depends largely on the type of ration fed to these animals. Horse and pig manure released lower CO_2 which might be due to that pig manure was low in fibrous materials and high in N content and horse manure had the smallest fraction of easily decomposable organic C. Odedina *et al.* (2011) also conducted a study in Nigeria that determined how different composition of pig, cattle, goat, and poultry manure affected the growth and yield of cassava. Poultry manure had the highest amount of Na, K, Ca and N of 0.28, 0.68, 1.92 and 1.38 % respectively leading to highest value of tuber girth.

2.5.2. Crop residues

Decomposition of residues is very important as they supply essential nutrients upon mineralization and improve soil biophysical conditions (Nyborg *et al.,* 1995). The decomposition of residues is controlled by environmental factors such as microbial activity, soil chemical and physical characteristics (Zaccheo *et al.,* 2002). Residue composition also affect its decomposability. For example, residues with leaves mixture are known to have higher rates of C and N mineralization and decompose faster than stem residues due to their more readily decomposable tissue composition (Quemada and Cabrera 1995; Bertrand *et al.,* 2006). Residues left on the soil surface under zero tillage had less lignin content and more N which resulted to a slow decomposition compared to the residues under conventional tillage (Lupwayi *et al.,* 2003). This is due to that the residues on the surface are not greatly exposed to microbial breakdown compared to those incorporated in the soil under conventional tillage (Lupwayi *et al.,* 2003). Tillage also affects residue decomposition through changes in soil temperature, aeration, soil microbial biomass carbon and microbial community abundance (Chen *et al.,* 2009; Miura *et al.,* 2015; Singh *et al.,* 2020). Soil microbial biomass has been recognized as the main driving force for mineralization of nutrients in crop residues (Abaye and Brookes, 2006). Some researchers have found that residues with high lignin content decompose more slowly than those with low lignin content as high lignin content of residues can also enhance nutrient immobilization especially for N (Melillo *et al.,* 1982). Palm and Sanchez (1990) stated that polyphenol concentration can influence the decomposition for a greater extent than lignin or nitrogen content of the residue. Polyphenols are known to reduce the decomposition by inhibiting enzyme actions. It is also known that residues of low C: N and C: P ratios, sufficient N: P ratio, and low lignin contents decompose faster and release more P during decomposition (Silver and Miya, 2001).

2.5.3. Compost

Composts are known to slowly decompose in soil and the continuous release of nutrients can sustain the microbial biomass population for longer periods of time compared with mineral fertilizers and its capability to release N in soils which depends on the amount and availability of carbon and nitrogen in the compost (Murphy *et al.*, 2007). Poor-quality or immature compost may tie up nitrogen in the soil and decrease the availability of nitrogen to the growing crop leading to low crop yield. The addition of compost improves the physical properties of soil and enhances nutrient availability and microbial activity, therefore enhancing the ability of soil to sustain plant growth (Diacono and Montemurro, 2010). A study done by Muhammad *et al.* (2007) investing how compost and superphosphate fertilizer affect plant growth and salinity of the soil showed that with the incorporation of the compost, the microbial biomass C-to-P was increased by the compost amendment only. This showed that compost does increase plant growth by nutrient release during decomposition. Mineralization rates from compost applications are relatively low, and compost is usually a poor short-term source of nitrogen. Recent studies have shown that typically no more than 15% of the nitrogen in the compost is made available to the plants.

2.5.4. Carbon dioxide emission and mineralization of N and P during decomposition of organic amendments

Soil microbial biomass has been recognized as the driving force for mineralization of residues in soil (Abaye and Brookes, 2006). Carbon and nitrogen mineralization are the main processes that regulate the availability of nutrients for plants. The rate of mineralization can be used to quantify the impact of different organic and inorganic materials on soil functions. From the organic amendments that have been used across the world, animal manure has been an important source of nitrogen and other nutrients but application of these organic manure in soil can increase CO_2 emissions. During decomposition of organic material, phosphorus also gets mineralized and its net mineralization in plant residues or manure depends on the total organic P content of the material. Mineralization of organic P is mediated by soil microorganisms and the rate and pattern in which it occurs is regulated by environmental conditions and residue quality. Changes in both soil moisture and temperature influence microbial activity and thereby affect P mineralization (Kabba and Aulakh, 2004).

The rate of soil carbon emissions during decomposition is strongly influenced by the amount and properties of added organic materials, soil processes and environmental conditions (i.e., temperature and water availability) (Agehara and Warncke, 2005). Several studies have shown that factors such as soil texture, temperature, moisture, pH, available C (labile and non-labile components of soil organic matter), and N content of the soil influence CO_2 emission from the soil. It was stated that higher labile carbon containing organic materials enhances CO_2 emission which results in less carbon accumulation in soil (Sylvia *et al.*, 2005). Results from an experiment done by Rahman (2013) show the above statement to be true. The objective of the study was to determine the rates of carbon dioxide emission from different organic materials. The poultry manure released high amount of carbon dioxide due to its high amount of nitrogen (2.09%) and high labile carbon content. Higher percentage of cellulose, hemicellulose and lignin in rice straw and roots slowed down its microbial degradation which resulted in less carbon dioxide emission.

CO_2 emissions is also highly influenced by management practices and storage of the organic material used. However, proper management of organic manures and wastes, conservation tillage, micro aggregation, and mulching can play an important role in reducing CO_2 emission, and thus increase C sequestration in soil (Russell *et al.*, 2005). CO_2 which is lost during manure storage is due to degradation by aerobic or methanogenic bacteria (Henrik *et al.*, 2014). Moreover, more CO_2 emission can occur from a tilled than from an undisturbed soil (no tillage) as tillage produces a soil microenvironment favorable for accelerated microbial decomposition of plant and animal residues (Rochette and Angers, 1999). Tillage breaks down soil aggregates, helps in mixing soil and organic particles, improves infiltration and water-holding capacity, and thereby increases CO_2 production, while reduced tillage tend to reduce emission of CO_2 due to less ploughing of soil which keeps the soil organic C unexposed.

2.6. Conclusion

Application of organic amendments in smallholder farms shows positive input for carbon storage and nutrient addition. The quality of these amendments, environmental factors and the way of application facilitate the decomposition rate and mineralization of N and P. For good soil fertility there is a need to understand quality of locally available organic amendments for remediating infertile soils. Different management practices affect nutrient return from residues input differently with no-tillage showing more SOC. Little effort has been done to show how tillage affect P pools.

Resource limitation causes imbalance and variability in soil fertility within fields and decomposition of these resources is driven by factors such as lignin content, C:N ratio and soil properties. More studies need to be done in analyzing how the addition of these different organic amendments affects soil physical, chemical and biological properties. There is a need to understand the effect of tillage and crop diversification on P pools, as most studies show contradiction on P availability due to tillage. Further research should focus on how soil fertility is affected within typologies in South African soils by management and quality of available resources and its contribution to mineralization of nutrients.

CHAPTER THREE

CARBON AND PHOSPHORUS FRACTIONS IN SMALLHOLDER FARMS OF UMBUMBULU AND MSINGA AS AFFECTED BY FARMER TYPOLOGY

3.1. Introduction

Smallholder farming constitutes 75% of agricultural land worldwide (Lowder *et al.,* 2016), but in Africa smallholder farmers are unable to secure sufficient and suitable land to grow crops and keep livestock (Langyintuo 2020). Smallholder farmers in Africa are faced with many challenges hindering production of high crop yield to fight food insecurity. High cost of fertilizer, less access to organic amendments, labor, institutional and socio-economic constraints have led to a negative impact on the yield, soil quality and fertility (Senyolo *et al.,* 2018). Improved land management practices are key to enhancing agricultural productivity and reduce poverty in smallholder farmers. Farming systems in smallholder settings are largely shaped by constant interaction with the local social and biophysical context (Pacini *et al.,* 2014). According to Mortmore and Adams (1999), this results in farming system diversity in space (i.e., based on resource endowment); variability through time and multidimensionality in terms of strategy (production and consumption decisions). Studies have thus categorized smallholder farmers into homogenous groups commonly referred to as typologies. Understanding the implication of this heterogeneity on soil carbon and phosphorus pools is necessary to ensure sustainable management for crop production and food security.

Most studies have shown how different management practices by farmers have led to nutrient loss from the soil but less experiments show how carbon and phosphorus pools are affected (Blair *et al.,*1995; Chantigny 2002; Sarker *et al.,* 2018; Verma *et al.,* 2010). Soil organic carbon is made up of different fractions including labile ones which are essential for nutrient cycling and the stable and recalcitrant pool, which plays a role in the fertility status of the soil. Agriculturally induced carbon dioxide release from the labile pools in soils may significantly reduce SOC stocks and increased C levels in the atmosphere (Farage *et al.,* 2007). Depletion of the SOC pools, degrades soil quality, reduces biomass productivity and impacts water quality (Jandl *et al.,* 2007). This has been widely observed in cultivated soils (Paustian *et al.,* 1997; Lal, 2004; Smith, 2004). Climate variability and change affect agricultural production levels and disrupt the livelihoods of many farmers (Schmidhuber and Tubiello, 2007). Change in climate will thus aggravate the poverty and food insecurity of smallholder farmers (Vermeulen *et al.*, 2012).

Agricultural management such as residue retention and organic input has been the most used management practices in smallholder farms to obtain high yield, but a few studies have shown how such practices affect soil fertility, the level of carbon pools present in soil and carbon sequestration process. Overuse or misuse of fertilizer may result in nutrient leaching and soil structural degradation causing a disorder in the distribution of soils microbial community thus affecting plant growth (Manna *et al.*, 2007). Farmers have mostly adopted the use of manure, compost and other organic fertilizers which have shown increase in carbon level and high yield for food security. A study that was done in sub humid areas of India by Mandal *et al.* (2007) showed that the input of manure in different cropping systems increased soil organic carbon. A similar study done by Majumder *et al.* (2008) showed that cropping with the use of nitrogen, phosphorus and potassium fertilizer and organic amendment increased total carbon content. This is because the carbon present in the manure is stabilized causing it to be more resistant to decomposition. Organic manures are known to be rich in nutrients and when applied into the soil as they improve soil structure and fertility. Application of manure increase SOC storage, improving the physical and biological properties of the soil but its decomposition rate is facilitated by the climate, soil texture, manure characteristics and how it is applied.

More long-term studies how different management practices affect soil carbon pools and carbon sequestration need to be conducted in Africa and across the world. Numerous studies about carbon pools have been done in tropical and subtropical regions as it is known that soils in such areas are associated with low organic carbon worldwide. There is little evidence regarding the feasibility of carbon sequestration and effects of management practices on carbon and phosphorus pools of smallholder farms in developing countries, especially in South Africa. Typical smallholder farms of South Africa vary in terms of climatic conditions and soil types, and soil management practices could be affected by farmer typologies with potential effects on dynamics of SOC and soil phosphorus. Understanding how different management practices affect soil organic carbon is of relevance to understand whether carbon is sequestered or lost as carbon dioxide emissions and if P is available for plant uptake in typical smallholder farms of South Africa. The KwaZulu-Natal Province of South Africa has variable soils and climate with some areas being wet while some are dry, leading to different agricultural practices within smallholder farms (Camp, 1999). Therefore, the objective of this study was to determine the effect of farmer typology, farm cropping system on organic carbon and phosphorus pools on typical smallholder farms in Msinga and uMbumbulu.

3.2. Methods and Material

3.2.1. Study sites

Two sites namely uMbumbulu (29º 29' 30" Latitude; 30º 51' 12" Longitude) and Msinga (28º 37' 05" Latitude; 30º 27' 36" Longitude), with different biophysical and socio-economic factors, were chosen for study purposes. uMbumbulu is a coastal area with poorly drained soils receiving an annual rainfall of 956 mm with temperatures ranging from 18.2 to 25.2°C (Camp, 1999). Msinga is a predominantly dry area dominated by high erosion hazard and shallow soils which receives rainfall of 598 to 740 mm annually and temperatures of 22°C up to 35°C (Institute of Natural Resources, 2007).

3.2.2. Soil characterization and fertility within farmer typology

Soil samples used in this study were collected from farms in these two sites (uMbumbulu and Msinga), including three farmer typologies, identified in terms of resource endowments present (resource endowed, minimum resource and resource constrained). Farmer typology was classified based on land size, livestock ownership and income from the farm as defined by Tittonell *et al.* (2010). Three farms were selected per typology and soil samples from farms with similar soil types were collected in triplicate from the 0-20 cm depth from homefields and outfields, for Msinga. Consideration was made that farmers manage different fields differently leading to different carbon and other nutrients present into the soil (Msinga). The identified fields for Msinga area were defined according to distance from household into homefields, which were closest to home <50m to 100m and outfields, which were furthest from home with at least 100 m from the homestead (Tittonell *et al.*, 2005; Zingore *et al.*, 2007). At uMbumbulu the different farmer typologies did not have distinct outfield but there were differences in cropping systems, including monocropping (maize, sweet potatoes and taro) and mixed cropping (cabbage, beans and spinach). The soil samples were air-dried for five days and homogenised before sieving at 2 mm sieve. Thereafter, the samples were characterised for pH, particle size, Ca, Mg, K, Mg Mn, P, Zn, total cations, acid saturation (Manson and Roberts 2000).

About 10g of soil was scooped into the sample cups with 25ml of 1M KCl solution and stirred at 400rpm for 5 minutes. The suspension was allowed to stand for 30 minutes, and the pH was measured using a gel-filled combination glass electrode. Ambic solution consisting of 0.25 M NH_4CO_3 + 0.01 M Na_2EDTA and 0.01 M NH_4F + 0.05 g/L superfloc was used to determine P, K, Zn, Cu and Mn. About 2.5g of soil with 25ml of the solution was stirred at 400rpm for 10 minutes in a stirrer. Available P was determined using molybdenum blue procedure (Hunter, 1974), K, Zn, Cu and Mn were determined using atomic absorption. Calcium, magnesium and acidity were also determined using KCl solution for extraction. About 25g of soil was scooped into sample cups with 25ml of 1M KCl and stirred at 400rpm for 10 minutes. About 5ml of the extract was diluted with 20ml of 0.0356 M $SrCl_2$ to determine Ca and Mg using atomic absorption. For extractable acidity, 10ml of the extract was diluted with 10ml of de-ionised water containing 2-4 drops of phenolphthalein and titrated with 0.005 M NaOH. Acid saturation was calculated from Ca, Mg, K and extractable acidity values.

For particle size distribution, 20g of soil sample was treated with hydrogen peroxide to oxidize the organic matter with 400ml of de-ionized water and left overnight. The clay and fine slit fractions were measured with a pipette and sand fractions were determined by sieving and the textural class was determined using textural triangle. Soil characterization is given in Table 3.1 and Table 3.2.

All three typology within different cropping systems had acidic pH<5 with high exchangeable Ca ranging between 690 ± 421 to 1160 ± 687 mg/kg (Table 3.1). There was no significant difference in exchangeable bases across all three different typology and cropping systems. Physico-chemical characteristics of soils from Msinga farms (Table 3.2) were generally not different from those of uMbumbulu farms (Table 3.1). Both cropping systems under 3 different typologies at uMbumbulu had a pH range of 3-5. The extractable P in soils was higher under homefield than in outfield of resource endowed and moderately endowed farmers.

Table 3.1: Soil physico-chemical characterization for uMbumbulu farms

	RESOURCE ENDOWED		MODERATELY ENDOWED		RESOURCE CONSTRAINED	
	MONO	MC	MONO	MC	MONO	MC
Acid saturation (%)	14 ± 13.3	9 ± 9.76	2 ± 1	8 ± 7	2 ± 1.73	5.25 ± 1.71
Exchangeable Ca (mg/kg)	719 ± 292	863 ± 226	1071 ± 370	915 ± 433	1160 ± 687	690 ± 421
Exchangeable Cu (mg/kg)	1.80 ± 0.369	2.41 ± 0.855	5.53 ± 4.03	4.12 ± 2.40	5.31 ± 2.90	3.73 ± 2.95
Exchangeable acidity (cmol/kg)	0.716 ± 0.550	0.583 ± 0.566	0.187 ± 0.096	0.464 ± 0.317	0.782 ± 1.16	1.29 ± 0.896
Exchangeable K (mg/kg)	101 ± 38.8	144 ± 65.4	82.5 ± 70	118 ± 72.9	130 ± 84	60.0 ± 22.2
Exchangeable Mg (mg/kg)	211 ± 136	215 ± 113	355 ± 97.2	287 ± 134	333 ± 216	119 ± 112
Exchangeable Mn (mg/kg)	5.15 ± 2.43	5.77 ± 4.34	5.84 ± 3.12	5.67 ± 1.47	5.79 ± 0.459	6.10 ± 2.79
Exchangeable P (mg/kg)	9.75 ± 6.48	13.7 ± 6.58	6.79 ± 1.68	12.3 ± 10.5	10.2 ± 5.43	9.33 ± 4.87
Total cations (cmol/kg)	6.30 ± 1.94	7.03 ± 1.23	8.66 ± 2.50	7.69 ± 2.95	9.65 ± 4.24	6.44 ± 2.12
Exchangeable Zn (mg/kg)	6.00 ± 6.69	5.24 ± 3.69	6.37 ± 6.85	3.47 ± 0.523	3.77 ± 1.12	1.48 ± 0.890
$pH_{(KCl)}$	4.36 ± 0.191	4.55 ± 0.370	4.59 ± 0.156	4.44 ± 0.359	4.54 ± 0.409	4.27 ± 0.197
Texture	Sandy clay loam	Sandy clay loam	Sandy clay loam	Clay	Sandy clay loam	Clay

Mono= monoculture system, MC= mix cropping system

Table 3.2: Soil physico-chemical characterization for Msinga farms

	RESOURCE ENDOWED		MODERTALY ENDOWED		RESOURCE CONSTRAINED	
	Homefield	Outfield	Homefield	Outfield	Homefield	Outfield
Acid saturation (%)	19 ± 27.1	37.3 ± 27.6	3.66 ± 2.51	4.33 ± 2.31	9 ± 14.7	0.666 ± 1.15
Exchangeable Ca (mg/kg)	657 ± 488	333 ± 338	1192 ± 554	843 ± 326	757 ± 356	827 ± 106
Exchangeable Cu (mg/kg)	2.05 ± 0.998	1.12 ± 0.135	1.73 ± 0.232	2.29 ± 1.45	2.28 ± 0.334	1.85 ± 0.088
Exchangeable acidity (cmol/kg)	0.521 ± 0.507	0.998 ± 0.575	0.130 ± 0.126	0.311 ± 0.208	0.381 ± 0.557	0.043 ± 0.038
Exchangeable K (mg/kg)	205 ± 141	102 ± 72.9	297 ± 227	159 ± 119	192 ± 113	159 ± 116
Exchangeable Mg (mg/kg)	175 ± 132	130 ± 142	248 ± 121	287 ± 127	182 ± 81.3	206 ± 50.7
Exchangeable Mn (mg/kg)	10.4 ± 3.15	4.17 ± 0.957	5.32 ± 2.96	14.9 ± 15.0	8.73 ± 6.89	5.69 ± 4.01
Exchangeable P (mg/kg)	38.1 ± 31.0	10.3 ± 6.88	27.4 ± 15.3	15.5 ± 3.86	20.3 ± 8.68	23.2 ± 12.8
Total cations (cmol/kg)	5.77 ± 3.36	3.99 ± 2.75	8.88 ± 4.09	7.29 ± 2.89	6.15 ± 1.91	6.27 ± 1.20
Exchangeable Zn (mg/kg)	11.9 ± 9.66	1.60 ± 1.04	10.4 ± 8.34	3.31 ± 0.713	10.6 ± 12.3	3.78 ± 2.27
$pH_{(KCl)}$	4.41 ± 0.833	3.94 ± 0.213	5.27 ± 1.03	4.18 ± 0.141	4.79 ± 1.12	4.97 ± 0.450
Texture	Sandy loam	Sandy loam	Clay	Clay	Sandy clay	Sandy clay loam

3.2.3. Soil carbon fractionation

Soil samples were physically fractionated using the method modified from Six *et al.* (2002) and Hook and Burke (2000). Briefly, 10g of air-dried soil was dispersed in 50 mL of sodium hexametaphosphate solution (5 g/L H_2O) by shaking on a reciprocal shaker for 18 hours at a speed of 180 rpm. The dispersed sample was then passed through 250 and 53 µm sieves. The materials left on the 250 µm sieve was quantified as coarse particulate organic carbon (cPOMC), and the fractions collected on the 53 µm sieve was used to quantify fine particulate organic carbon (fPOMC). Thereafter, the different fractions were oven-dried at 102°C and the mass of each fraction was determined after drying. Soil materials that passed through 53 µm sieve were dried at 105 °C and then were finely ground for the determination of mineral associated organic carbon (MAOC) content. Thereafter, the SOC in the fractions was analyzphysiced using the Walkley-Black method (Mylavarapu *et al.,* 2014; Walkey and Black 1934). For this, 0.5g of each fraction was treated with 10 ml potassium dichromate and 20 ml sulphuric acid. The mixture was allowed to cool for 20 minutes under the fumehood, thereafter, 170 ml deionized water was added followed by 10 ml phosphoric acid. The samples were then titrated with ammonium ferrous sulphate. The concentration of each fraction was reported per mass of the fraction.

Dissolved organic carbon (DOC) was extracted from 10g of soil sample in 50ml distilled water in 100ml centrifuge tubes and shaken for 30 minutes. After shaking, the soil-water suspension was centrifuged at 3500 rpm for 10 minutes and after filtered using Whatman No. 1 Filter paper into a storage bottle (Zhao *et al.,* 2012). Thereafter, C concentration was determined using 10 ml of the extracted and analyzed using Walkley-Black method.

3.2.4. Soil phosphorus fractionation

Soil P fractions were determined as described by Zhang (2009) for non-calcareous soils. For this, 1g of soil samples was treated using 50 ml 1M ammonium chloride (1M NH_4Cl) for soluble P. After 30 minutes of shaking, the suspension was centrifuged at 4000 rpm and then filtered using Whatman No. 1 filter paper into 50ml volumetric flasks and was filled up to volume with deionized water. The soil residue was then treated with 50 ml of 0.5M ammonium fluoride (0.5M NH4F), followed by shaking for one hour and was centrifuged at 3500 rpm for 10 minutes then filtrated into 100ml volumetric flask. The soil residue was washed twice with 25 ml saturated sodium chloride, centrifuged at 3500 rpm for 10 minutes, and filtered into the same flask with Al-P extracts, thereafter, the volumetric flask was filled up to the marker using deionized. Iron phosphate was extracted from the same soil residue using 50ml of 0.1M sodium hydroxide (0.1M NaOH), after shaking for 17 hours then centrifuged at 3500 rpm for 10 minutes and filtered using Whatman No.1 filter paper. The soil residue was washed twice using saturated 25 ml sodium chloride. For reductant soluble P extraction, 40 ml of 0.3M sodium citrate dihydrate (0.3M $Na_3C_3H_6O_7$) and 5 ml of 1M sodium bicarbonate (1M $NaHCO_3$) was added to the soil residue and heated for 15 min in a water bath at 85°C. Thereafter, 1 g of sodium dithionate ($Na_2S_2O_2$) was added and followed by rapid stirring, then, the suspension was heated again for 15 minutes. The extractants were then filtered using Whatman No.1 filter paper. The soil residue was then washed twice using 25 ml of saturated sodium chloride. These washings were combined with reductant soluble P extract. Calcium phosphate was determined using 0.25 M sulphuric acid (0.25 M H_2SO_4), shaken for one hour and centrifuged. The soil was washed following the same procedure as described for Al-P and Fe-P pools. Phosphorus concentrations in various solutions were determined using phospho-molybdate method (Murphy and Riley, 1962).

3.2.5. Statistical analysis

The analysis of variance (Two-way ANOVA) was performed for carbon and phosphorus pools across different farmer typologies and (i) cropping systems for uMbumbulu and (ii) field type for Msinga using GenStat Ed 18. The least significant difference (LSD) at 5% level was used to compare the means of C and P pools. Spearman's rank was used for correlation between carbon and phosphorus fractions.

3.3. Results

3.3.1 Characteristics of organic amendments from uMbumbulu and Msinga

Maize residues had lower pH and all elemental concentrations except carbon when compared to manures and accelerator (Table 3.3). Goat manure had higher pH, Zn, P and lower Mn than cattle manure. The Accelerator had higher P, Ca, Zn, Mn and Cu while Fe and Al were lower than for goat and cattle manure. While total C was similar between maize residues and Accelerator, and higher than the other resources, all the nutrients were lower in maize residues than the other organic resources.

Table 3.3: Characteristics of organic amendments from uMbumbulu

Properties	Goat	Cattle	Maize residues	Accelerator
C (%)	28.2 ± 4.26	25.5 ± 1.58	36.3 ± 1.35	35.9 ± 0.57
N (%)	2.22 ± 0.41	2.09 ± 0.12	1.32 ± 0.16	2.87 ± 0.08
Lignin (%)	30.0 ± 0.22	52.4 ± 0.29	19.2 ± 0.09	15.8 ± 0.89
P (%)	0.56 ± 0.13	0.42 ± 0.04	0.13 ± 0.02	1.57 ± 0.10
K (%)	4.05 ± 1.42	2.61 ± 0.29	0.91 ± 0.03	4.32 ± 0.15
Ca (%)	1.24 ± 0.20	1.02 ± 0.10	0.13 ± 0.03	4.48 ± 0.21
Mg (%)	0.76 ± 0.08	0.67 ± 0.07	0.19 ± 0.03	1.04 ± 0.07
Zn (mg kg^{-1})	259 ± 11	166 ± 17.0	23.9 ± 2.64	826 ± 25
Mn (mg kg^{-1})	282 ± 61	639 ± 65.0	37.8 ± 1.13	1142 ± 35
Cu (mg kg^{-1})	24.9 ± 2.4	27.7 ± 3.80	3.10 ± 0.14	149 ± 6.6
Fe (mg kg^{-1})	11029 ± 3.63	11224 ± 825	233 ± 4.14	4304 ± 346
Al (mg kg^{-1})	17495 ± 7420	17308 ± 1356	382 ± 30.5	2143 ± 187
pH $_{(KCl)}$	9.28 ± 0.05	8.90 ± 0.02	4.78 ± 0.47	7.02 ± 0.01

values on the table represent mean ± standard deviation.

Similar to uMbumbulu, maize residue pH and all elemental concentrations were lower than goat and cattle manure (Table 3.4) except for carbon concentration which was 38.7 ± 1.35 higher. Cattle manure had higher C, N, Mn and lower Zn, Fe and Al than goat manure. While total N was similar between maize residues and goat manure.

Table 3.4: Characterization of organic amendments from Msinga

Properties	Goat	Cattle	Maize residues
C (%)	19.6 ± 4.26	31.1 ± 0.70	38.7 ± 1.35
N (%)	1.47 ± 0.12	2.40 ± 0.04	1.16 ± 0.34
Lignin (%)	36.4 ± 0.31	29.9 ± 0.39	5.26 ± 0.05
P (%)	0.43 ± 0.18	0.52 ± 0.01	0.25 ± 0.05
K (%)	1.73 ± 0.41	2.12 ± 0.08	0.77 ± 0.12
Ca (%)	1.48 ± 0.72	1.43 ± 0.04	0.08 ± 0.02
Mg (%)	0.51 ± 0.13	0.80 ± 0.02	0.18 ± 0.03
Zn (mg kg$^{-1)}$	415 ± 283	221 ± 2.47	41.8 ± 4.05
Mn (mg kg^{-1})	503 ± 205	789 ± 17.0	34 ± 10.7
Cu (mg kg^{-1})	31.7 ± 18.5	24.8 ± 3.46	2.44 ± 0.53
Fe (mg kg^{-1})	18389 ± 4754	7742 ± 363	96.5 ± 36.0
Al (mg kg^{-1})	15392 ± 2149	6063 ± 697	111 ± 65.5
pH $_{(KCl)}$	8.23 ± 0.70	8.28 ± 0.01	5.61 ± 0.51

values on the table represent mean ± standard deviation.

3.3.2. Carbon and Phosphorus fractions

There was no significant difference in soil C fractions within the typology, cropping system and field type ($p>0.05$) for both uMbumbulu and Msinga (Table 3.5). The fractions for uMbumbulu under mixed cropping ranged between 0.229-38.1 g/kg and 0.184-40.3 g/kg in monocropping. Msinga fractions ranged between 0.252-18.1 g/kg at homefield and 0.398-14.6 g/kg at outfield.

Table 3.5: Carbon fractions under different typology, cropping system and fields in uMbumbulu and Msinga.

Factor	Total C (g/kg)	c-POMC (g/kg)	f-POMC (g/kg)	MAOC (g/kg)	DOC (g/kg)
			uMbumbulu		
Cropping system					
Mixed cropping	38.1	20.8	8.34	4.53	0.229
Monocropping	40.3	26.0	5.71	4.08	0.184
LSD (p=0.05)	10.74	7.88	3.76	1.08	0.209
Typology					
Rich	36	23.3	7.75	4.46	0.286
Medium	36.9	21.4	5.51	3.41	0.142
Poor	44.6	25.4	7.81	5.06	0.191
LSD (p=0.05)	13.16	9.65	4.62	1.32	0.256
			Msinga		
Field type					
Homefield	18.1	5.70	3.17	5.10	0.252
Outfield	14.6	4.05	3.14	4.91	0.398
LSD (p=0.05)	7.12	3.91	2.30	1.90	0.3845
Typology					
Resource endowed	14.8	3.53	2.96	4.19	0.396
Moderately endowed	20.1	7.67	4.43	5.31	0.151
Resource constrained	14.3	3.43	2.08	5.51	0.429
LSD (p=0.05)	8.72	4.79	2.81	2.32	0.471

Five pools of P where fractionated but there was no significant difference between the pools from different field type and cropping system in uMbumbulu and Msinga soils except Al-P which was higher in uMbumbulu soil under mixed cropping (Table 3.6). The P fractions ranged between 11.8-310 mg/kg under mixed cropping and 8.9-224 mg/kg under monocropping in uMbumbulu. For Msinga the fractions ranged between 28.6-212 mg/kg for homefields and 16.3-192 mg/kg for outfields.

Table 3.6: Phosphorus fractions under different typology, cropping system and fields in uMbumbulu and Msinga.

Factor	Available P	Soluble +loosely bound P	Al-P	Fe-P	Reductant-P	Ca-P
			mg/kg			
			uMbumbulu			
Cropping system						
Mixed cropping	11.8	33.5	183	157	310	34.6
Monocropping	8.9	33.5	175	159	224	38.3
LSD (p=0.05)	5.56	3.92	6.9	41.6	220	3.91
Typology						
Resource endowed	11.7	35.0	182	175	145	38.4
Moderately endowed	9.6	32.9	177	161	209	37.2
Resource constrained	9.8	32.6	178	137	447	33.6
LSD (p=0.05)	6.81	4.80	8.4	50.9	270	4.79
			Msinga			
Field type						
Home field	28.6	34.6	188	163	212	63.1
Out field	16.3	33.3	192	132	174	40.0
LSD (p=0.05)	16.19	3.77	25.6	68.6	121	39.1
Typology						
Resource endowed	24.2	33.7	187	160	134	43.4
Moderately endowed	21.4	35.7	196	134	173	75.1
Resource constrained	21.8	32.5	187	148	273	36.0
LSD (p=0.05)	19.8	4.62	31.4	84.0	148	47.9

Soluble +loosely bound P= soluble phosphorus and loosely bound phosphorus; Al-P= aluminum bound phosphorus; Fe-P= Iron bound phosphorus; Reductant P= dithionite extractable phosphorus; Ca-P= calcium bound phosphorus.

Carbon fractions when compared between the sites showed significantly higher Total C, cPOMC and fPOMC in uMbumbulu than Msinga soil, with no differences in MAOC and DOC between the sites (Figure 3.1).

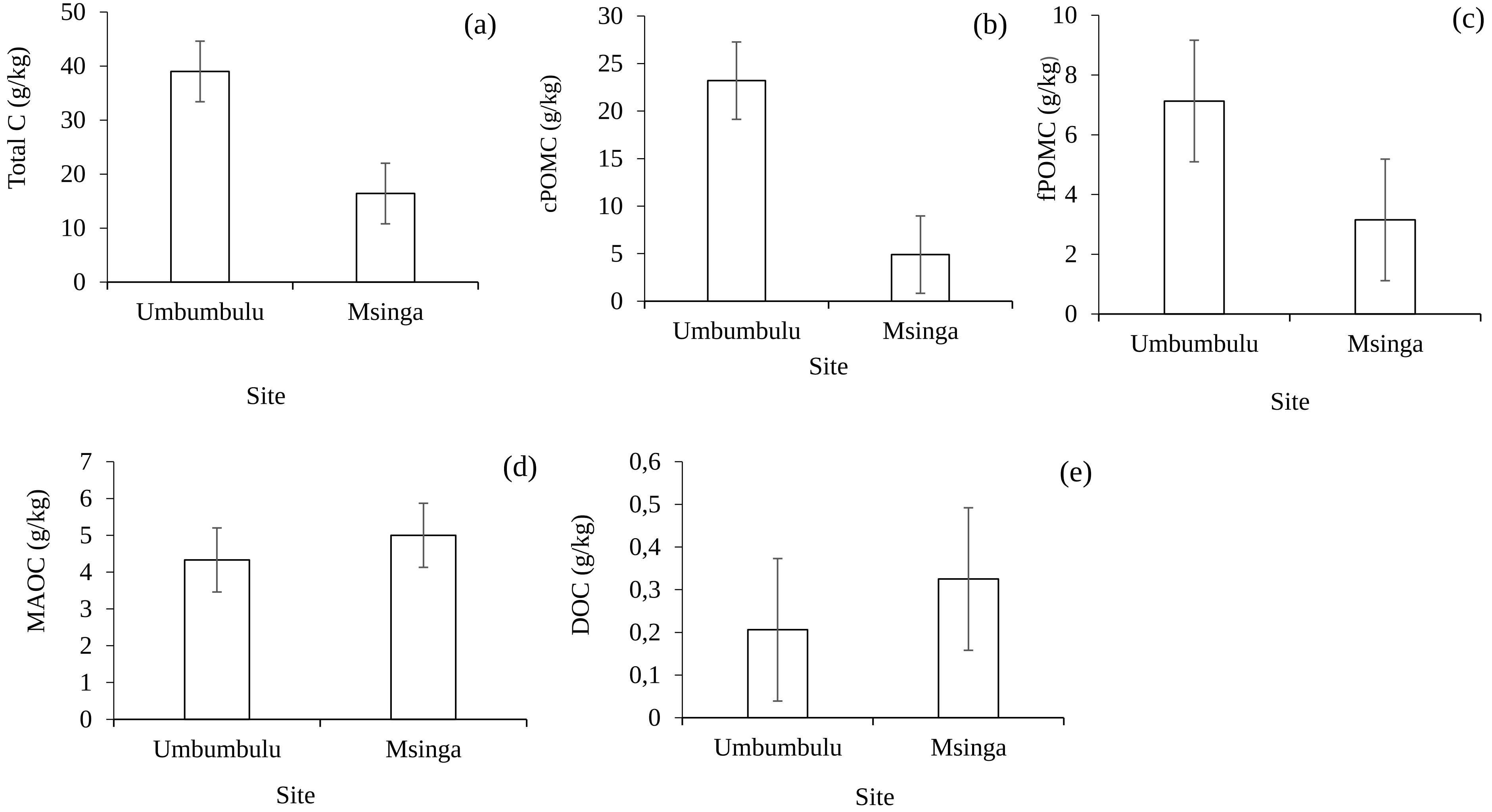


Figure 3.1: Carbon fractions between uMbumbulu and Msinga area. Figure a, b, c, d and e indicates Total C, cPOMC, fPOMC, MAOC and DOC, respectively.

Except for available P, the other P fractions in the two sites had no significant differences (Figure 3.2). The Msinga soil had significantly higher available P (22.5 mg/kg) than uMbumbulu (10.4 mg/kg)

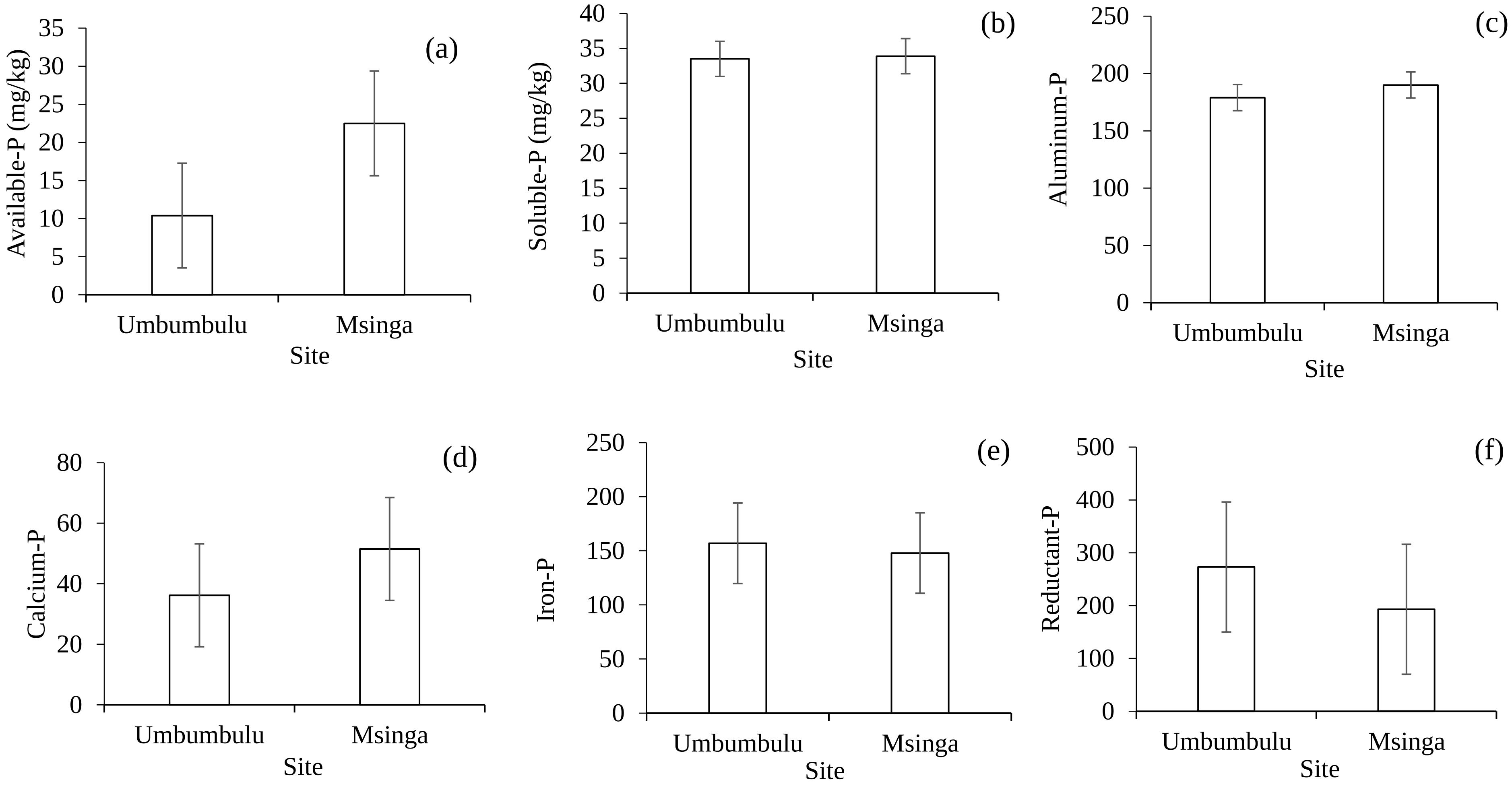


Figure 3.2: Phosphorus fractions between uMbumbulu and Msinga with figure a, b, c, d, e and f indicating Available P, soluble-P, Al-P, Ca-P, Fe-P and Reductant-P, respectively.

Total C from uMbumbulu soil was strongly positively correlated with cPOMC and negatively correlated with Fe-P. The cPOMC was negatively with Fe-P while fPOMC was positively correlated with MAOC, DOC and Al-P. MAOC was positively correlated with DOC but negatively with Ca-P. The DOC was also positively correlated with Fe-P and negatively with reductant P. Reductant P was negatively correlated with soluble P, Fe-P and DOC (Table 3.7). The Ca-P pool was correlated positively with Fe-P and negatively with MAOC and reductant P.

Table 3.7: Spearman's rank correlation coefficients of soil organic carbon and inorganic phosphorus fractions for uMbumbulu soil

	Total C	cPOMC	fPOMC	MAOC	DOC	Soluble-P	Al-P	Fe-P	Red-P	Ca-P
Total C	1.00									
cPOMC	**0.833*** **	1.00								
fPOMC	0.242	-0.226	1.00							
MAOC	0.138	0.010	**0.394***	1.00						
DOC	0.180	-0.143	**0.678*** **	**0.481** **	1.00					
Soluble-P	-0.235	-0.120	-0.154	0.083	-0.050	1.00				
Al-P	-0.012	-0.277	**0.381***	0.050	0.256	-0.243	1.00			
Fe-P	**-0.391***	**-0.369***	0.102	0.084	**0.471** **	0.258	0.150	1.00		
Red-P	0.015	-0.053	-0.146	-0.132	**-0.355***	**-0.493** **	0.100	**-0.450** **	1.00	
Ca-P	-0.035	0.033	-0.128	**-0.502** **	0.049	0.143	0.027	**0.305***	**-0.396***	1.00

*,** and *** represent significant correlations at p < 0.05, <0.01 and <0.001.

For Msinga soils, total C and cPOM were significantly correlated negatively with DOC, and positively to all other fractions of carbon and phosphorus except MAOC. The DOC was negatively correlated with all other SOC pools and all P pools, while soluble P was positively correlated with all other P pools. The fPOMC was also positively correlated soluble P, Al-P and Ca-P. While Al-P was positively correlated with Fe-P and reductant P.

Table 3.8: Spearman's rank correlation coefficients of soil organic carbon and inorganic phosphorus fractions for Msinga soil

	Total C	cPOMC	fPOMC	MAOC	DOC	Soluble-P	Al-P	Fe-P	Red-P	Ca-P
Total C	1.00									
cPOMC	**0.856*****	1.00								
fPOMC	**0.585****	**0.546****	1.00							
MAOC	0.247	0.005	0.222	1.00						
DOC	**-0.674*****	**-0.490****	**-0.319***	-0.313	1.00					
Soluble-P	**0.483***	**0.558****	**0.636*****	0.061	**-0.432***	1.00				
Al-P	**0.763*****	**0.760*****	**0.325***	0.158	**-0.406***	**0.319***	1.00			
Fe-P	**0.521****	**0.572****	0.150	-0.298	**-0.426***	**0.397***	**0.505****	1.00		
Red-P	**0.519****	**0.581****	0.288	0.207	**-0.319***	**0.315***	**0.525****	0.310	1.00	
Ca-P	**0.441***	**0.456***	**0.568****	**-0.315***	**-0.562****	**0.449***	0.103	**0.503****	0.217	1.00

*, ** and *** represent significant correlations at p < 0.05, <0.01 and <0.001.

Based on the combined data for uMbumbulu and Msinga soils (Table 3.9), total C was correlated positively to cPOMC and fPOMC, and negatively with DOC. The cPOMC was positively correlated with fPOMC and negatively with DOC and Al-P. The DOC was also negatively correlated with reductant P and Ca-P. The soluble P was positively correlated with Fe-P and Ca-P, while Al-P was positively correlated with Fe-P and reductant P. The Fe-P was also positively correlated with Ca-P.

Table 3.9: Spearman's rank correlation coefficients of soil organic carbon and inorganic phosphorus fractions from combined data of uMbumbulu and Msinga.

	Total C	cPOMC	fPOC	MAOC	DOC	Soluble-P	Al-P	Fe-P	Red-P	Ca-P
Total C	1.00									
cPOMC	**0.942*** **	1.00								
fPOMC	**0.665*** **	**0.545*** **	1.00							
MAOC	0.002	-0.114	0.125	1.00						
DOC	**-0.324***	**-0.342****	-0.032	0.070	1.00					
Soluble-P	0.043	0.057	0.183	0.076	-0.197	1.00				
Al-P	-0.118	**-0.242***	0.071	0.092	0.025	-0.036	1.00			
Fe-P	0.159	0.170	**0.220***	-0.158	-0.002	**0.304***	**0.223***	1.00		
Red-P	0.194	0.180	0.087	0.015	**-0.349****	-0.121	**0.242***	-0.144	1.00	
Ca-P	-0.035	-0.072	0.068	**-0.291***	**-0.233***	**0.262***	0.152	**0.359****	-0.103	1.00

*, ** and *** represent significant correlations at p < 0.05, <0.01 and <0.001.

3.4. Discussion

Many studies have shown that different management practices within typology in smallholder farms affect soil quality and fertility. The difference in management practices is due to different socio-economic factors within farmers (Tittonell *et al.,* 2010). Msinga area is classified as a dry area receiving about 750mm of rainfall annually with Mispah and Glenrosa soil forms (Nyiraruhimbi 2012). Results from Tables 3.5 and 3.6 showed no significant difference of carbon and phosphorus pools between typologies and cropping systems for uMbumbulu and between typology and field type for Msinga. Although many studies have shown that management practices affect carbon and phosphorus pools, the results from this study showed that this effect could be insignificant for the typical smallholder farms of South Africa, particularly those who practice similar management (i.e. Mulching and crop residue retention) as those of uMbumbulu and Msinga. The differences of the pools between the sites could be explained by differences in biophysical factors such as climate, topography and and soil characteristics, as affected by parent material. Thus, the higher total C, cPOMC and fPOMC in uMbumbulu than Msinga soil (Figure 3.1) could be because uMbumbulu area is located in a coastal area receiving higher rainfall resulting in higher biomass input than Msinga. In agricultural soils, carbon and phosphorus tend to be more present at the topsoil due to practices such as deep tillage and Msinga soils are classified as soils with high erosion hazard which might have caused a loss in carbon and phosphorus. The annual loss of carbon from topsoil in African soils is estimated to be 0.22 t C/ha (Sanchez *et al.,* 1997) and this might be due to factors such as topography, land use history, present soil condition and management practices. The higher available P in Msinga than uMbumbulu soils could make more P available for plants uptake. The difference in the soluble P was not clear as there were no major differences in pH and soil texture. uMbumbulu soil did not result in significantly higher Al-P, Fe-P, reductant P and Ca-P than Msinga.

Most smallholder farmers are known to allow grazing of livestock after harvesting which affect soil properties. The uMbumbulu setting had lower numbers of livestock, and residues retained add more to SOC than Msinga. Drier climate coupled with overgrazing of livestock and other factors have also led to substantial decreases in SOC and nutrient stocks, especially in soils of Msinga. The similarity in P fractions between uMbumbulu and Msinga soils could be due to lack of major textural and pH differences. In acidic soils P precipitates with soluble Al and Fe and become unavailable for plant uptake. It was expected for Fe-P to show significant difference in these soils, but the results showed no different. Some smallholder farmers under different typology apply manure as organic fertilizer but its application may be of no significant effect to Fe and Al fixation mechanisms possibly because the P added through the amendments may be low and get taken up by plants before fixation.

The strong positive correlation between total C and cPOMC in uMbumbulu soils (Table 3.7) suggested that SOC is mostly stored as cPOMC (Witzgall *et al.,* 2021). The negative correlation between DOC and Red-P suggested that the increase in DOC reduced fixation of P to Red-P possibly due to competitive adsorption of P and DOC while the presence of DOC increases microbial activity and microbial P, also reducing P fixation (Li *et al.,* 2021). The cPOMC was negatively correlated to Fe-P suggesting that high organic content inhibited the binding of P to Fe due to competition on the binding sites (Kleeberg and Kozerki. 1997). For Msinga soils, total C and cPOMC were positively correlated to all other C and P fractions but negatively correlated to DOC (Table 3.8). This might be due to that high organic carbon in soil might impede sorption of DOC due to less binding sites available (Mavi *et al.,* 2012). Al-P being positively correlated to Fe-P and Red-P might be due to P fixation into these different forms as a result of acidic conditions. With the two sites combined (Table 3.9), less positive correlation occurred which might be due to the soils having different properties hence less correlation.

3.5. Conclusion

The study has shown that different management practices by smallholder farmers with uMbumbulu and Msinga area under different typology, field type and cropping system do not affect the carbon and phosphorus fractions in soils as no significant different were seen within carbon and phosphorus fractions. High temperature affects microbial activity which control the rate of organic matter decomposition affecting the amount of SOC content present in soil. uMbumbulu area have high temperature than Msinga area hence the significant differences of Total carbon, c-POMC and f-POMC between the two areas. Soil P has been viewed to be lower in hot and wet tropical regions than in cold temperate regions but there was no significant difference of P fractions between the areas. More study needs to be done to evaluate carbon and phosphorus fractions under different climate conditions and topography.

CHAPTER FOUR
CHARACTERISTICS OF LOCAL ORGANIC AMENDMENTS FROM UMBUMBULU AND MSINGA AND THEIR NITROGEN AND PHOSPHORUS RELEASE IN SOIL

4.1. Introduction

Conventional agricultural practices such as the application of chemical fertilizers and intensive tillage negatively affect soil fertility. While the fertility status of soils is affected by soil-forming factors, including climate and parent material, management factors make major contributions. Many studies have shown that intensive tillage caused aggregate breakdown leading to the loss of soil stability, while run-off and the resultant erosion of soils with chemical fertilizers cause eutrophication (Glibert *et al.*, 2005; Jiang-Tao and Zhang 2007). Intensive tillage operations and the associated aggregate breakdown expose organic matter protected in micro aggregates resulting in its oxidation, further lowering concentration of soil organic carbon (SOC). Furthermore, the addition of most chemical fertilizers increased biomass production and provides labile substrate and increase activity of soil microorganisms, leading to rapid decomposition of soil organic matter, lowering SOC, making the soil more erodible, while contributing to the emission of greenhouse gases such as carbon dioxide, methane, and nitrous oxide. Soils from smallholder farms are known to be generally low in nutrients due to low application of fertilizers and conventional management practices putting a significant constraint to crop productivity.

The low use of chemical fertilizer is mainly a result of its high costs for the resource constrained farmers. The addition of organic amendments has shown great benefits in improving soil physical, chemical, and biological properties and crop productivity. While Cesarano *et al.* (2017) showed that synthetic fertilizers resulted in higher crop yield than organic materials, due to more readily available nutrients than from organics, which need to be mineralized to be available, the organic amendments make an important contribution in low input crop production systems. Lax *et al.* (1994) and Qadir *et al.* (2001) showed that the addition of organic materials to soils increased water infiltration, water-holding capacity and aggregate stability. Usage of organic input can increase soil fertility by releasing nutrients needed by crops during decomposition when incorporated into the soil. The application of organic materials result in release of nutrients such as nitrogen and phosphorus into the soil which microorganisms and plants tend to compete for during decomposition (Kaye and Hart 1997). Decomposition and mineralization of nutrients is affected by the organic inputs and the soil fertility status, with effects on microbial biomass and activity. Fertile soils are known to have a high decomposition rate and faster carbon mineralization due to their soil structure and higher enzyme activities (Huang 2000; Fontaine *et al*., 2011; Lang *et al*., 2012). The effects of organic amendments on SOC and mineral N and P may depend on the type of amendment used.

Organic material such as animal and green manure, organic waste, compost, and biochar have been presented as a reliable and effective approach for soil fertility recovery (Himmelstein *et al*.,2014; Tejada *et al.,* 2009; Jones et al., 2012; Lehmann *et al*., 2011). While heavy application of manure from commercial animal production systems may cause serious environmental challenges due to heavy nutrient loads (Wodzinski and Ullah, 1996), its use may be of great benefit in low input crop production systems. In China a 17-year study using organic amendment, crop rotation, and NPK fertilizer by Hao *et al.* (2008) showed that farmyard manure (rice straw and animal manure) increased SOC content by 25-65%. Similarly, in Zimbabwe, Nyamangara *et al.* (2001) showed that the application of cattle manure increased SOC by 10 to 38% in the 0-10 cm layer. Bayu *et al.* (2005) and Murwira *et al*. (1995) reported that cattle manure was a critical resource supplying nutrients, raising soil pH and increasing SOC. Manure is therefore beneficial as it improves soil properties (Sommerfeldt and Chang 1985) and crop yield (Ginting *et al*., 1998b; Sutton *et al*., 1986).

Many studies have shown that crop residues return nutrients into the soil when retained after harvesting, with more positive effects on chemical, physical and biological properties than when incorporated into the soil (Mandal *et al.,* 2004; Turmel *et al.*, 2015). Moreover, incorporation of crop residues has been shown to increase soil carbon content (Gong *et al*., 2009; Lu *et al.,* 2009). Zhao *et al*. (2015) showed that incorporation of maize, wheat, and rice residues increases soil carbon storage when compared to straw removal. However, on smallholder farms, the types of organic materials are more variable, and the quantities depend on availability while the quality is generally poor. Co-application of different materials may have synergistic effects on SOC and nutrient cycling, in soils of poor fertility status. The combined use of organic materials such as animal manures, crop residues, and compost has been shown to be highly beneficial for crop production due to its positive effect on soil fertility and nutrient uptake by plants (Chen 2006). The potential benefits could depend on the type and quality of the available organic resources.

Smallholder farms in South Africa are variable in terms of socio-economic status, soil types, climatic conditions and management. Most of the farmers in sub-saharan Africa depend on organic amendments for improving soil quality and productivity (Bationo *et al.,* 2005; Fliebbach *et al*.,2006). The most common organic amendments found and used on smallholder farms in South Africa include animal manures and crop residues (Mkile 2001; Adediran *et al.*, 2003). Msinga and uMbumbulu are typical examples of smallholder farms in KwaZulu-Natal Province and they differ significantly in climate and soil types. The characteristics and nutrient release of different organic inputs could differ between the regions, due to differences in climatic conditions and soil types. The most common manures in Msinga and uMbumbulu are those from cattle and goats, and their characteristics need to be established to understand their potential contribution to SOC and nutrient cycling, as affected by regional differences. In addition to cattle manure, farmers in these regions also retain crop residues after harvesting, especially maize stalks. Application of manure coupled with retention of crop residues could have a synergistic or moderating effect on nutrient release from these resources than when applied separately. Considering that maize residues usually have higher C:N ratios (78:1) than animal manures (21:1) (Zareei and Khodaei, 2017), the nutrient release from combinations of these organic wastes may be moderated affecting their availability to crops. Understanding the quality of organic inputs and the effect of their combinations on the nutrient release is essential for nutrient management and crop production on smallholder farms in Msinga and uMbumbulu. The objective of this study was to determine the effect of (i) type and source (region) of organic amendment on its quality and N and P release in soils and (ii) combinations of organic materials on mineral N and P in soils.

4.2. Methods and materials

4.2.1. Characteristics of soils and organic amendments

The soils used in this study were collected from Msinga and uMbumbulu. The site descriptions are given in full detail under Materials and Method section of Chapter 3. The soil samples were collected from a depth of 0-20cm from each field of nine homesteads from each area and combined to make a compost sample for the incubation set-up. Soil pH, organic carbon (C) and nitrogen (N), available phosphorus (P), exchangeable K, manganese (Mg), calcium (Ca), exchangeable acidity and available magnesium (Mn), copper (Cu) and zinc (Zn) were analyzed at Cedara using standard methods as described by Manson and Roberts (2000). The available P was 42.7 mg kg^{-1} for soil from Msinga and 11.04 mg kg^{-1} for uMbumbulu (Table 4.1). Both soils had an acidic pH (4.554.61). There were no significant differences ($p>0.05$) in all other soil properties between uMbumbulu and Msinga.

Table 4.1: Selected characteristics of soils (0-20 cm depth) from uMbumbulu and Msinga used for incubation set-up.

Soil properties	uMbumbulu	Msinga
C (%)	3.21 ± 0.032	1.77 ± 0.126
N (%)	0.101 ± 0.006	0.111 ± 0.008
P (mg kg^{-1})	11.04 ± 1.38	42.7 ± 10.4
K (mg kg^{-1})	123 ± 20.3	159 ± 39.5
Ca (mg kg^{-1})	894 ± 64.1	812 ± 78.8
Mg (mg kg^{-1})	185 ± 10.20	190 ± 17.2
Zn (mg kg^{-1})	7.94 ± 1.33	7.70 ± 1.86
Mn (mg kg^{-1})	4.48 ± 0.083	11.1 ± 0.929
Cu (mg kg^{-1})	2.51 ± 0.414	1.99 ± 0.261
Exch acidity (cmol/kg)	0.359 ± 0.162	0.118 ± 0.043
Total cations (cmol/kg)	6.66 ± 0.220	6.14 ± 0.601
Acid saturation. (%)	5.33 ± 2.52	2 ± 1
$pH_{(KCl)}$	4.55 ± 0.251	4.61 ± 0.148

values on the table represent mean ± standard deviation, exch acidity= exchangeable acidity

The organic materials (cattle manure, goat manure, accelerator and maize residues) were collected from different homesteads and each amendment was mixed to make a composite sample for each region. The accelerator is a commercial compost material produced by Gromor (Pty) Ltd and is used by one of the farmers at uMbumbulu and was therefore treated as a positive control in the incubation experiment. The organic amendments were not distinguished by typology due to the limitation of the organic resources, and the exchange of organic materials between typologies of the smallholder farmers (some poor farmers obtain manures from the relatively rich). The organic amendments were dried at 75 ºC and milled (<0.84mm) before subsamples were ashed at 450 ºC overnight and digested in 1M HCl. The digest was analyzed for P, aluminum (Al), potassium (K), calcium (Ca), magnesium (Mg), copper (Cu), manganese (Mn), and zinc (Zn) using an Inductively

Coupled Plasma -Optical Emission Spectroscopy (ICP-OES) machine. Total C and N were analysed using LECO CNS 2000 (Leco Corporation, Michigan, USA). Maize residues had lower nitrogen content compared to other organic amendments with high C:N ratio (Table 4.2). Lignin content percentage was higher in cattle manure (52.4 ± 0.29) than in other amendments. The Accelerator had higher P, Zn, K, Ca, Mg, Cu and Mn than all other amendments (Table 4.2).

Table 4.2: Characteristics of mixed organic amendments from uMbumbulu used for incubation

Properties	Goat	Cattle	Maize Residues	Accelerator
C (%)	34.6 ± 0.12	25.5 ± 1.58	38.5 ± 0.44	35.9 ± 0.57
N (%)	2.08 ± 0.09	2.09 ± 0.12	0.908 ± 0.16	2.87 ± 0.08
C/N	16.6	12.2	42.4	12.5
P (%)	0.53 ± 0.02	0.42 ± 0.04	0.088 ± 0.01	1.57 ± 0.10
C/P	65.2	60.7	438	22.9
K (%)	3.3 ± 0.06	2.61 ± 0.29	1.10 ± 0.04	4.32 ± 0.15
Ca (%)	1.25 ± 0.16	1.02 ± 0.10	0.156 ± 0.01	4.48 ± 0.21
Mg (%)	0.701 ± 0.02	0.67 ± 0.07	0.254 ± 0.05	1.04 ± 0.07
Zn (mg/kg)	236 ± 10.4	166 ± 17	32.3 ± 1.16	826 ± 25
Mn (mg/kg)	235 ± 12.3	639 ± 65	44.5 ± 0.58	1142 ± 35
Cu (mg/kg)	20.3 ± 1.16	27.7 ± 3.8	6.79 ± 0.07	149 ± 6.6
Fe (mg/kg)	10871 ± 1188	11224 ± 825	3079 ± 568	4304 ± 346
Al (mg/kg)	19869 ± 2843	17308 ± 1356	5782 ± 1155	2143 ±187
Ash (%)	65.0 ± 2.19	52.5 ± 1.90	48.3 ± 2.38	29.0 ± 1.38
pH $_{(KCl)}$	7.15 ± 0.59	8.90 ± 0.02	5.66 ± 1.10	7.02 ± 0.01
Lignin (%)	30.0 ± 0.22	52.4 ± 0.29	19.2 ± 0.09	15.8 ± 0.894

values on the table represent mean ± standard deviation.

Similar to uMbumbulu, maize residues from Msinga had higher C and lower N compared to other organic materials (Table 4.3). Cattle manure had higher pH, P, K, Mn, Al and Mg compared to goat manure and maize residues.

Table 4.3: Characteristics of mixed organic amendments from Msinga used for incubation

Properties	Goat	Cattle	Maize Residues
C (%)	21.1 ± 1.15	31.1 ± 0.70	42.2 ± 0.04
N (%)	1.40 ± 0.01	2.40 ± 0.04	1.13 ± 0.01
C/N	15.1	12.9	37.3
P (%)	0.39 ± 0.03	0.52 ± 0.01	0.21 ± 0.02
C/P	54.1	59.8	201
K (%)	1.25 ± 0.10	2.12 ± 0.08	0.70 ± 0.07
Ca (%)	1.48 ± 0.20	1.43 ± 0.04	0.14 ± 0.01
Mg (%)	0.47 ± 0.05	0.80 ± 0.02	0.25 ± 0.02
Zn (mg/kg^{-1})	462 ± 121	221 ± 2.47	33.6 ± 1.59
Mn (mg/kg^{-1})	428 ± 66.5	789 ± 17.0	41.2 ± 1.84
Cu (mg/kg^{-1})	30.2 ± 4.23	24.8 ± 3.46	2.90 ± 0.54
Fe (mg/kg^{-1})	23353 ± 1792	7742 ± 363	142 ± 70.5
Al (mg/kg^{-1})	25147 ± 1974	6063 ± 697	85.6 ± 19.1
Ash (%)	83.56 ± 1.44	41.8 ± 0.75	43.0 ± 0.76
pH $_{(KCl)}$	7.80 ± 0.19	8.28 ± 0.01	6.26 ± 0.73
Lignin (%)	36.44 ± 0.31	29.99 ± 0.39	5.26 ± 0.05

values on the table represent mean ± standard deviation.

4.2.2. Mineralization of N and extractable P from organic amendments.

Two incubation experiments were conducted in the dark in a constant temperature room (25^{o}C) and were set up in a completely randomized design, with the treatment combinations in triplicates. The first incubation experiment (experiment 1) was conducted with soil and organic amendments from uMbumbulu. The treatments were (i) soil only (control) (ii) goat manure (iii) cattle manure (iv) accelerator (v) maize residue (vi) maize residues + cattle manure (vii) maize residues + goat manure (viii) maize residues + accelerator. All the organic amendments were added at a rate of

1% (15 g amendment in 1.5 kg of soil) and mixed thoroughly for homogeneity before the soil was moistened to 85% of field capacity (FC) moisture content, estimated by saturating the soil and draining it for 48 hours, followed by oven drying. The containers were loosely capped to allow for gas exchange. The incubation experiment was conducted for 84 days, with sampling at 0, 7, 14, 28, 42, 56 and 84 days. Moisture correction was done based on weight loss, after accounting for sample removal, after every 3 days until day 84 of incubation. The soil samples were analyzed for pH, mineral-N (ammonium- and nitrate-N), extractable P per sampling day while total carbon was only analyzed for day 84. The second incubation experiment (Experiment 2) was conducted with soil and organic materials from Msinga, and the set-up, management, sampling and analyses were exactly the same as those for the first experiment.

4.2.3. Soil analysis.

Soil pH was determined using OHAUS 2100 pH meter in 1M KCl and distilled water (1:5; soil: solution) after stirring for a few seconds, standing for 30 min followed by stirring again, and standing for 10 minutes. Ammonium- and nitrate-N were extracted from fresh samples with 2M KCl, where 2g of soil was added to a 50ml test tube with 20ml of the extracting solution (2M KCl), shaken on a reciprocal shaker at 3500rpm for 30 minutes, and filtered using Whatman No. 1 Filter paper, before analysis using Gallery Discrete Autoanalyser (Rayment and Lyons, 2011). Phosphorus was extracted following the AMBIC-2 method (Non-Affiliated Soil Analysis Working Committee of South Africa, 1990). The AMBIC-2 extracting solution contained 0.25 M NH_4CO_3 + 0.01 M Na_2EDTA + 0.01 M NH_4F + Superfloc (0.05 g L^{-1}), and the pH was increased to pH 8 by adding a concentrated ammonia solution. Each sample (2.5 g) was transferred into 50mL test tubes, where 25 ml of extraction solution was added. The test tubes were shaken on a reciprocal shaker at 3500rpm for 15 minutes and the mixtures were filtered using Whatman No.1 filter paper. An aliquot (2ml) of the filtrate was pipetted into a glass test tube, and 8 ml of distilled water was added. A phosphate blue color reagent (10ml) was added slowly, while shaking to allow mixing, and the solution was allowed to stand for 50 minutes to allow for blue color development (molybdenum-blue method). The extractable P was then read on a UV/VIS spectrophotometer at a wavelength of 670 ɳm (Murphy and Riley, 1962). The results for both mineral N and extractable P were expressed in mg kg^{-1} soil and then normalized to g kg^{-1} N present, to show the relative mineralization of the nutrients from the materials and the soil. For total carbon, the soil samples collected after 84 days of incubation were oven-dried for 24 hours, ground and sieved to pass through a 500 µm sieve, before analysis using the LECO Trumac (CNS) autoanalyzer (Leco Corporation, 2012).

4.2.4. Statistical analysis.

The different soil properties were subjected to analysis of variance (ANOVA) for each sampling time in each incubation experiment to assess the effects of different manures and maize residues on mineral-N, pH, extractable P and total C in soil using GenStat 18th Ed. The least significant difference (LSD) at the 5% level was used to separate treatment means.

4.3. Results

4.3.1 Mineralization of N and extractable P from organic amendments in soils.

4.3.1.1 Soil ammonium N

Ammonium-N concentration in soil (mg kg^{-1} soil) showed no significant differences across all treatments from day 28 to day 84 in both experiments (Figure 4.1a and 4.1c). The maximum ammonium-N was reached in the accelerator treatment with 10.5 mg kg^{-1} (uMbumbulu) and 9.5 mg kg^{-1} soil (Msinga), after 42 days of incubation. Ammonium-N concentration in both uMbumbulu and Msinga soils (Figure 4.1a and 4.1c) increased from day 0 to day 7 and started decreasing after day 7 till day 28. When expressed in g kg^{-1} N in the soil, ammonium-N showed significant differences from day 0 to day 56 across all treatments for experiment 1 (Figure 4.1b). The uMbumbulu soil treated with the accelerator showed a rapid increase in ammonium-N within the first 14 days. Treatments with maize residues had the lowest concentration (Figure 4.1b and 4.1d). The concentration of ammonium-N between all the treatments decreased from day 42 till last day (84) of incubation ranging from 6.6-71 g kg^{-1} N (Figure 4.1b and 4.2d). The concentrations of ammonium-N were close to undetectable levels at28 and 84 days of incubation in both soils. For uMbumbulu soil, the treatments without residues had higher ammonium-N (g kg^{-1} of N) than where residues were added, including where there was co-application with manures and accelerator, at 42 and 56 days. The change of ammonium-N concentrations between all treatments were the same at day 7 and 14, with accelerator having the highest followed by goat and cattle manure, while those with residues had the lowest in Msinga soil (Figure 3d).

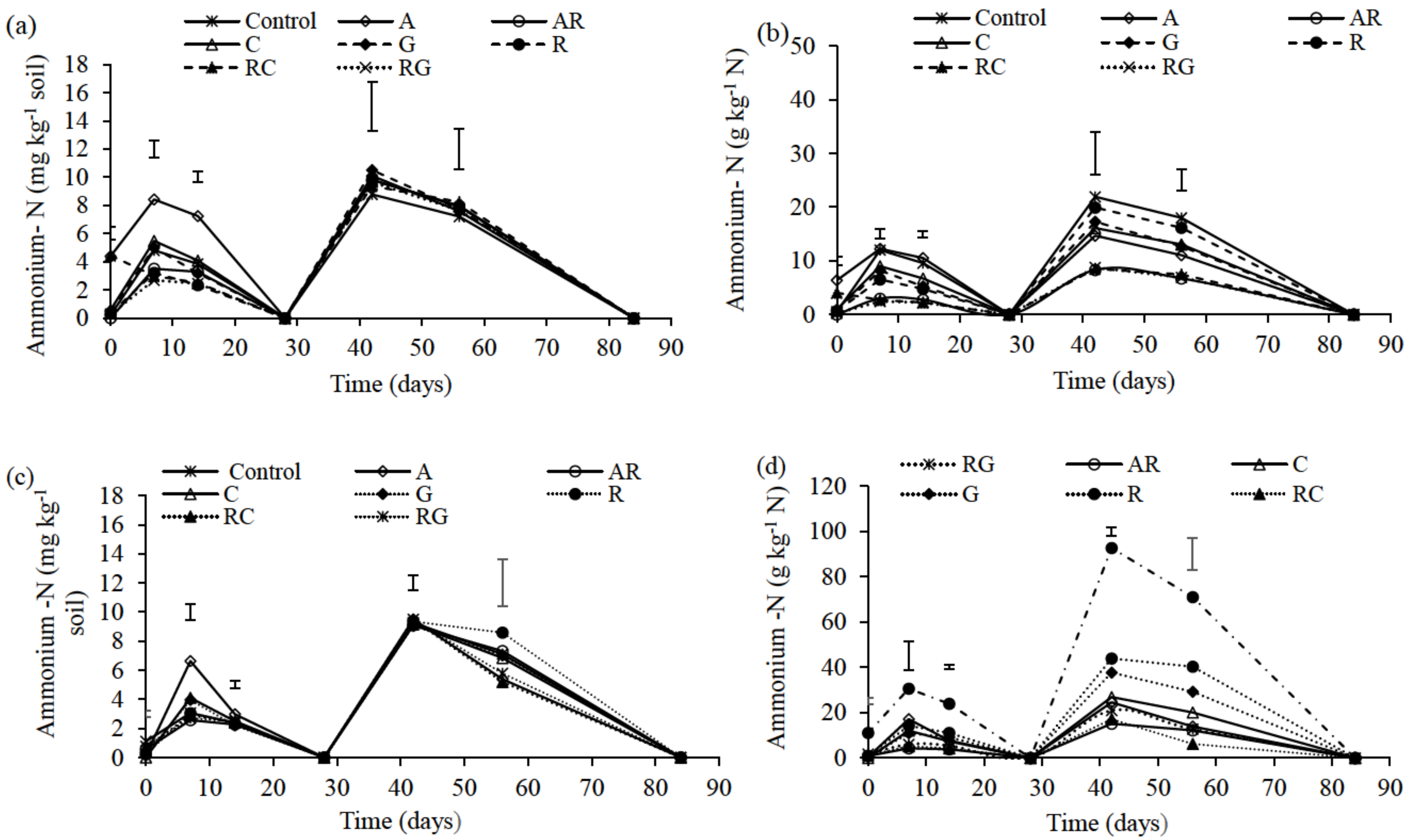


Figure 4.1: Ammonium-N concentration under different organic amendment treatments. uMbumbulu soil amended with organic amendments from uMbumbulu (a and b), Msinga soil amended with organic amendments from Msinga (c and d). Vertical error bars indicate LSD ($p<0.05$). Control=soil, A= soil with accelerator, R= soil with maize residues, G= soil with goat manure, C= soil with cattle manure, RG= soil with maize residues and goat manure, RC= soil with maize and cattle manure, AR= soil with maize and accelerator.

4.3.1.2 Soil nitrate N

In Experiment 1 (uMbumbulu soil), the nitrate-N (mg kg^{-1} soil) in an accelerator treatment was similar to goat and cattle manure but higher than the other treatments after days 7 and 14 (Figure 4.2a). Beyond 14 days the accelerator alone treatment had higher nitrate-N than cattle and goat manures. The control and accelerator+residueswere higher than all other treatments with residues throughout the incubation days (Figures 4.2a). The control had higher nitrate-N than all treatment combination containing maize residues except for the accelerator+maize residues which had similar concentration between 28 to 84 days of incubation. When expressed in g kg^{-1} of N, the nitrate-N in the accelerator, goat and cattle manures, and the control treatments was higher than in the treatment combinations with maize residues, throughout the incubation (Figure 4.2b).

The results of Experiment 2 followed the same trends as for Experiment 1, with the nitrate-N (mg kg^{-1} soil) in an accelerator treatment being similar to goat and cattle manure at the beginning of the incubation and higher than the other treatments (including maize residues) after 7 day (Figure 4.2c). Beyond 14 days the accelerator treatment had higher nitrate-N than cattle and goat manures, the control and accelerator+residues, which were higher than all other treatments with residues throughout the incubation days (Figures 4.2c). Like Experiment 1, the control had higher nitrate-N than all treatment combinations containing maize residues between 14 to 56 days of incubation except for the accelerator+maize residues between 14 to 56 days, which had similar. After 84 days of incubation, the control had similar nitrate N as the treatments with maize residues except the accelerator+maize residues, which had higher concentration (Figure 4.2c). When expressed in g kg^{-1} of N, the nitrate-N in the control was higher than all other treatments throughout the incubation period (Figure 4.2d). The accelerator, goat and cattle manures had higher nitrate-N (g kg^{-1} N) than in the treatment combinations with maize residues, from day 14 to 42 except that there were no significant differences with the treatments with residues only and accelerator+maize residues on day 84 (Figure 4.2d).

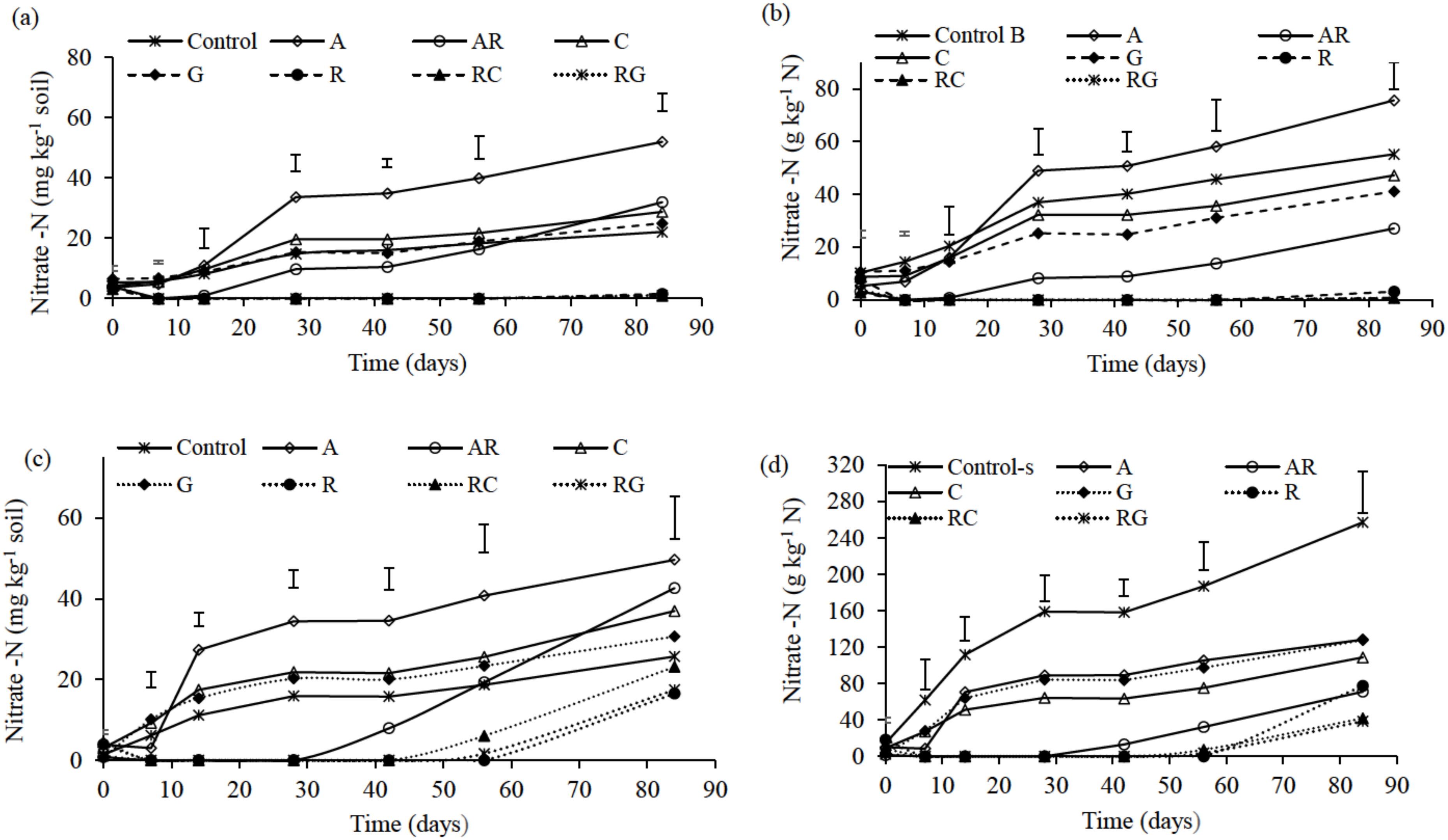


Figure 4.2: Nitrate-N concentrations under different organic amendments treatment. Soil with organic amendments from uMbumbulu (a and b), Soil with organic amendments from Msinga (c and d). Vertical error bars indicate LSD ($p<0.05$). Control=soil, A= soil with accelerator, R= soil with maize residues, G= soil with goat manure, C= soil with cattle manure, RG= soil with maize residues and goat manure, RC= soil with maize and cattle manure, AR= soil with maize and accelerator.

4.3.1.3 Mineral-N

Mineral-N concentration followed the same trend as nitrate-N for accelerator treatment as it increased after day 14 of incubation (Figure 4.3a, b, c and d). A combination of maize residues with either cattle or goat manure (RC, RG) in experiments 1 and 2 (Figure 4.3a and 4.3c) showed a decrease in the Mineral-N. There was a significant difference of mineral-N concentration among the treatments in both experiments (Figure 4.3a and 4.3c). From day zero to day 84 accelerator treatment was significantly higher than accelerator+maize residues treatment in both soils. Mineral-N in soil of N present (g kg^{-1} N) showed the same trend as mineral-N (mg kg^{-1} of soil) (Figure 4.3b and 4.3d)

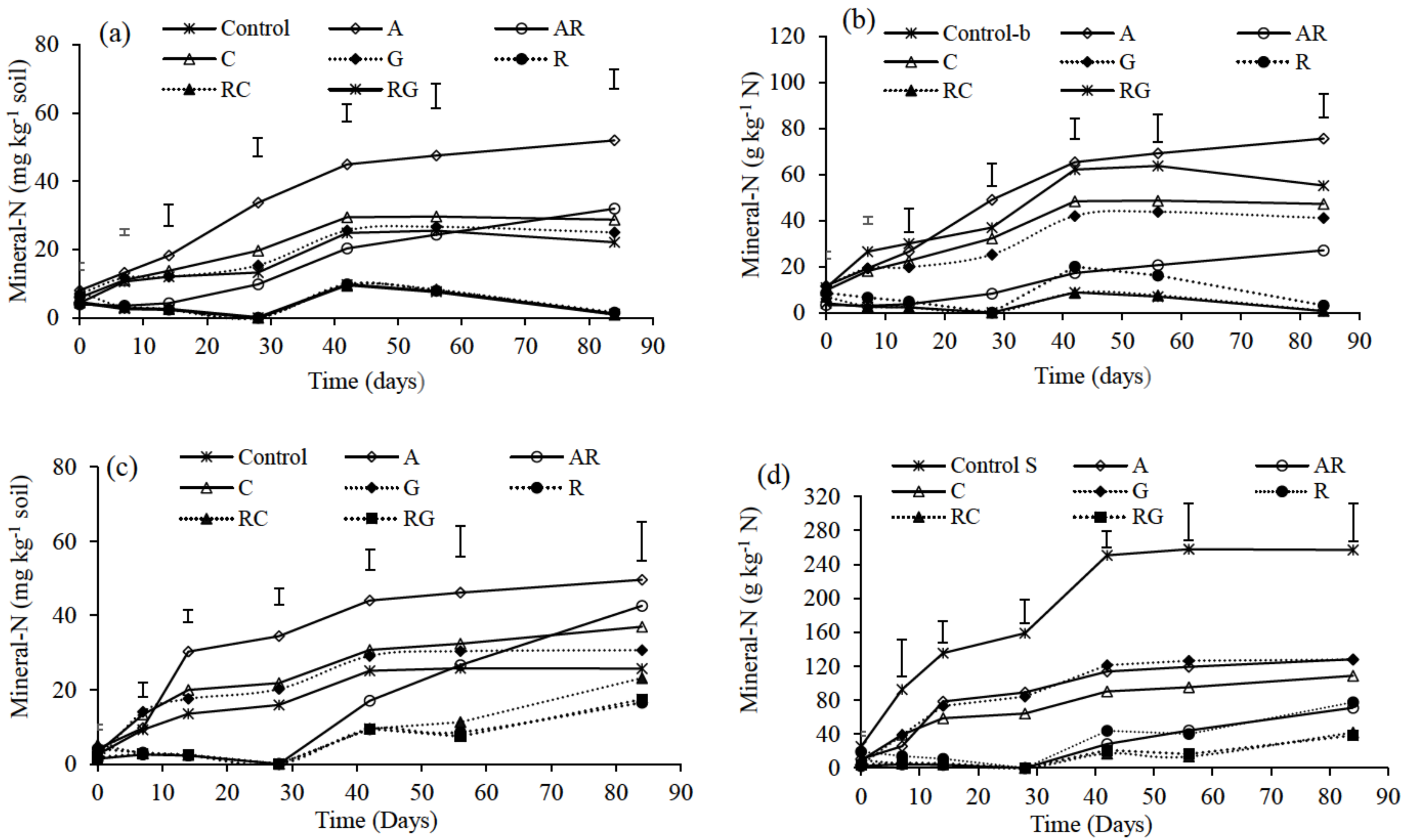


Figure 4.3: Mineral-N concentrations under different organic amendments. Soil with organic amendments from Mbumbulu (a and b), Soil with organic amendments from Msinga (c and d). Vertical error bars indicate LSD ($p<0.05$). Control=soil, A= soil with accelerator, R= soil with maize residues, G= soil with goat manure, C= soil with cattle manure, RG= soil with maize residues and goat manure, RC= soil with maize and cattle manure, AR= soil with maize and accelerator.

4.3.1.4 Extractable P

Among all the treatments from day 0 to 84, extractable P concentration (mg kg^{-1} soil) showed no significant difference in both Experiment 1 and 2 (Figure 4.4a and 4.4c). The experiment showed fluctuations in extractable P concentrations throughout the incubation period, with highs at 7, 28, and 56 days and lows after 14, 42 and 84 days, irrespective of treatment. The same trend was observed in Experiment 2 (Figure 4.4c), with no differences between the treatments. When extractable P concentration was expressed in g/kg N, the fluctuations of the concentrations followed the same trends as when expressed in mg kg^{-1} soil, but there were significant differences among treatments. For Experiment 1, co-application of maize residues with an organic amendment, in uMbumbulu soil resulted in lower P concentrations than the other treatments throughout the incubation period except day 42 (Figure 4.4b). For experiment 2, the co-application of maize residues with other amendments resulted in lower extractable P than the control treatment, throughout the incubation study. In addition, at 56 and 84 days, the goat manure and residues only treatments also had higher extractable P than where residues were combined with another organic amendment.

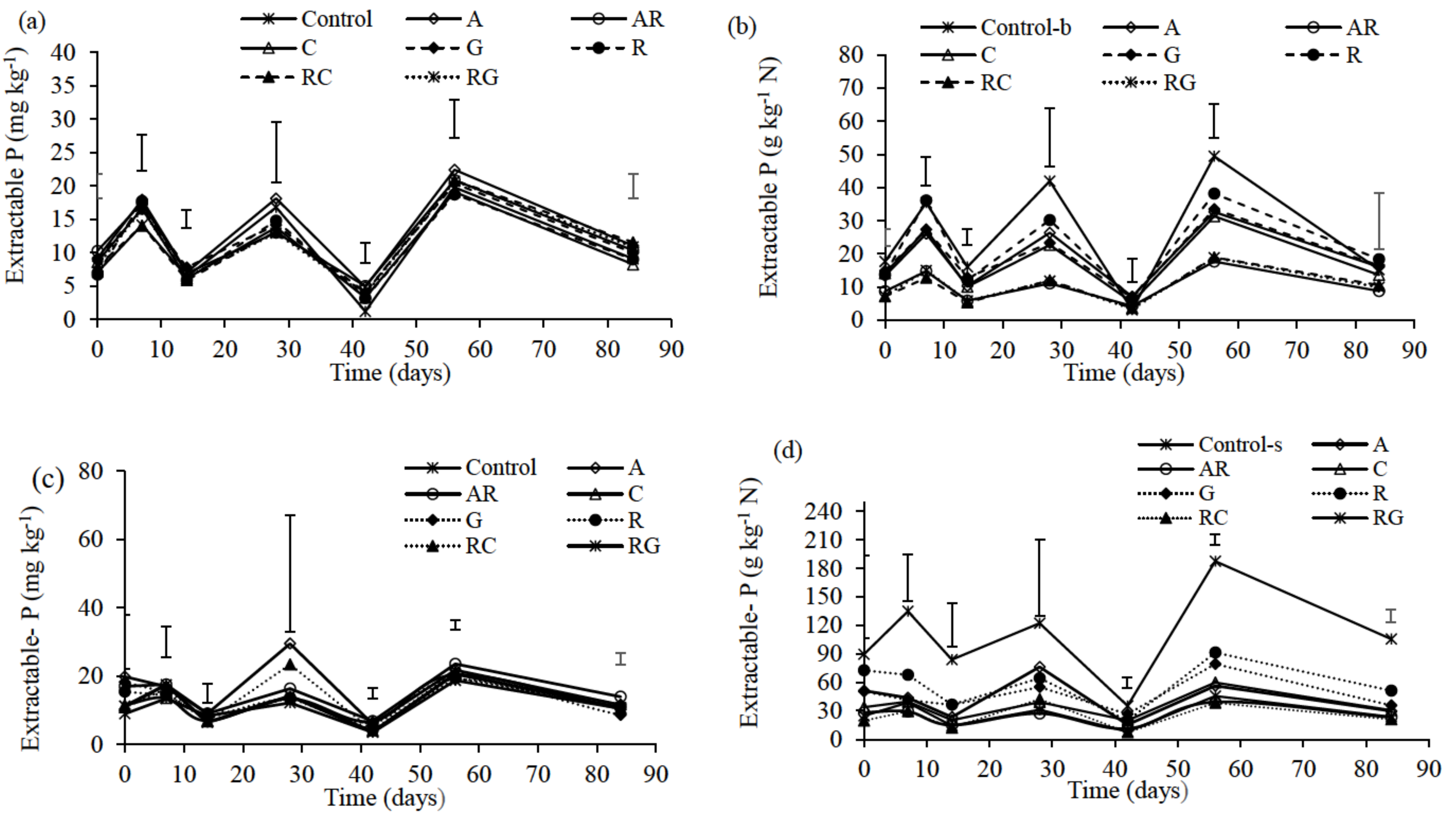
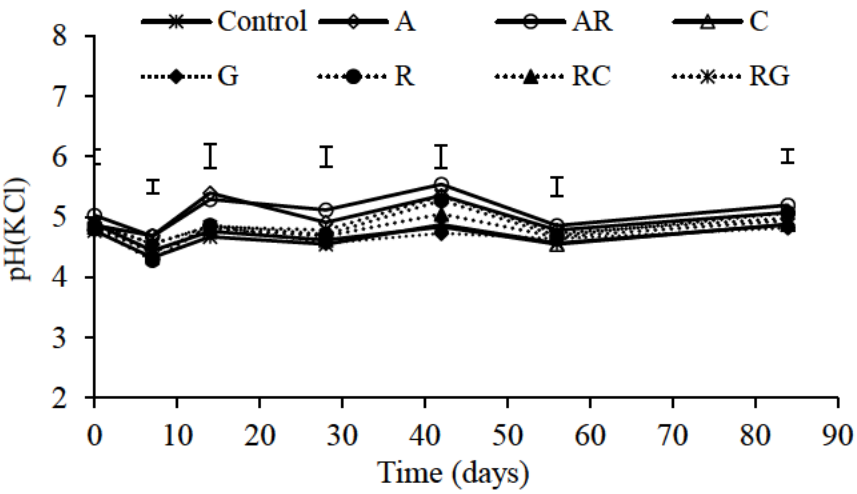


Figure 4.4: Concentration on P extracted under different organic amendments. Soil with organic amendments from uMbumbulu (a and b), Soil with organic amendments from Msinga (c and d). Vertical error bars indicate LSD ($p<0.05$). Control=soil, A= soil with accelerator, R= soil with maize residues, G= soil with goat manure, C= soil with cattle manure, RG= soil with maize residues and goat manure, RC= soil with maize and cattle manure, AR= soil with maize and accelerator.

4.3.1.5 Change in soil pH

There were significant differences in soil pH for all th0e incubated days, except day 0 and day 56 for those from uMbumbulu (Figure 4.5a), and day 0 for those from Msinga (Figure 4.5b). uMbumbulu soils treated with accelerator and with accelerator + maize residues, had the highest pH on days 14, 28, 42 and 84), while the control was among the lowest, throughout the incubation period. In Experiment 1, the pH of uMbumbulu soil treated with maize residues alone or with cattle manure showed no significant differences but it showed a significant difference when compared with goat manure or accelerator for day 7 only. In Experiment 2, treatments with accelerator and accelerator+maize residues from Msinga had significantly higher pH than where maize residues alone were added, on days 14, 28 and 56 and the control had lowest pH throughout the incubation

A.



B.

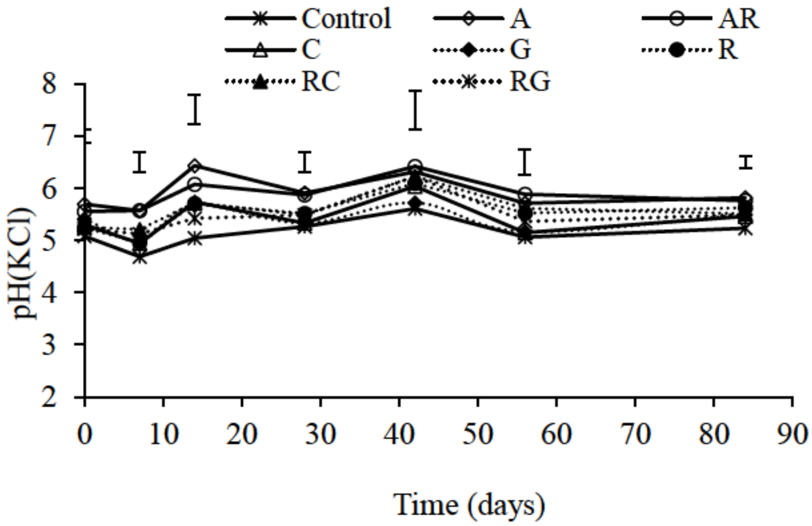


Figure 4.5: Change in pH under different treatments of organic amendments with incubation days. Mbumbulu soil with organic amendments from Mbumbulu (A), and Msinga soil with organic amendments from Msinga (B). *Control=soil, A= soil with accelerator, R= soil with maize residues, G= soil with goat manure, C= soil with cattle manure, RG= soil with maize residues and goat manure, RC= soil with maize and cattle manure, AR= soil with maize and accelerator.*

4.3.1.6 Total Carbon

There were no significant differences in SOC between all the treatments at day 84 of incubation, in both experiments from uMbumbulu (Figure 8A) and Msinga (Figure 8B). In uMbumbulu, the SOC ranged from 3.00 to 3.73%, while it ranged from 1.77-1.97% at Msinga.

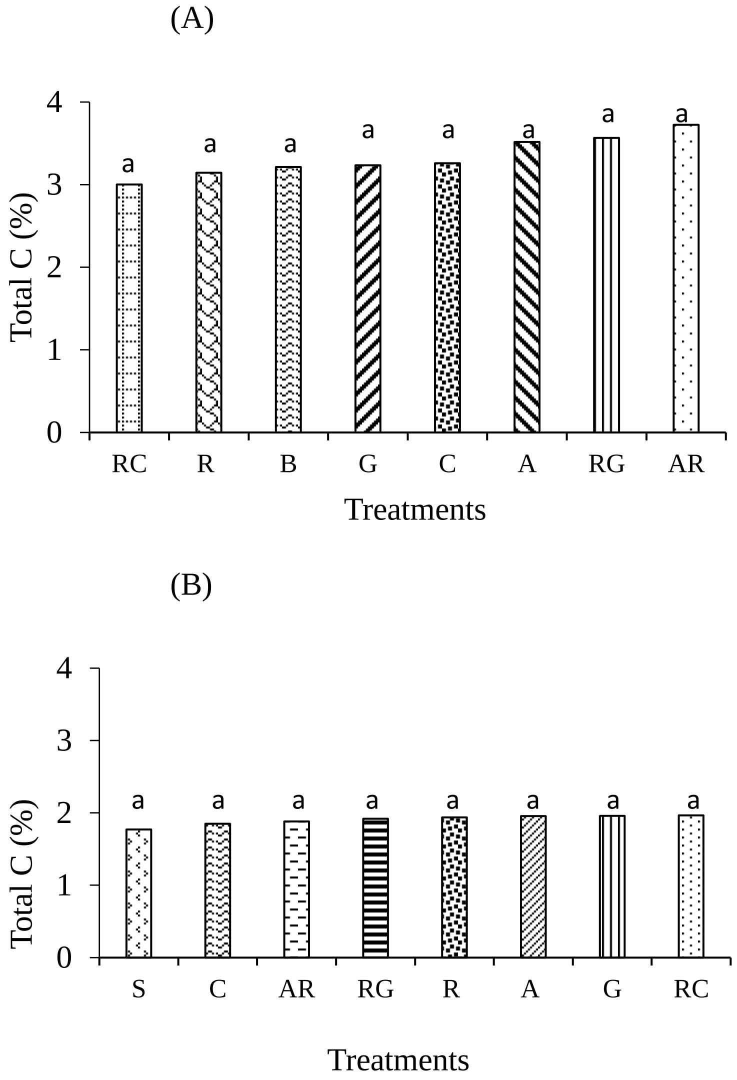


Figure 4.6: Total carbon at day 84 of incubation. (A) Soil with organic amendments from uMbumbulu, (B) Soil with organic amendments from Msinga. Letters indicate the different. *C=soil, A= soil with accelerator, R= soil with maize residues, G= soil with goat manure, C= soil with cattle manure, RG= soil with maize residues and goat manure, RC= soil with maize and cattle manure, AR= soil with maize and accelerator.*

4.4 Discussion

Organic manures are essential sources of nutrients to plants, especially N, which contributes to the N demand for growing crops. The lower N content, higher C:N ratio and lowest bases and micronutrients of maize residues (Table 4.2 and 4.3) compared to other organic amendments in both study sites, particularly could lead to lower decomposition leading to lower available nutrients into the soil. The view was supported by the results of mineral N which were lowest in treatments with maize residues that those without (Figures 3, 4 and 5). Plant residues with high nitrogen content when incorporated into the soil results in high decomposition rates and nutrient release (Swift *et al.*, 1979). However, the slower decomposition could result in great SOC storage. Vahdat *et al.* (2011) determined the critical value that allow lignin decomposition to be 25% with no N mineralization or immobilization when >25%. Thus, lower lignin content in maize residues from both areas could result in greater N mineralization with Msinga maize having lower lignin content percentage of 5.26 ± 0.05. However, the N mineralization results appeared to be more related to N content, C:N ratio, and other nutrients as cattle manure and goat manure from both areas had lignin content above 25% which result in low N mineralization. Amendments with low lignin content, like the Accelerator (15.8%), are expected to decompose faster and stimulate phosphatase enzyme activity which contribute to high available P (Garg and Bahl 2008), compared to other amendments. A study that was done by Palm and Sanchez (1990) on three legumes to evaluate their decomposition and N release showed that *Erythrina sp*. with low lignin (9.7%) decomposed faster when compared to *Inja edulis* and *Cajanus Cajan* (16.3% and 10.2%), releasing more P (4.32%) into the soil. In 2004, Baggie *et al.* found similar results where *Gliricidia* material with low lignin content decomposed faster and released the highest acid-exchangeable P concentration (<500 mg kg$^{-1)}$ after two weeks of incubation.

The higher C:N, C:P and lower nutrient composition in maize residues could have limited microbial activity and mineralization of nutrients, irrespective of the lower lignin content, than the other organic resources. The higher C:P ratio for the maize residues (>200:1) compared to other amendments suggests that this resource could result in P immobilization (Shepherd and Withers 1999). Azeez and Van Averbeke (2010) showed that poultry manure mineralized P faster compared cattle and goat manure to due to lower C:P ratio (Chadwick *et al.*, 2000; Trinsoutrot *et al.*, 2000). Organic amendments with low P and high C: P ratio are known to release less P (Gagnon and Simard 1999), due to microbial immobilization. The lowest C/P in the Accelerator showed that the P in this resource could rapidly mineralize making P available for plant uptake while maize residues could limit availability of P. The lower percentage lignin (5.26 ± 0.045) in maize residues from Msinga when compared with those from uMbumbulu might be due to the climatic differences and this indicate that maize residues from uMsinga are of good quality for nutrient addition. The lower lignin explains the generally greater N mineralization in most incubation days from the maize residues from Msinga than uMbumbulu.

The higher iron and aluminum in goat and cattle manures might be due to that the sample contained some soil and considering that the soils of these two regions are acidic, they may have high concentrations of iron and aluminum oxides. Msinga goat and cattle manures followed a similar trend as of uMbumbulu manures with high Fe and Al. The high concentrations of Fe and Al in the manures could have been limited microbial activity and decomposition than the Accelerator. The Accelerator also had higher bases than other amendments supporting greater microbial activity and more nutrients are added and released into the soil. These results are supported by greater N mineralization in the Accelerator than the other organic resources. Considering that the soils from the two sites were generally similar, except for SOC, which was higher in the soil from uMbumbulu than Msinga, the mineralization of N and P in the soils could essentially be explained by the differences in the quality parameters of the organic amendments. The results of the incubation experiments showed a distinct low NH_4^+-N for all treatments, for both sites (soils) on day 28, which could be due to moisture content as watering was limited, as there were restrictions to the laboratory due to the COVID-19 pandemic.

Different organic amendments decompose and release nutrients, including NH_4^+-N and NO_3^--N. The higher NH_4^+ concentration in the control soil from Msinga than all other treatments for day 42 and 56 (Figure 2D) might be because the NH_4^+ got utilized by soil microorganisms or was lost through volatilization, due to higher microbial activity where organic amendments were applied into the soil (Iritani and Arnold 1960). The higher ammonium-N in the accelerator treatment for day 7 and 14 than the manures and maize residue treatments was a result of higher N present in the accelerator added (Table 3.3), considering that all the amendments were added at the same rate of 1%. The fact that the control treatment had among the highest ammonium-N released, when normalized for the N present (g/kg N), both in uMbumbulu (Experiment 1) and Msinga (Experiment 2) soils except on day 28 and 84, indicated that the N in soil organic matter was among the most mineralizable. The higher ammonium-N concentration (g/kg N) in the accelerator treatment than maize residues at day 14 was due to higher N, P and other nutrients of initial nutrient content of the accelerator, and lower C:N and C:P ratios of, resulting in more rapid decomposition (Table 4.2 & 4.3). This is consistent with Marschner *et al.* (2015*)* who found that grass residues with low C:N ratio was associated with more available C, N and P than residue with high ratio in South Australia. Similarly, Zare and Ronaghi (2019) showed how poultry and cattle manure released more ammonium-N due to the higher N content and lower C:N ratio. The lower ammonium-N (g/kg N) in soils treated with maize residues combination with either cattle manure, goat manure and accelerator, than when applied separately could partly be explained by higher C:N of maize residue (37:1- 42:1), which is known to result in N immobilization. These views were further supported by the lower nitrate-N (in g/kg N), in treatments with maize residues than the other treatments in both soils. The generally higher ammonium-N in the soils from Msinga than uMbumbulu can be due to relatively higher pH at Msinga, which support activity of bacteria involved in the mineralization of N. The increase in NH_4^+ from day 0 to day 7 and sharp decrease from day 7 to 28 in both uMbumbulu and Msinga soil (Figure 2b and 2d) corresponded with increases in NO_3^- concentration (Figure 3b and 3d). An increase in NO_3^- concentration (mg/kg soil) with days may be a result of the activity of nitrifying bacteria, which converts NH_4^+ into NO_3^- .

The NO_3^- concentration when presented in mg/kg of soil was lower from day 7 to day 84 of incubation in maize residue treatment compared to other amendments, due to slow decomposition, mineralization and nitrification of N because of higher C:N ratio compared to the other treatments. Treatments with maize residues had zero nitrate-N concentration (in mg/kg N present and g/kg of soil) from day 7 to day 56 meaning it was under the detectable range in both uMbumbulu and Msinga soils. This might be due to when nitrate-N was under undetected range NH_4^+-N was lower limiting nitrification process, making maize residues less beneficial for farmers to N cycling when applied in the soil. The higher nitrate-N in the control treatment in uMsinga soils (g/kg N) than all other treatments with incubation days might be due higher NH_4^+-N and more nitrifying microorganisms which convert ammonia to nitrate. The generally lower NO_3^- concentration in all treatments in uMbumbulu soil compared to Msinga soil could be due to uMbumbulu being slightly more acidic with pH of 4.55limiting nitrification. Nitrifying bacteria are more active in less acidic soils. Yao *et al.* (2011) showed that nitrification activity was higher in neutral or slightly alkaline conditions in Southeast China due to active microorganisms. Nitrification is less active in highly acidic soils (pH<4.5) (De Boer and Kowalchuk 2001). The increase in mineral-N (ammonium- + nitrate-N) with progressive incubation (Figure 4b and 4d) was due to net mineralization that occurred during the incubation period. It was also expected of mineral-N to increase with time because organic manures have a higher concentration of total N, and variation in mineralization among treatment was due to more labile organic N compounds and high levels of microbial biomass and activity in manure (Abbasi *et al.,* 2012). This agreed with the similar report of Singh *et al*. (1992). Mineral-N in early incubation days was low in treatments of maize residues combined with either cattle or goat manure but later increased which suggest that composting of the combined resources may be required to derive immediate benefits.

Application of organic amendments would mineralize and release high levels of nitrogen (>120 g/kg N), which may be above the recommendation rate of most crops; including maize which requires 120 kg/N ha to achieve a 10 t/ha yield (Fertilizer Society of South Africa. 2007). The 128 g/kg of nitrate-N concentration released by an accelerator amendment (A at day 84 of incubation), is too high for crops such root vegetables and might be lost through groundwater contamination. However, this might be not applicable to field conditions as environmental factors are not controlled as they change with time and season. The higher nitrate-N concentration in g/kg N present from Msinga amendments than uMbumbulu might be due to the chemical composition of the amendments, and the slightly higher soil pH, which can result in higher mineralization rate. Acidic soils tend to inhibit microbes affecting decomposition rate as it drastically decreases microbe respiration at pH below 4, and nitrification is particularly negatively affected. Application of the organic amendments from Msinga could be more beneficial than those from uMbumbulu soils in the short-term. The drastic increase in nitrate-N in treatments combined with maize residues after day 56 of incubation suggested that the N in these residues could became available for uptake by a subsequent crop.

Soil pH is known to affect nutrient solubility and influences its sorption or precipitation with Al and Fe (Hue 1992). A decrease in soil pH in all treatments for experiments 1 and 2 (Figure 4.5a and b) from day 0 to day 7 might be due to the soil's high exchangeable acidity (Table 4.1). High exchangeable acidity caused more Al^{3+} and H^+ ions, and the addition of basic cations from organic manure could have forced Al^{3+} out of the exchange sites and subsequently forced to be inactive by forming complexes with organic molecules (Azeez and Averbeke 2012). There was a variable decrease and increase in soil pH with incubation days in all treatments. This might be due to proton consumption during decarboxylation of organic acid anions which occurs during decomposition (Yan *et al.,* 1996). Soils treated with an accelerator in Experiments 1 and 2 (Figure 4.5a and 4.5b) had higher pH values throughout the incubation days when compared to other treatments. This might be due to high pH of accelerator (Table 4.2) at the time of application or proton exchange between the soil and the amendments (Wong *et al.,* 1998). Acidic conditions in the soil are associated with high soluble Al and Fe and oxides of these elements, which fix P, causing P deficiency in plants (Troeh and Thompson 1993). Extractable P concentration is expected to decrease with a decrease in soil pH due to P fixation by Al and Fe in acidic soils. The lower P concentration in treatments where maize residues were combined with other organic amendments and the control could be because of the C:P ratio of the maize residues which may have caused immobilization of P.

The lack of significant differences in total carbon after day 84 of incubation in uMbumbulu (3.0-3.73%) and Msinga soil (1.72-1.97%) (Figure 4.6A and 4.6B), might be because of low levels of C released from the added 1% of organic amendments, which translated to a maximum of 0.42% C added as maize residues, while a significant portion of the amendments was decomposed and potentially released as CO_2.

4.5 Conclusion

Characterization of the organic amendments showed that Msinga amendments are more beneficial due to high concentration of nutrient available for plant uptake than amendments from uMbumbulu. Maize residues had lower nutrients and lignin but higher C:N and C:P than the manures and the Accelerator, in both areas. The Accelerator had higher nutrients, lower lignin, C/N and C/P than the cattle and goat manures in both areas making it more beneficial for farmers to use as it decomposes faster. Application of these organic amendments increased mineral-N (ammonium-N and nitrate-N) with high concentrations in g/kg N from both uMbumbulu and Msinga areas. High mineralization of these amendments with an increase in nutrient release could be sufficient to improve soil fertility and increase crop productivity in these soils. The organic amendments from Msinga can be recommended for soil fertility improvement as they increased the ammonium-N and nitrate-N concentration, especially when applied to soils from the same region. Accelerator with low lignin content decomposed faster, releasing more P and N, which could be sufficient in increasing crop production on smallholder farms. Maize residues, when combined with either cattle or goat manure released low mineral-N concentration than when applied alone. Combined application of manures with maize residues may restrict nutrient release into the soil, while the Accelerator can be recommended for use by farmers who can afford it. The co-application of Accelerator with maize residues could be more effective than co-application of maize residues with cattle, goat manure. Further studies need to be done under field conditions to make clear recommendations as incubation studies have controlled factors, and accelerator is still a limited resource to smallholder farmers. Low application of manures and maize residues is off less efficiency to return carbon into the soil as microbes tend to use the available carbon to decompose these amendments.

CHAPTER 5
GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

5.1 General Discussion

Soil fertility decline in smallholder farmers pose a huge impact on crop productivity as most developing countries depend on production from smallholder farmers. Chemical fertilizers have become more expensive for smallholder farmers, and they are not environmentally friendly. Many studies have been done on how the use of organic amendments as fertilizers increase mineral-N and extractable P during decomposition and mineralization, but limited work have been done in South Africa smallholder farmers with how it can return carbon into the soil. Use of these amendments will release nutrients into the soils thus increase soil fertility status. Many soils from smallholder farmers in South Africa are associated with high erosion (Garland *et al.,* 2000; Le Roux *et al.,* 2008) and organic amendments of good quality and quantity can restore carbon and phosphorus loss in these soils. The main objective was to investigate how management practices affect carbon and phosphorus pools and the use of organic amendments in returning nutrients into the soil.

The lack of significant differences in the results from the study showed that the different typologies, and the associated management practices, did not affect carbon and phosphorus pools in the soil. Farmers from different typology practiced different management, but fractionation of the pools showed no difference in uMbumbulu and Msinga, and this could be because of the low rates of application of carbon and phosphorus as components of organic amendments and fertilizer in these smallholder farm settings. The lack of effect of the amendments on soil C and its fractions on both soils in chapter 4 support the results in chapter 3 where typology showed no effect on fractions. This could also result from low C sources input coupled with decomposition and CO_2 emission. Furthermore, the lack of significant differences in extractable P between the treatments in Chapter 4 and also in P pools in chapter 3 showed that P was not affected by farm typology, field type and cropping system in the study areas. The study showed that some homesteads borrowed cattle or goat manures from others, which suggests that insufficient quantities of manures were applied. There was significant correlation of carbon and phosphorus fractions, particularly in Msinga soil, and to a lesser extent, uMbumbulu soil. This showed that increase in SOC in these smallholder areas could increase availability of P and its other forms in soils, which could be beneficial to crops grown. Application of organic amendments to these soils could release nutrients and improve carbon storage in the soil. Application of the organic amendments such as the accelerator, goat and cattle manures resulted in increased availability of mineral N during incubation. However, maize residue application in acidic soils released ammonium-N and nitrate-N concentration slowly than the accelerator amendment due to the residues having high C:N ratio and low decomposition rate. Extractable P from maize residues could be beneficial to the crops as maize residues released higher concentration of P due to low lignin content but it should be applied prior to cultivation to allow it to decompose and release nutrients. This will enhance the availability of the nutrients to plants, hence increase crop yields. Release of mineral-N with progressive incubation in the accelerator treatment is explained by low lignin content and low C:N ratio. Few smallholder farmers own livestock leading to low availability of manures for farmers to apply on the soils. Application of combined manures with maize residues resulted in low concentration of mineral-N into the soil. This could be due to low maize residue lignin content affecting the decomposition of these amendments.

5.2 Conclusion

Difference in typology, field type and cropping system had no effect on soil carbon and phosphorus pools under different management practices and use of organic amendments do return nutrients into the soil improving soil fertility. Total C, cPOMC and fPOMC were different between uMbumbulu and Msinga due to difference in temperature with uMbumbulu characterized warm average temperature compared to Msinga (Camp, 1999). Msinga amendments were more beneficial for nutrient release and mineralization than uMbumbulu amendments due to high concentration of mineral-N (ammonium-N and nitrate-N). Soil pH fluctuated with incubation days in treatments with amendments addition. High mineralization of these amendments improves soil fertility and quality as maize residues and accelerator had low lignin content resulting in more N mineralization. Co-application of Accelerator and maize increased the concentration of mineral-N than co-application of maize with goat ad cattle manure. Application of the accelerator+maize residues would be more of beneficial for farmers than maize residues+cattle manure and maize residues+goat manure.

5.3 Recommendations

With no relationship on how management practices affect carbon and phosphorus fractions, more work needs to be done to provide an understanding on how other environmental factors such as climate and topography affect carbon and phosphorus fractions in soils of different region. Accelerator shown to be more of good quality in mineralization of N and P compared to cattle manure, goat manure and maize residues but field trials also need to be done to understand how these organic amendments decompose and mineralize under many uncontrolled environmental conditions. Further studies on degradation of organics such as manures and maize residues through co-composting are needed to determine whether immediate nutrient benefits can be derived.

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